FINAL PROJECT – TI 184833

DEVELOPING AN APPLICATION OF INVENTORY ROUTING PROBLEM FOR MANAGING BATTERY SWAP STATIONS

FITRI ANNISAAULKARIMAH
NRP. 02411640000140

SUPERVISOR:
Dr. Eng. Ir. Ahmad Rusdiansyah, M.Eng., CSCP. CLTD.
NIP. 196811091995031003

DEPARTMENT OF INDUSTRIAL SYSTEM AND ENGINEERING
FACULTY OF INDUSTRIAL TECHNOLOGY AND SYSTEMS ENGINEERING
INSTITUT TEKNOLOGI SEPULUH NOPEMBER
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APPROVAL SHEET

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Author:
FITRI ANNISAAULKARIMAH
NRP 02411640000140

Approved by:
Supervisor

Dr. Eng. Ir. Ahmad Rusdiansyah, M.Eng., CSCP. CLTD.
NIP. 196811091995031003

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DEVELOPING AN APPLICATION OF INVENTORY ROUTING PROBLEM FOR MANAGING BATTERY SWAP STATIONS

Name	: Fitri Annisaaulkarimah
Student ID	: 02411640000140
Department	: Industrial and System Engineering
Supervisor	: Dr. Eng. Ir. Ahmad Rusdiansyah, M.Eng., CSCP. CLTD.

ABSTRACT

The trend of electric vehicle keeps increasing annually, especially due to a campaign of “EV 30@30”. This campaign has a target of minimum 30 % of deployment of electric vehicles (EVs) in the world by 2030. Currently, EV is refueled with charging scheme by plugging the EV into a charging outlet. A study found that availability of charging infrastructure and charging time became one of the reasons for people to not buying electric vehicle. However, this issue could be overcome by using battery swapping concept. Battery swapping concept is a system where fully charged battery could be obtained by exchanging it with the depleted battery in a Battery Swap Station (BSS). To maintain the availability of fully charged batteries in the BSSs, each BSS is completed with centralized charging platform. Besides, a fleet of vehicles could be operated to distribute fully charged batteries from Center Battery Station (CBS) to replace the depleted batteries in BSSs. CBS should know the inventory level of BSS in order to determine the appropriate delivery quantity. This research develops an Inventory Routing Problem (IRP) model to create distribution plan that minimizes stock-out in BSSs with decision over time only. The IRP model is developed by considering stochastic demand and state of charge (SoC) of each battery in each BSS. To determine the appropriate amount of replenishment unit to each BSS, a minimum acceptable SoC (α) value is required. The model is developed heuristically in Microsoft Excel 2016 using Visual Basic for Application (VBA). Besides developing the IRP model, two numerical experiments are also conducted in respect of total cost and total lost sales.

Keywords : Inventory Routing Problem (IRP), Battery Swap Station (BSS), State of Charge (SoC)

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The author realizes that there are still many drawbacks in this research. Hence, the author welcomes any critics and suggestions for this research. At the end, author hopes that this research could give insights to any interested parties.

Surabaya, August 2020

Author

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CHAPTER 1
INTRODUCTION

In this chapter will be explained the background of this research, the main problem to be solved, the objectives of the research, the benefits of the research, the limitations and assumptions of the research, and the outline of the report in general.

1.1 Background of Problem

Electric Vehicle (EV) is a vehicle that powered either partially or fully by electric power. It is mainly divided into three categories that are Battery Electric Vehicle (BEV), Plug-In Hybrid Electric Vehicle (PHEV), and Hybrid Electric Vehicle (HEV). BEV is an electric vehicle that fully consists of the rechargeable battery and none of the fuel tank. On the other hand, PHEV is an electric vehicle consists of the rechargeable battery and fuel tank, so does HEV. Even though HEV has both battery and fuel tank, it could not be recharged from the power grid that becomes a huge difference to BEV and PHEV.

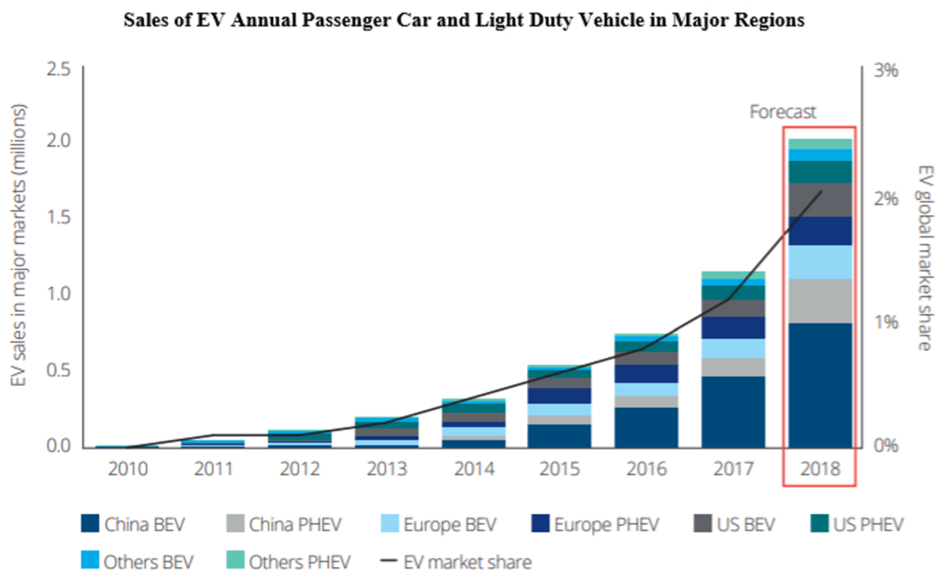

Figure 1.1 Electric Vehicle Sales and Global Market Share in Major Regions

Source: International Energy Agency (IEA), HIS Markit in Deloitte (2019)

Electric vehicle, especially BEV attracts more people every year as the number of Battery Electric Vehicle (BEV) grew in a positive trend from 2010 to 2018. The deployment of EV is also predicted to keep increasing annually because of the "EV 30@30" campaign that was declared during the 8th Clean Energy Ministerial (CEM) in 2017. "EV 30@30" is a campaign of accelerating the deployment of electric vehicles by setting a target of a minimum of 30% of new electric vehicles (except two-wheelers) sales in 2030. Despite the positive growth of EV deployment, there are still some barriers to be overcome before the customers of EV become a majority. In 2018, a survey on the global automotive customer was conducted by Deloitte to understand customer concerns on Battery Electric Vehicles (BEV). As shown in Figure 1.2, there are four most important concerns regarding BEV that are lack of charging infrastructure, cost/price premium, driving range, and required charging time.

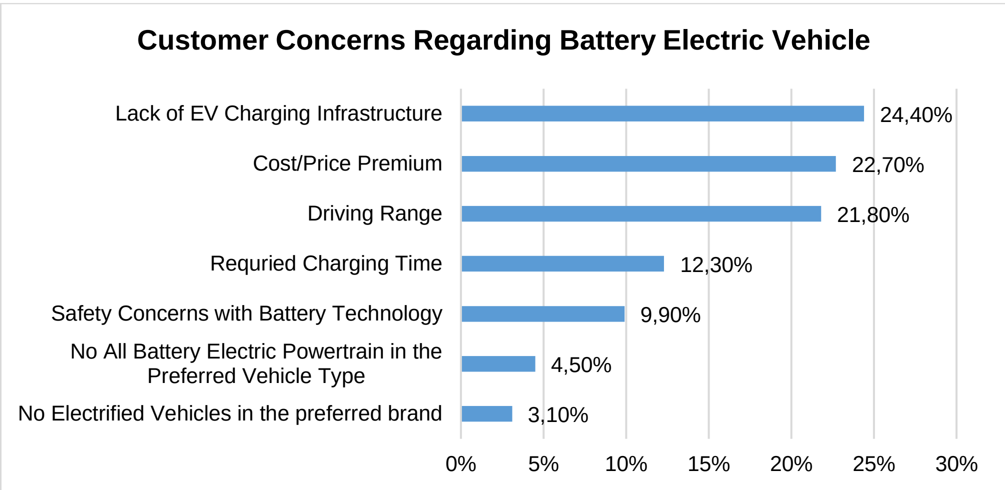

Figure 1.2 Customer Concerns on BEV

Source: Deloitte Global Automotive Consumer Survey (2018) in Deloitte (2019)

Most EV charging schemes are based on plugging the EV either into an individual outlet or into a Battery Charging Station (BCS) and leave the car for hours to be fully charged (Mahoor, Hosseini, Khodaei, & Kushner, 2017). Not only requires enough place for the EV, but it also requires a longer time than fueling a gasoline vehicle. According to Worley, O. & Klabjan, D. (2011), the charging time issue on behalf of EV owner can be overcome by swapping the empty battery with the fully charged battery. This method, which is called as battery swapping, could take less than 10 minutes for the whole swapping operation. It is recognized as much faster than conventional vehicles and the fastest recharging stations to get the vehicle ready for riding (Yang & Sun, 2014). Battery Swap Station (BSS) offers various advantages for the EV owner such as 1) accelerating the EV refueling time, 2) increasing the probability of having longer trip distance, and 3) reducing the cost of having appropriate private charging infrastructure. Moreover, compared to the common charging scheme, battery swapping allows the depleted batteries to be charged for the night at a discounted electricity price.

Figure 1.3 A GoStations of Gogoro

Source: Toll (2019)

The battery swapping concept was initially developed in 2007 by an Israeli start-up company named Better Place. With the main purpose of helping finish the global auto industry’s reliance on oil, Better Place signed an agreement with Renault-Nissan automobile to manufacture an electric car with a swappable battery. Better Place also built an extensive electrical infrastructure for charging stations, automatic battery swap stations, and integrative management software for the charging network. However, the expected vehicle sales of Batter Place were not satisfied due to poor operational performance and lacking another auto manufacturer willing to manufacture an electric car with a detachable battery (Dvir & Emet, 2016). It led to bankruptcy of Better Place in 2013 that was also considered as the end of battery swapping technology.

Despite the Better Place's failure, currently several EV manufacturers are developing the battery swapping technology. For instance are NIO as a Chinese electric car manufacturer and Gogoro as a Taiwanese electric motorcycle manufacturer. NIO has already had more than 100 NIO Power Swap in China with a claim of three minutes of battery swapping process by using a robot to replace the depleted battery with a fully charged one. On the one hand, Gogoro has coming up with more than 1,664 GoStations in Taiwan that requires only six seconds of battery swapping process without any interaction of robot within the process.

BSS has a main objective to ensure the service availability for battery swapping, meaning that every arrival time of EV should be provided with fully charged batteries. Therefore, a centralized charging platform exists within a BSS to recharge the depleted batteries. Besides depending on the BSS charging platform, a fleet of vehicles could be operated to swap the depleted batteries with the fully charged batteries in every BSS (Hof, Schneider, & Goeke, 2017). This could be considered as an alternative to help maintaining or increasing the stock of fully charged batteries in the BSS. Hence determining the appropriate vehicle routing plan for the distribution network is important in affecting the BSS service level. In the battery swapping service model, the batteries can be classified into three states: (1) available status, when the battery is fully charged; (2) charging status, when the battery is in charging condition; and (3) waiting for charging status, when the battery is replaced by the customer (Wu, Xu, Li, Yuan, & Chen, 2017). The battery state classifications would help the Center Battery Station (CBS) to determine the appropriate amount of fully charged battery to be distributed by the vehicle to BSSs. Thus, the battery swapping supply chain is considered under Vendor Management Inventory (VMI) system because the replenishment unit to each BSS is identified by CBS, as a supplier, by considering the inventory level of the BSS to ensure no stock-out will occur.

To manage the inventory level of each BSS, CBS should determine the appropriate distribution plan that has the least cost and least probability of causing stock-out at the BSS. The distribution plan covers vehicle routing, replenishment unit, and shipment time to each BSS. This problem is then considered as Inventory Routing Problem (IRP) because the routing scheme should pay attention to the inventory level of each BSS to deliver the required quantity without causing any stock-out on the BSSs. This research focuses on developing an Inventory Routing Problem (IRP) to minimize stock-out at Battery Swap Stations (BSS) with a study case of the electric motorcycle battery. Furthermore, the model will be constructed with the heuristic approach and will be developed by using Microsoft Excel 2016 Visual Basic for Application (VBA).

1.2 Problem Formulation

The problem that becomes the main subject in this research is how to determine a distribution plan using the IRP model that minimizes total cost and minimizes stock-out at the Battery Swap Stations.

1.3 Objectives

The objectives of this research are as follows.

1. To develop an Inventory Routing Problem (IRP) model considering stochastic demand and State of Charge (SoC) of batteries in Battery Swap Stations (BSSs).
2. To conduct numerical experiments on the model and analyze the results regarding to total cost and total lost sales.

1.4 Benefits

The benefits of this research are as follows.

1. To learn how to develop an Inventory Routing Problem (IRP) model for managing Battery Swap Stations (BSSs).
2. As a reference for the electric vehicle industry and related parties of creating a distribution plan to manage the service level in BSS using the Inventory Routing Problem (IRP) model.
3. To fill the gap in Inventory Routing Problem (IRP) research and battery swapping system research.

1.5 Limitations and Assumptions

In this subchapter will be mentioned the limitations and assumptions used in this research.

1.5.1 Limitations

The limitations used in this research are as follows.

1. There is only one type of battery used in the research.
2. The demand is generated from the beginning of truck operational time until the end of the day.
3. The number of depot is one.
4. The recharging system only exists in BSSs.
5. The model adopts a single period.

1.5.2 Assumptions

The assumptions used in this research are as follows.

1. All BSSs have the same maximum inventory level.
2. All BSSs have sufficient power supply to recharge all batteries from empty to full.
3. CBS has sufficient capacity to meet the demand.
4. The charging rate of the battery is static and deterministic.
5. All elements in the battery swapping system are in normal condition and able to operate normally.
6. The initial inventory of each BSS is equal to its maximum capacity.
7. There is none of the ordering cost.
8. The depleted batteries have the same initial State of Charge (SoC) that is 0%.
9. Only fully charged batteries that are available to be occupied by the electric vehicle owner.
10. No interruption exists during the battery delivery process by the truck.
11. All BSSs have the same value of minimum acceptable SoC (α).
12. CBS has sufficient amount of vehicle.

1.6 Report Outline

This subchapter consists of the report outline with a brief explanation of each chapter. The explanations are as follows.

CHAPTER 1 INTRODUCTION

This chapter gives the general information about the problem and the output of this research. It consists of research background, problem formulation, objectives of the research, benefits of the research, and assumption and limitation conducted in the research.

CHAPTER 2 LITERATURE REVIEW

This chapter consists of a brief explanation about the main references of this research and the comparisons to other related researches. The references include battery swapping concept, vendor managed inventory, and inventory routing problem.

CHAPTER 3 RESEARCH METHODOLOGY

This chapter explains the overall processes of conducting this research. The overall processes of this research will be depicted using a flowchart.

CHAPTER 4 MODEL DEVELOPMENT

This chapter discusses the development of the Inventory Routing Problem (IRP) in this research. It will be presented in terms of mathematical formulation, algorithm, and model verification.

CHAPTER 5 NUMERICAL EXPERIMENT AND ANALYSIS

This chapter consists of numerical experiments conducted using the IRP model and its result analysis. The results will be analyzed by considering total cost and total lost sales.

CHAPTER 6 CONCLUSION AND SUGGESTION

This chapter contains the conclusion of overall research regarding to the research objectives. Moreover, the suggestion will be included for further research.

CHAPTER 2
LITERATURE REVIEW

This chapter consists of information that is used as the preliminary study of the research. It consists of supporting theories for the research and the research's position regarding other researches.

2.1 Battery Swapping System

Battery swapping is a different approach to refueling electric vehicles by replacing the depleted batteries with fully charged batteries in a Battery Swap Station (BSS). Compared to the plug-in charging system, the battery swapping system offers several advantages, such as shorter service time and lower cost for EV users (Liu, et al., 2018). To ensure the Quality of Service (QoS) of the battery swapping system, each BSS should reserve sufficient fully-charged batteries to fulfill the battery swapping demand from EV users (Zhao, Zhang, & Wang, 2019). There are two ways of charging depleted batteries in the battery swapping system, which are using central charging in Battery Charging Station (BCS) and local charging in the BSS. In the battery swapping system, the fully-charged batteries will be transported from BCS to BSSs while the depleted batteries will be collected in the BSSs before being transported to the BCS. The battery flow in the battery swapping system forms a closed-loop supply chain that further will be considered as a closed battery logistics loop (Liu, et al., 2018). The closed battery logistics loop considers the BSSs without charging feature, thus the battery will be recharged in BCS or charging bay.

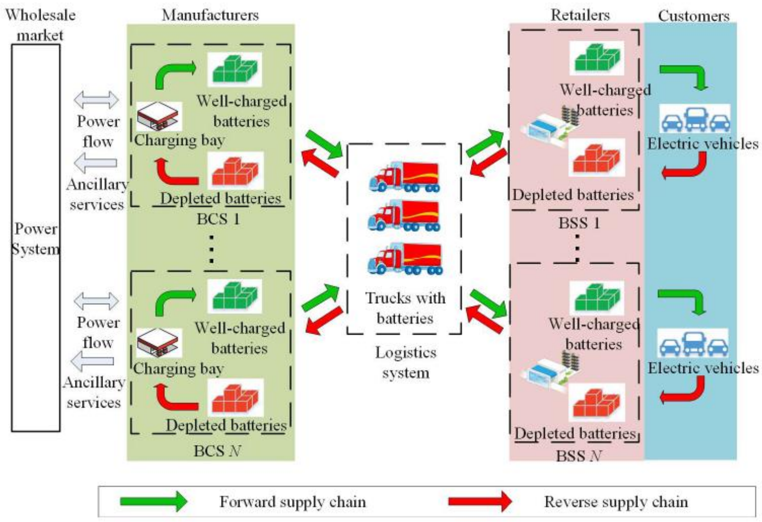

Figure 2.1 A Battery Logistics Loop

Source: Liu, et.al (2018)

There are three main subsystems in the battery swapping system; BCS, BSS, and logistics system connecting BSS and BCS. BCS has responsibilities to charge the depleted batteries and supply fully-charged batteries to BSS. While BSS is responsible to provide battery swapping service to the EVs, and also to charge the depleted batteries if the BSS has supporting charging feature. Since BCS and BSS are in different locations, the logistics system is responsible for transporting the batteries among the BCS and the BSS with a transportation network and a fleet of vehicles.

2.2 Battery Swapping Service Model

Battery swapping system provides service for EV users to replace their depleted batteries with the available fully-charged batteries in the BSS. Besides being a fully-charged batteries provider, BSS also acts as the depleted batteries collector and might have an additional role to charge the depleted batteries. According to these roles, the batteries in the BSS could be divided into three states that are (1) available status, when the battery is fully charged and ready for the swapping service; (2) charging status, when the battery is in charge; and (3) waiting for charging status, when the battery is replaced in a certain period (Wu, et al., 2017).

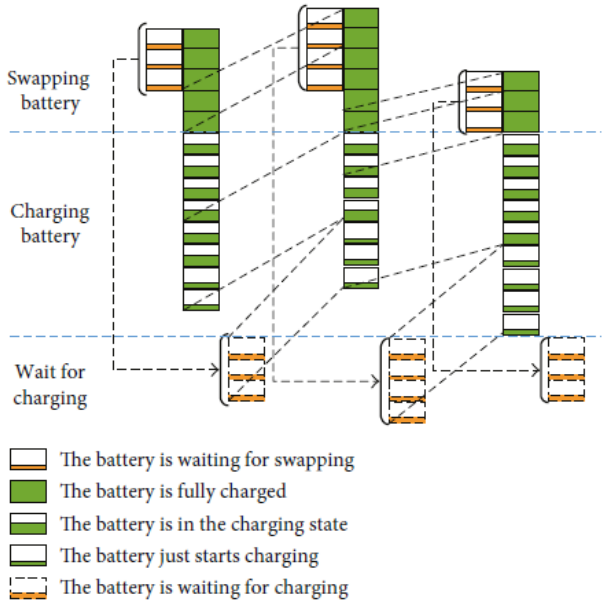

Figure 2.2 Battery Swapping Service Model

Source: Wu, et al. (2017)

In the battery swapping system, the availability of fully-charged batteries should be maintained to avoid any unfulfilled demand by prohibiting any stockout in all BSSs. Hence, it is necessary to track the inventory level of each BSS to determine the appropriate amount of fully-charged battery to be delivered to each BSS. The required information of each BSS' inventory level is the amount of each battery state for all three states, which will be modeled with mathematical formulations as in Wu, et al. (2017) below.

N_B = total number of power battery systems in the BSS

N_{CH} = total number of chargers in the BSS

N_S = number of EVs that can be served by the BSS

$N_A(i)$ = number of fully charged batteries in time slot *i*

$N_C(i)$ = number of battery in a charging in time slot *i*

$N_{NA}(i)$ = number of battery that will complete charging in time slot *i*

$N_{WB}(i)$ = number of battery that is replaced in time slot *i*

$N_{EV}(i)$ = total number of EVs waiting to swap a battery in time slot *i*

$N_{NEV}(i)$ = number of EVs coming to the BSS to swap a battery in time slot *i*

$N_{WEV}(i)$ = number of EVs waiting to swap a battery that has not yet completed battery swapping in time slot i

$N_{SEV}(i)$ = number of EVs having completed battery swapping in time slot i

T_{B_Cha} = battery charging time

SOC_{init} = initial State of Charge (SOC) of a charging battery

SOC_{end} = finished State of Charge (SOC) of a charging battery

W_B = rated capacity of a battery

P_{Cha} = constant charging power

Total number of EVs that wait to swap a battery in time slot i or $N_{EV}(i)$ is calculated as follows.

$$N_{EV}(i) = N_{NEV}(i) + N_{WEV}(i-1). \quad (2.1)$$

$$N_{EV}(i) = N_{SEV}(i) + N_{WEV}(i). \quad (2.2)$$

The number of batteries in different states differs dynamically to time. To determine the number of fully charged available battery systems in time slot i, the following formulation is used.

$$N_A(i) = N_A(i-1) - N_{SEV}(i-1) + N_{NA}(i-1). \quad (2.3)$$

The battery that just fully charged should rest for some time to reach a steady-state before discharge. Hence, the battery will be available in the time slot after it has completed charging. On the one hand, the replaced battery reaches the charging state in the following time slot. The replaced battery system will be charged in the next time slot because the BSS has a charger for every replaced battery system on the charging platform. The number of charging state battery systems in time slot i can be calculated as follows.

$$N_C(i) = N_C(i-1) - N_{NA}(i-1) + N_{SEV}(i-1). \quad (2.4)$$

The replaced batteries begin charging in a constant power charging mode during the following time slot. In this mode, its charging time is related to the initial State of Charge (SOC) and the final SOC of the charging battery.

$$T_{B\_Cha} = \frac{(SOC_{end} - SOC_{init}) \times W_B}{P_{Cha}}. \quad (2.5)$$

In order to maintain the availability of battery swapping service, fully charged batteries should be enough to meet the EV swapping demand in every time slot.

$$N_A(i) > N_{EV}(i). \quad (2.6)$$

In the following time slot *i* + 1, the new fully charged batteries transition to an available state, and new EVs come to the battery swapping service.

$$N_A(i) + N_{NA}(i) > N_{EV}(i) + N_{NEV}(i+1). \quad (2.7)$$

According to (2.3) and (2.7), the following equation is derived. $N_{NA}(i)$, $N_{NEV}(i)$, and $N_{NEV}(i+1)$ are forecasted values while other parameters in (2.8) are known in time slot *i*.

$$N_{NA}(i) > N_{NEV}(i) + N_{NEV}(i+1) + N_{WEV}(i-1) - N_A(i-1) + N_{SEV}(i-1) - N_{NA}(i-1). \quad (2.8)$$

Meanwhile, as the batteries may take several time slots to complete battery charging, it may not be fully charged. The charging time for a battery can be calculated with (2.5). moreover, (2.8) requires to be applied to time slot *i* + n with the following formula.

$$N_{NA}(i) + N_{NA}(i+1) + \cdots + N_{NA}(i+n) > N_{NEV}(i) + N_{NEV}(i+1) + N_{NEV}(i+2) + \cdots + N_{NEV}(i+1+n) + N_{WEV}(i-1) - N_A(i-1) + N_{SEV}(i-1) - N_{NA}(i-1). \quad (2.9)$$

The lower limit of battery systems charging quantity in time slot i is determined by $N_{NA}(i+n)$. Hence, the minimum charging power can be calculated as follows.

$$P_{Cha\_min}(i) = P_{Cha} \times N_{NA}(i+n). \qquad (2.10)$$

In actual battery swapping service, the number of EVs coming to the BSS is considered as stochastic. Thus, the forecast value of $N_{NEV}(i)$ will always include uncertainty errors. In responding to the forecast errors, having more fully charged batteries available in reserve should be considered. On the other hand, keeping a lot of fully charged batteries in reserve is not an economical solution. Hence, an optimal charging strategy is required to consider both forecast errors and the charging economy.

2.3 Vendor Managed Inventory

Vendor Managed Inventory (VMI) is a collaborative commerce initiative where suppliers are authorized to manage the buyer's inventory of stock-keeping units. It integrates operations between suppliers and buyers through information sharing and business process engineering (Yao, Evers, & Dresner, 2005). Information sharing of buyers and suppliers consists of buyers' demand and their inventory status. Furthermore, suppliers could use this information to plan the production, plan the deliveries schedule, and manage the order volumes and inventory levels at the buyers' stock-keeping facilities.

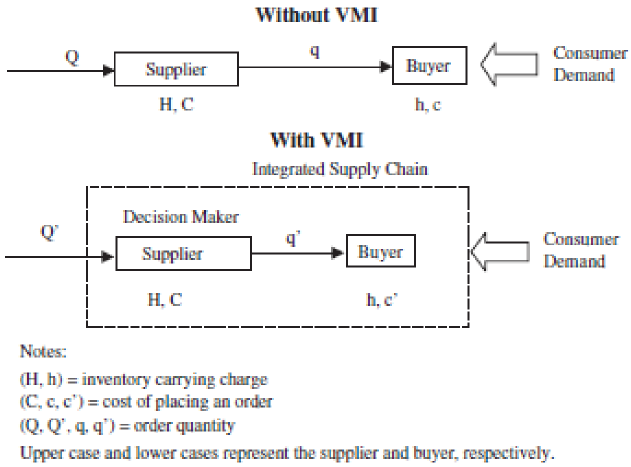

Figure 2.3 Supply Chain Modeling Framework considering VMI

Source : Yao, Evers, & Dresner (2015)

VMI has advantages of reducing inventory costs for both supplier and buyer and improve the customer service levels such as reducing order cycle times and increasing fill rates. In a supply chain with no presence of VMI, the supplier will observe the customer demand only through the buyers' ordering policy (indirect method). While with VMI, the supplier's information system will receive the customer demand data (direct method).

2.4 Inventory Routing Problem

Inventory Routing Problem (IRP) is the integration of inventory management, vehicle routing, and delivery-scheduling decisions. It was initially considered as a variation of the VRP model and developed heuristics to put inventory costs into consideration. The main difference between IRP and VRP is that IRP is based on customers' usage while VRP is based on customer' orders. The objective of IRP is to minimize the average distribution costs during the planning period without causing stock-outs at any of the customers (Campbell, et al., 1998). Three decisions should be made by IRP, which are (1) time to serve customers, (2) delivered quantities to the customer when it is served, and (3) the delivery route that will be used.

According to Bertazzi, L. & Speranza, M. G. (2012), there are four main characteristics of an IRP, which are the shipping times and the planning horizon, the structure of the distribution policy, the objective of the policy, and the decision space. Further explanations are as follows.

1. The shipping times and the planning horizon

   The planning horizon is divided into two that are infinite and finite. Whether the shipping times of an IRP is possible in three types that are:

   - Continuous: a shipment can be performed, starting from zero, with no limitation to a specific time.
   - Continuous with a minimum intershipment time: a shipment can be performed at any time, starting from zero, with the intershipment time between any pair of consecutive shipments meets the given minimum intershipment time.
   - Discrete: the shipments can be performed only at multiples of a minimum intershipment time.

2. The structure of the distribution policy

   Several types of the distribution policy are as follow:

   - Zero Inventory Ordering (ZIO): any customer will be replenished if and only if its inventory level is equal to zero.
   - Periodic: with a period of P, any shipment will be performed at time t, $0 \leq t \leq P$, and will be repeated at times $t + kP$ with $k = 1, 2, \dots$.
   - Frequency-based: the periodic policies with shipments are performed based on one or several frequencies.
   - Full Load: only full load vehicles that are used for the shipments.
   - Direct Shipping: a shipment route with only one customer and any customer will be visited directly from the supplier.
   - Order-up-to- Level: the delivered quantity to any customer that is served should equal to a value that can increase the customer’s inventory level to the defined maximum inventory level.
   - Maximum Level: the delivered quantity to any customer could be any value such that the inventory level at the customer is not greater the defined maximum level.

- Fixed Partition: the set of customers is divided into some sets and each set is served independently and separately from the other set.
- Partition-based: this type generalizes the fixed partition policies where a route may only visit customers of a set or also customers of specific combinations of two or more sets.

3. The objective of the policy

   The objective function determined for an IRP model might vary between minimization of the transportation cost only, minimization of the inventory costs only, and minimization of the sum of inventory costs and transportation cost. Minimizing only the transportation cost is a suitable objective for a situation where the inventory costs are not relevant compared to the transportation cost. Having infrequent transportation with highly loaded vehicles might be expected for this case. Whether minimizing only the inventory cost is appropriate when the focus is on inventory management. This situation is likely to happen when frequent transportation is committed. Moreover, minimizing the sum of both costs is more suitable than minimizing only one of them when the decision-maker is responsible for all the cost components.

4. The decision space

   The decision space in IRPs always include timing and quantities and may also include the routing. Therefore, there are two types of decision space in IRPs that are :

   - Decisions over time only: the IRP only concerns the times and delivered quantities to the customers while the routes are given.
   - Decisions over time and space: the IRP decides delivery time to each customer, delivered quantities at each time, and the routes traveled by the vehicles at the same time.

On the one hand, according to Coelho, Cordeau, & Laporte (2014), IRP has numerous variations that further will be explained into two sections, which are the basic version and the extension version. The basic version of IRP is classified according to seven criteria as depicted in table 2.1 that are time horizon, structure, routing, inventory policy, inventory decisions, fleet composition, and fleet size. For the first criteria, IRP can consider the time horizon to be finite or infinite. While for the structure, it defines the distribution structure of supplier to customer. The structure within an IRP model may vary into three types; one-to-one, one-to-many, or many-to-many. One-to-one structure means that there will only one supplier serving one customer. Therefore, one-to-many means that one supplier will serve many suppliers. This type of structure is recognized as the most commonly used in the IRP model. Many-to-many structure, the most less-frequently used among these three structures, defines the existence of many suppliers to serve many customers.

Table 2.1 Variants of IRP Basic Version

Criteria	Possible Options		
Time Horizon	Finite	Infinite	
Structure	One-to-one	One-to-many	Many-to-many
Routing	Direct	Multiple	Continuous
Inventory Policy	Maximum Level (ML)	Order-up-to level (OU)	
Inventory Decisions	Lost sales	Back-order	Nonnegative
Fleet Composition	Homogeneous	Heterogeneous	
Fleet Size	Single	Multiple	Unconstrained

Source : (Coelho, Cordeau, & Laporte, 2014)

In routing criteria, there are direct, multiple, and continuous as its classifications. Direct routing indicates that there is only one customer for each route, multiple routing indicates several customers in the same route, and continuous routing indicates that none of the central depot is in the route. For inventory policy, it defines the pre-established rules to replenish customers. These two policies, Maximum Level (ML) and Order-up-to Level (OU), are the most commonly used. When an IRP model is under ML policy, it means that the replenishment level is flexible although bounded by the capacity available at each customer. Whether an OU policy determines the delivered quantity based on the gap between a customer’s current inventory level and the maximum inventory capacity.

As the following criteria, inventory decision specifies how to model the inventory management. Lost sales or allowing the inventory to become negative may lead to the occurrence of back-order and serving corresponding demand in the following stage. However, if back-ordered is not allowed, uncovered demand will be considered as lost sales and potentially given a penalty for the stock out. The consideration of nonnegative inventory can be applied in a deterministic context. Fleet composition indicates the type of fleet used either homogenous or heterogeneous, and fleet size indicates the number of fixed vehicles in the model.

The extended version from the basic IRP depends on the time of when the demand information is available. If the demand information is fully available to the decision-maker at the beginning of the planning horizon, the IRP is considered as deterministic. Thus if the demand information only known for its probability distribution, the IRP is considered as stochastic.

2.5 Inventory Routing Problem (IRP) Model

In solving an IRP with a single capacitated vehicle, a branch-and-cut algorithm was proposed by Archetti, et al. (2007). The problem is about a product that is shipped from a supplier to several retailers, where it is reduced in a deterministic and time-varying way over a given period. Archetti, et.al composed the mathematical model covering three scenarios, which are Inventory Routing Problem with Order-Up to policy (IRP-OU), Inventory Routing Problem with Maximum Level policy (IRP-ML), and Inventory Routing Problem (IRP). The formulations are notations are described as follows.

Notations:

$\mathcal{M}$	= retailers; {1, 2, …, n}
H	= time horizon
$t \in \mathcal{T}$	= discrete time; {1, 2, …, H}
r_{0t}	= product quantity available at the supplier
r_{st}	= product quantity consumed at the retailer
s	= retailer; $s \in \mathcal{M}$
B_0	= starting inventory level at supplier

U_s = maximum inventory level at each supplier

I_{s0} = starting inventory level at retailer

x_{st} = product quantity shipped to retailers s at time t

I_{st} = inventory level of retailer s at time t

h_0 = unit inventory cost at the supplier

B_t = inventory level at supplier at time t

h_s = unit inventory cost of retailer $s \in \mathcal{M}$

C = vehicle capacity

c_{ij} = transportation cost from i to j

y_{ij} = 1, if j immediately follows i in the route traveled at time t; 0, otherwise

x_{st} = 1, if retailer s is served at time t; 0, otherwise.

Objective function

$$\text{Min} \quad \sum_{t\in\mathcal{T}'} h_0 B_t + \sum_{s\in\mathcal{M}} \sum_{t\in\mathcal{T}'} h_s I_{st} + \sum_{i\in\mathcal{M}'} \sum_{j\in\mathcal{M}',j<i} \sum_{t\in\mathcal{T}'} c_{ij} y_{ij}^t \qquad (2.13)$$

Subject to

1. Inventory definition at the supplier, where $r_{00} = 0$ and $x_{s0} = 0, s \in \mathcal{M}$

$$B_t = B_{t-1} + r_{0t-1} - \sum_{s\in\mathcal{M}} x_{st-1} \qquad t \in \mathcal{T}' \qquad (2.14)$$

2. Stockout constraints at the supplier to guarantee that supplier has sufficient inventory level to deliver the total quantity delivered to the retailers at time t for each delivery time $t \in \mathcal{T}$

$$B_t \geq \sum_{s\in\mathcal{M}} x_{st} \qquad t \in \mathcal{T} \qquad (2.15)$$

3. Inventory definition at the retailers, where $x_{s0} = r_{s0} = 0, s \in \mathcal{M}$

$$I_{st} = I_{st-1} + x_{st-1} - r_{st-1} \qquad s \in \mathcal{M}\ t \in \mathcal{T}' \qquad (2.16)$$

4. Stockout constraints at the retailers

$$I_{st} \geq 0 \qquad s \in \mathcal{M}\ t \in \mathcal{T}' \qquad (2.17)$$

5. Order-up-to level constraints to guarantee that the quantity x_{st} shipped to each retailer s at each time $t \in \mathcal{T}$ is either $U_s - I_{st}$ if s is served at time t,

and zero otherwise. Let z_{st} be a binary variable that equal to one if the retailer s is served at time t, and zero otherwise.

$$x_{st} \geq U_s z_{st} - I_{st} \qquad s \in \mathcal{M}\ t \in \mathcal{T} \qquad (2.18)$$

$$x_{st} \leq U_s - I_{st} \qquad s \in \mathcal{M}\ t \in \mathcal{T} \qquad (2.19)$$

$$x_{st} \leq U_s z_{st} \qquad s \in \mathcal{M}\ t \in \mathcal{T} \qquad (2.20)$$

6. Capacity constraints to the transportation capacity

$$\sum_{s\in\mathcal{M}} x_{st} \leq C \qquad t \in \mathcal{T} \qquad (2.21)$$

7. Routing constraints to guarantee that a feasible route should visit all retailers served at time t for each time $t \in \mathcal{T}$.

   a. If at least one retailer $s \in \mathcal{M}$ is visited at time t, the route traveled at time t should visit the supplier. Let z_{0t} be a binary variable equal to one if the supplier is visited at time t and zero if otherwise.

$$\sum_{s\in\mathcal{M}} x_{st} \leq C z_{0t} \qquad t \in \mathcal{T} \qquad (2.22)$$

   b. If deliveries are made at time t (i.e., $z_{it}$is equal to one for some $i \in \mathcal{M}'$), then

$$\sum_{j\in\mathcal{M}',j<i} y_{ij}^t + \sum_{j\in\mathcal{M}',j>i} y_{ji}^t = 2z_{it} \qquad i \in \mathcal{M}'\ t \in \mathcal{T} \qquad (2.23)$$

   c. Sub-tours elimination constraints for some $k \in \varphi$

$$\sum_{i\in\varphi} \sum_{j\in\varphi.j<i} y_{ji}^t \leq \sum_{i\in\varphi} z_{it} - z_{kt} \qquad \varphi \subseteq \mathcal{M}\ t \in \mathcal{T} \qquad (2.24)$$

8. Non-negativity and integrality constraints

$$x_{st} \geq 0 \qquad s \in \mathcal{M}\ t \in \mathcal{T} \qquad (2.25)$$

$$y_{ij}^t \in \{0,1\} \qquad i \in \mathcal{M}\ j \in \mathcal{M}, j < i\ t \in \mathcal{T} \qquad (2.26)$$

$$y_{i0}^t \in \{0,1,2\} \qquad i \in \mathcal{M}\ t \in \mathcal{T} \qquad (2.27)$$

$$x_{it} \in \{0,1\} \qquad i \in \mathcal{M}'\ t \in \mathcal{T} \qquad (2.28)$$

Valid inequalities

Theorem 1 (valid for IRP-OU, IRP-ML, IRP)

$$I_{st} \geq (1 - z_{st}) r_{st} \qquad s \in \mathcal{M}\ t \in \mathcal{T} \qquad (2.29)$$

Theorem 2 (valid for IRP-OU, IRP-ML, IRP)

$$I_{st-k} \geq \left(\sum_{j=0}^{k} r_{st-j}\right)\left(1 - \sum_{j=0}^{k} z_{st-j}\right) \qquad s \in \mathcal{M}\ t \in \mathcal{T}\ \mathrm{k} = 0,1,\dots,\mathrm{t} - 1 \qquad (2.30)$$

Theorem 3 (valid for IRP-OU)

$$I_{st} \geq U_s z_{st-k} \sum_{j=t-k}^{t-1} r_{sj} \qquad s \in \mathcal{M}\ t \in \mathcal{T}\ \mathrm{k} = 1,2,\dots,\mathrm{t} - 1 \qquad (2.31)$$

Theorem 4 (valid for IRP-OU and IRP-ML)

$$\sum_{j=1}^{t} z_{sj} \geq \left\lceil \frac{\sum_{j=1}^{t-1} r_{sj} - I_{s0}}{U_s} \right\rceil \qquad s \in \mathcal{M}\ t \in \mathcal{T} \qquad (2.32)$$

Theorem 5 (valid for IRP-OU)

$$\sum_{s \in \mathcal{M}} \left(U_s - I_{s0} + \sum_{j=1}^{t-1} r_{sj}\right) z_{st} \leq tC \qquad t \in \mathcal{T} \qquad (2.33)$$

Theorem 6 (valid for IRP-OU, IRP-ML, and IRP)

$$z_{st} \leq z_{0t} \qquad s \in \mathcal{M}\ t \in \mathcal{T} \qquad (2.34)$$

Theorem 7 (valid for IRP-OU, IRP-ML, and IRP)

$$y_{i0}^{t} \leq 2 z_{it} \qquad i \in \mathcal{M}\ t \in \mathcal{T} \qquad (2.35)$$

$$y_{ij}^{t} \leq z_{it} \qquad i \in \mathcal{M}\ j \in \mathcal{M}\ t \in \mathcal{T} \qquad (2.36)$$

In order to solve IRP-OU, the model implemented includes formulations (2.13) – (2.28) and valid inequalities (2.29) – (2.31) and (2.34) – (2.36) but excluding constraint (2.24). To solve IRP-ML, formulations used are (2.13) – (2.28), valid inequalities (2.29), (2.30), and (2.34) – (2.36), excludes constraints (2.18), (2.20), and (2.24). While to solve IRP are using formulations (2.13) – (2.28) and valid inequalities (2.29), (2.30), and (2.34) – (2.36) without constraints (2.18) – (2.20) and (2.24).

2.6 Electric Vehicle – Inventory Scheduling Problem (EV-ISP) Model

Electric Vehicle – Inventory Scheduling Problem (EV-ISP) model is an inventory scheduling problem model developed by Ahmad (2019) to determine the appropriate delivered battery quantities with a given route by considering stochastic demand and recharging time at Battery Exchange Station (BES). It was developed by referring to the IRP model of Archetti, et. al (2007) and the optimal charging model of Wu, et. al (2017). As depicted in Figure 2.4, a fleet of vehicles will visit each BES according to the route that has been determined before. The visiting order helps the vehicle acknowledge the replenishment unit for each BES at time *t* by demand on BES at time *t* and the number of potentially recharged battery at time *t*. At every BES, the inventory level of the empty battery, recharging battery, and full battery are influenced by the stochastic demand and its recharging capacity. The BES's inventory level is the basis of either the BES requires external supply by the vehicle or not.

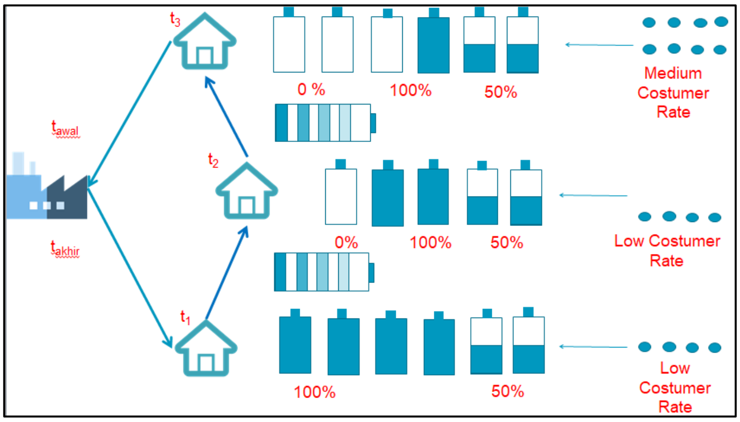

Figure 2.4 EV-ISP Conceptual Model

Source : Ahmad (2019)

There are three types of costs in the total cost, which are transportation cost, material handling cost, and replenishment cost. The formulations of EV-ISP model are specified as follows.

Objective Function

Min Z =

$$\sum_{\forall i\in M}\sum_{\forall j\in M}\sum_{\forall t\in T}\sum_{\forall k\in K} C_T d_{ij} v_{ij} X_{ijtk} + \sum_{\forall i\in M}\sum_{\forall j\in M}\sum_{\forall t\in T}\sum_{\forall k\in K} C_M t_{UL} Y_{itk} + \sum_{\forall i\in M}\sum_{\forall j\in M}\sum_{\forall t\in T} C_R Q_{itk} \quad (2.37)$$

Subject to :

1. Inventory at the BES

$$I_{it} = I_{i(t-1)} + Q_{itk} - D_{it} \qquad \forall i \in I, \forall t \in T \quad (2.38)$$

2. Delivered quantity, recharge capacity, and inventory level at time *t* should be less than equal to BES capacity.

$$Q_{itk} + W_{Ri} + I_{it} \leq W_i \qquad \forall i \in I, \forall t \in T, \forall k \in K \quad (2.39)$$

$$W_{Ri} \leq t_R r_{Ri} \qquad \forall i \in I, \forall t \in T \quad (2.40)$$

3. No stockout is allowed at the BES

$$I_{it} \geq 0 \qquad \forall i \in I, \forall t \in T \quad (2.41)$$

$$D_{it} \leq W_i \qquad \forall i \in I, \forall t \in T \quad (2.42)$$

4. The inventory level at the BES should be less than equal to BES maximum capacity

$$I_{it} \leq W_i \qquad \forall i \in I, \forall t \in T \quad (2.43)$$

5. Delivered quantity to BES *i* should not exceed the left capacity of BES *i*

$$Q_{itk} \leq W_i - I_{i(t-1)} \qquad \forall i \in I, \forall t \in T, \forall k \in K \quad (2.44)$$

$$Q_{itk} \leq W_i Y_{itk} \qquad \forall i \in I, \forall t \in T, \forall k \in K \quad (2.45)$$

6. Quantity loaded to vehicle *k* should not exceed its maximum capacity

$$\sum_{\forall i\in I} Q_{itk} \leq Z_k \qquad \forall t \in T, \forall k \in K \quad (2.46)$$

$$W_{itk} - W_{jtk} + Z_{k+1} X_{ijtk} \leq Z_k - Q_{jtk}$$

$$\forall i \in I, \forall \mathrm{j} \in \mathrm{J}, \forall t \in T, \forall k \in K \quad (2.47)$$

7. Delivered quantity to BES *i* should less then equal to loaded capacity of vehicle *k*

$$Q_{itk} \leq W_{itk} \qquad \forall i \in I, \forall t \in T, \forall k \in K \qquad (2.48)$$

8. Total delivered quantity by vehicle *k* should less than equal to its capacity

$$W_{itk} \leq Z_k \qquad \forall i \in I, \forall t \in T, \forall k \in K \qquad (2.49)$$

9. Non-negativity and integrality constraints

$$X_{ijtk} \in \{0,1\} \qquad (2.50)$$

$$Y_{itk} \in \{0,1\} \qquad (2.51)$$

$$Q_{itk} \geq 0 \qquad (2.52)$$

Notations:

M = BES where M={1, 2, 3, …, n} and depot for $M = \{0\}$

K = vehicle; {1, 2, 3, …, *k*}

T = time; {1, 2, 3, …, *t*}

C_T = transportation cost per traveling time

C_M = material handling cost per minute

C_R = replenishment cost

d_{ij} = distance between vertex *i* and vertex *j*

t_{ij} = traveling time between vertex *i* and vertex *j*

D_{it} = demand at BES *i* at time *t*; $i \in I, t \in T$

W_i = capacity of BES *i*; $i \in I$

W_{Ri} = recharge capacity; $i \in I$

I_{it} = inventory level at BES *i* at time *t*; $i \in I, t \in T$

r_{Ri} = recharging rate at BES *i* at time *t*; $i \in I, t \in T$

t_{UL} = loading/unloading time of battery at BES *i* at time *t*; $i \in I, t \in T$

t_R = battery recharging time at BES

Z_k = capacity of vehicle *k*; $k \in K$

v_{ij} = velocity of vehicle

W_{itk} = total delivered quantity by vehicle *k* at BES *i* at time *t*

X_{ijtk} = 1, if vertex j is directly visited after vertex i at time t by vehicle k; 0, otherwise.

Y_{itk} = 1, if BES i is visited by vehicle k at time t; 0, otherwise

Q_{itk} = delivered quantity to BES i at time t by vehicle k

Besides the EV-ISP model, Ahmad (2019) also developed models that represent the inventory level on BES. These models are divided into the battery swapping model and battery charging model. Mathematical models of both models are as follow.

a. Battery Swapping Model

$$N_{EV}(i) = N_{NEV}(i) + N_{WEV}(i-1) \quad (2.53)$$

$$N_{EV}(i) = N_{SEV}(i) + N_{WEV}(i-1) \quad (2.54)$$

$$N_{A}(i) = N_{A}(i-1) - N_{SEV}(i-1) + N_{NA}(i-1) \quad (2.55)$$

$$N_{C}(i) = N_{C}(i-1) - N_{NA}(i-1) + N_{SEV}(i-1) \quad (2.56)$$

b. Battery Charging Model

$$N_{A}(i) > N_{EV}(i) \quad (2.57)$$

$$N_{A}(i) + N_{NA}(i) > N_{EV}(i) + N_{NEV}(i+1) \quad (2.58)$$

$$N_{NA}(i) > N_{NEV}(i) + N_{NEV}(i+1) + N_{WEV}(i-1) - N_{A}(i-1) + N_{SEV}(i-1) - N_{NA}(i-1) \quad (2.59)$$

$$N_{NA}(i) + N_{NA}(i+1) + \cdots + N_{NA}(i+n) > N_{NEV}(i) + N_{NEV}(i+1) + N_{NEV}(i+2) + \cdots + N_{NEV}(i+1+n) + N_{WEV}(i-1) - N_{A}(i-1) + N_{SEV}(i-1) - N_{NA}(i-1) \quad (2.60)$$

Notations:

$N_A(i)$ = quantity of available battery to be swapped at time slot t

$N_C(i)$ = quantity of charging battery at time slot t

$N_{NA}(i)$ = quantity of finished charging battery at time slot t

$N_{EV}(i)$ = quantity of electric vehicle waiting to swap its battery at time slot t

$N_{NEV}(i)$ = quantity of electric vehicle arriving to swap its battery at time slot t

$N_{SEV}(i)$ = quantity of electric vehicle finisihing the battery swapping at time slot t

$N_{WEV}(i)$ = quantity of electric vehicle not yet finisihing the battery swapping at time slot t

2.7 Research Position

In this subchapter, this research is compared to previous research in Inventory Routing Problem (IRP) and Battery Swapping System related topics. Since the study on the IRP model for managing battery swap stations has not been widely discussed, research on battery swapping system related topics is considered. Study on researches with the related topic is committed to help determining the appropriate method and model to solve the problem. The lists and comparisons of previous researches regarding this research are depicted in the following tables.

Table 2.2 List of Previous Researches

No	Title	Authors	Year	Type	Research Object
1	A Branch-and-Cut Algorithm for a Vendor-Managed Inventory-Routing Problem	Claudia Archetti, Luca Bertazzi, Gilbert Laporte, and Maria Grazia Speranza	2007	Journal	One-to-many shipment with single vehicle
2	Battery Swap Station Location-Routing Problem with Capacitated Electric Vehicles	Jun Yang, Hao Sun	2014	Journal	Battery Swapping Stations and Electric Vehicles
3	An Optimal Charging Strategy for PV-Based Battery Swapping Stations in a DC Distribution System	Shengjun Wu, Qingshan Xu, Qun Li, Xiaodong Yuan, and Bing Chen	2017	Journal	PV-based Battery Swapping Stations
4	Solving The Battery Swap Station Location-Routing Problem with Capacitated Electric Vehicles Using and AVNS Algorithm for Vehicle-Routing Problems With Intermediate Stops	Julian Hof, Michael Schneider, and Dominik Goeke	2017	Journal	Battery Swapping Stations and Electric Vehicles
5	Optimizing Spare Battery Allocation in an Electric Vehicle Battery Swapping System	Michael Dreyfuss and Yahel Giat	2017	Proceeding	Window fill rate in Battery Swapping Stations
6	*Perancangan Model dan Algoritma Inventory Scheduling Problem (ISP) untuk Pengelolaan Swapped Battery pada Battery Exchange Station (BES): Studi Kasus Motor Listrik*	Nofan Hadi Ahmad	2019	Thesis	Battery Swapping Stations of Electric Motorcycle

Table 2.3 Comparison between Previous Researches

No	Research's Author	Model	Problem Characteristic												Method	Decision Variable
			Single Depot	**Multi customers**	**Single product**	**Capacitated vehicle**	**Deterministic demand**	**Stochastic demand**	**Gasoline based vehicle**	**Electric vehicle**	**Recharging rate**	**State of Charge (Soc)**	**Photovoltaic (PV) based BSS**	**Reguler electricity based BSS**		
1	Archetti, et. al (2007)	Vendor-Managed Inventory-Routing Problem (VMIRP)	V	V	V		V								Branch-and-cut algorithm	Delivered quantity and vehicle route
2	Yang & Sun (2014)	Electic Vehicles battery Swap Stations Location Routing Problem (BSS-EV-LRP)	V	V	V	V	V			V					SIGALNS and two-phase TS-MCWS	BSS location strategy and vehicle routing
3	Wu, et. al (2017)	Battery swapping service model and battery charging model											V		PSO algorithm	Optimal charging strategy in BSS

No	Research's Author	Model	Problem Characteristic												Method	Decision Variable
			Single Depot	**Multi customers**	**Single product**	**Capacitated vehicle**	**Deterministic demand**	**Stochastic demand**	**Gasoline based vehicle**	**Electric vehicle**	**Recharging rate**	**State of Charge (Soc)**	**Photovoltaic (PV) based BSS**	**Reguler electricity based BSS**		
4	Hof, Schneider, Goeke (2017)	Location Routing Problem (LRP) with intermediate stops	V	V	V	V	V			V					AVNS algorithm	BSS location strategy and vehicle routing
5	Dreyfuss & Giat (2017)	Battery allocation problem		V	V										TWT and WFR algorithm	Number of battery allocated to BSSs
6	Ahmad (2019)	Electric Vehicle – Inventory Scheduling Problem (EV-ISP)	V	V	V	V		V		V	V			V	Constructive Heuristic	Replenishment unit and delivering schedule
7	**This Research**	**Inventory Routing Problem (IRP)**	**V**	**V**	**V**	**V**		**V**	**V**			**V**		**V**	**Constructuve Heuristic**	**Replenishment unit and delivering schedule**

In 2007, Archetti, et.al researched inventory routing problem using a branch-and-cut algorithm. The object of the research was a distribution system with a supplier to several suppliers over a given time horizon. By adapting vendor managed inventory, the supplier should monitor the inventory level of each retailer to determine the appropriate replenishment policy in which none of the stock-out is allowed. This research had outputs of delivered quantity to each retailer in each discrete-time and the vehicle route that minimizing total cost. Besides, Archetti, et.al also created three scenarios that are IRP with Order-Up-to policy (IRP-OU), IRP with Maximum Level policy (IRP-ML), and basic IRP. The IRP model of Archetti at.al becomes the main reference of this research because of the similarity in object characteristics.

Yang & Sun had research on battery swap stations and electric vehicles in 2014. The main objectives are to determine the appropriate location of BSSs and the routing of EVs as the distributing vehicle with constraint of battery driving range limitation. In order to solve the problem, there are two methods proposed in the journal that are a four-phase heuristic called SIGALNS and a two-phase heuristic called TS-MCWS. SIGALNS consists of Sweep heuristic, Iterated Greedy, Adaptive Large Neighborhood Search, and Improvement heuristic for EV location routing problem (BSS-EV-LRP). While TS-MCWS is the combination of Tabu Search and Modified Clarke and Wright Saving. Besides these two objectives, Yang & Sun also analyzed in terms of economics and the environment.

For the next three years, Wu, et.al published research on determining the optimum charging strategy for PV-Based Battery Swapping Stations with cost-efficiency. The charging strategy is recognized as a factor that will influence the self-consumption of PV-BSS and its service availability. Particle Swarm Optimization (PSO) algorithm was developed to determine the optimal charging power.

The study conducted by Yang & Sun in 2014 was extended being researched by Hof, Schneider, and Goeke in 2017. Problems to be solved in the research were similar to Yang & Sun's, which are the appropriate location of BSSs and the routes of electric vehicles to serve a set of customers with cost-efficiency. The difference was the proposed method that Hof, Schneider, and Goeke used Vehicle Routing

Problem with Intermediate Stops (VRPIS) with Adaptive Variable Neighborhood Search (AVNS) algorithm.

Dreyfuss and Giat also proposed a research of the battery swapping system in 2017 that specifically was optimizing battery allocation in the BSSs regarding to the window fill rate and cost-efficiency. The window fill rate was the probability of a customer entering the BSS would exit within a certain time window. In order to solve this problem, Dreyfuss and Giat used the same algorithm as in their previous research of optimal spares allocation in an exchangeable-item repair system with a tolerable wait. The algorithm uses two criteria that are Truncated Waiting Time (TWT) and Window Fill Rate (WFR).

Ahmad (2019) proposed research on developing an Electric Vehicle-Inventory Scheduling Problem (EV-ISP) for managing inventory level of BSS. This model considered the stochastic demand and recharging rate on the BSS. However, in this research, the recharging rate is considered to be unit/minute instead of in a specific state of charge. Compared to these researches, this research will focus on developing the Inventory Routing Problem (IRP) model to generate a distribution plan for managing BSS. This research will refer to the EV-ISP model by Ahmad (2019) by considering stochastic demand and state of charge of each battery in the BSS.

CHAPTER 3
RESEARCH METHODOLOGY

This chapter consists of methods in conducting this research. It will be explained through the flowchart and explanations.

3.1 Research Methodology

There are four main processes in accomplishing this research, which are constructing model, verifying model, performing numerical experiments and analyzing the results, and deriving conclusions and suggestions. All processes are depicted in figure 3.1.

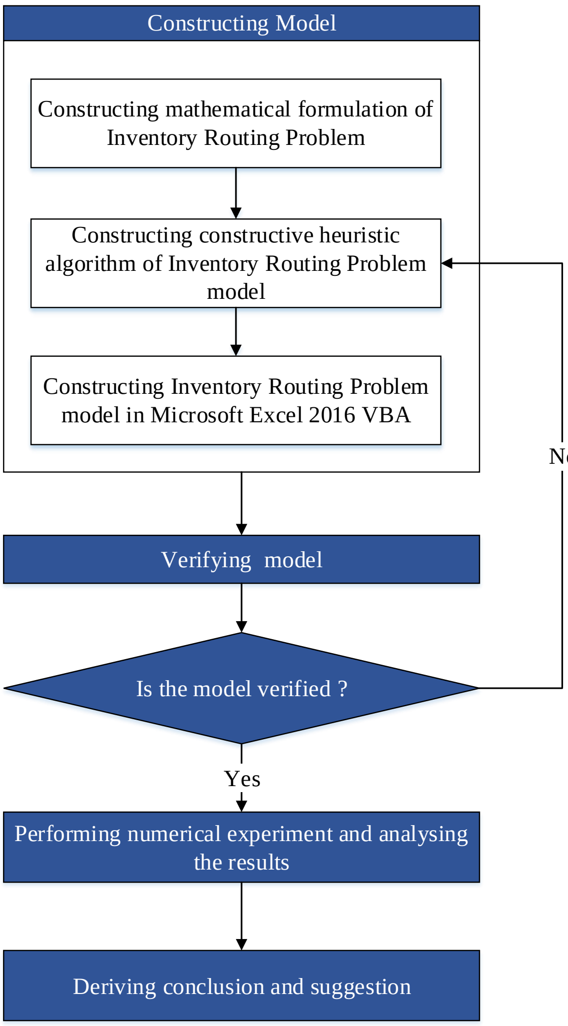

Figure 3.1 Flowchart of Research Methodology

3.2 Research Methodology Description

In this subchapter, each activity will be described as follows.

3.2.1 Constructing Model

The first step in developing the IRP model for this research is constructing mathematical formulations of the model. It is important to help understanding more about the problem and also as a guide for developing the heuristic algorithm. The mathematical formulations will mainly refer to EV-ISP developed by Ahmad (2019) due to similarities in research scope and object. After constructing the mathematical model with some adjustments due to the differences of EV-ISP with this research, the model algorithm of solving the problem will be developed heuristically. The IRP model will be performed according to the algorithm by using Visual Basic for Applications (VBA) feature in Microsoft Excel 2016.

3.2.2 Verifying Model

After constructing the model, a set of data will be used to perform a basic experiment with the model. The result then will be analyzed either it violates any of the model constraints or not. If violation of any constraint does not exist, then the model is verified. Otherwise, the constructive heuristic algorithm should be adjusted until no violation is performed.

3.2.3 Numerical Experiment

There are two types of numerical experiments to be executed by the verified model. The first numerical experiment has a purpose to determine the appropriate value of minimum acceptable SoC (α) and intershipment time that minimizes total cost and total lost sales. The value of α and internshipment time are deterministic with variation more than one. This experiment will be performed for each level of demand as there will be four types (low, medium, high, and very high) of demand at the BSS. While the second numerical experiment has an aim to determine either additional shipment, where there are some nodes not visited in the same shipment with others, is required or not for each type of demand in each data set. The intershipment time becomes a decision variable as the probability of having multi vehicles in a planning horizon existing. The results of all numerical experiments will be collected and analyzed by concerning each objective.

3.2.4 Conclusion and Suggestion

In the last process, the conclusion of the research will be summarized according to the research objectives. Furthermore, some recommendations will be constructed for further research.

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CHAPTER 4
MODEL DEVELOPMENT

In this chapter will be explained the model description, model formulation, model algorithm, and model verification.

4.1 Model Description

The Inventory Routing Problem (IRP) model developed aims to minimize stock-out on all BSSs in the distribution scheme of fully charged batteries by a fleet of vehicles from Center Battery Station (CBS) to a set of Battery Swapping Stations (BSSs). In this distribution scheme, the BSSs have two roles that are providing battery swapping service to electric vehicle owners and recharging the depleted batteries. To increase the service level of BSSs, the external supply of fully charged batteries is considered as important since there is a probability of BSSs experiencing stock-out. These fully charged batteries are concerned as the anticipation stock for the BSSs. The external supply involves CBS, the main depot of all batteries, to exchange batteries in the BSSs with fully charged batteries. One of the efforts to make the operations of the supply chains more efficient is to adopt a scheme called Vendor Managed Inventory (VMI) (Rusdiansyah & Tsao, 2005). With VMI, the replenishment unit and delivering time become the authority of the supplier instead of the retailer. In this case, CBS acts as the supplier and BSS acts as the retailer that will be further considered as a service provider. In VMI, the supplier needs to obtain accurate information on the inventory level at the service provider to determine the appropriate value of the replenishment unit and delivery time. Therefore, each BSS is considered equipping an Electronic Data Interchange (EDI) device to support CBS gathering information of end-customer demand and inventory level on each BSS in real-time. The end customer demand is important for CBS to determine the expected empty batteries while the inventory level helps the CBS to acknowledge the amount of batteries on each state as well as the SoC of each battery in the BSS.

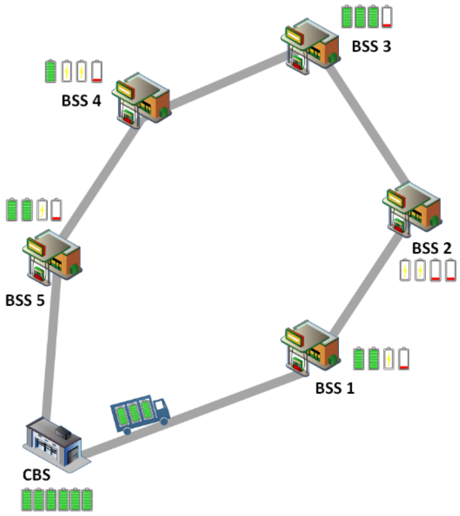

Figure 4.1 Distribution Scheme of Battery Swapping System

The decision space of this IRP model is a decision only over time, meaning that the IRP model only concerns the delivery time and replenishment unit to each BSS. The route will be pre-determined using the TSP model and the decision will be determined using this model. With a planning horizon of a single day, the demand is considered as continuous and stochastic to depict a more realistic situation. Since the inventory level of BSS is sensitive to time, the time will be divided into time slots, becoming discrete, to help acknowledging the inventory level of BSS. The batteries in the BSS can be classified into the following three states that will affect the determination of the replenishment unit as follows.

Table 4.1 Battery States in BSS

No	State	Description
1	Empty	Battery with SoC equals to 0 and is waiting to be charged at time t
2	Recharge	Battery that is currently in charging mode with SoC between 0 and 100 at time t
3	Ready	Battery with SoC equals to 100 at time t that is ready to be used

In this model, the replenishment unit will be determined by considering the minimum acceptable SoC in the BSS. All batteries with SoC value below the minimum acceptable SoC (α) in the BSS are considered as batteries that require to be replenished in the BSS. This value will be taken into consideration by CBS as the delivered quantity to the BSS. Since α can be any positive value, there is a probability that the inventory level of BSS not meeting its maximum capacity as the vehicle arrived at the BSS. Hence, this IRP model follows the Maximum Level (ML) policy where the replenishment unit can be any positive value that is less than equal to the maximum capacity of the BSS.

4.2 Model Formulation

The mathematical formulation of this model is constructed based on the Electric Vehicle-Inventory Scheduling Problem (EV-ISP) model and the BES Inventory model by Ahmad (2019). However, there are some adjustments that this model does not have recharge capacity and the unit of recharge rate is not (unit/time). Instead, this model considers minimum acceptable SoC (α), and the unit of the recharge rate is (%/time).

4.2.1. Notation

All notations used in this IRP model are as follows.

1. Notation of variable sets

M	BSS; $\{1, 2, 3, \ldots, n\}$
M'	depot; $\{0\}$
K	vehicle; $\{1, 2, 3, \ldots, k\}$
T	time; $\{1, 2, 3, \ldots, t\}$
P	State of Charge (SoC) value; $\{0\%, 1\%, \ldots, p\}$
S	shipment; $\{1, 2, \ldots, s\}$

2. Notation of cost

$\mathrm{C_T}$	transportation cost per traveling time
$\mathrm{C_M}$	material handling cost per minute
$\mathrm{C_R}$	replenishment cost per battery

3. Notation of vertex

$\mathrm{d_{ij}}$	distance between node *i* and node *j*
$\mathrm{t_{ij}}$	traveling time between node *i* and node *j*
$\mathrm{D_{it}}$	demand at BSS *i* at time *t*; $\mathrm{i \in M, t \in T}$
$\mathrm{W_i}$	capacity of BSS *i*; $\mathrm{i \in M}$
α	minimum acceptable SoC in BSS
$\mathrm{I_{it}}$	inventory level at BSS *i* at time *t*; $\mathrm{i \in M, t \in T}$
$\mathrm{r_{Ri}}$	recharging rate at BSS *i* at time *t*; $\mathrm{i \in M, t \in T}$
$\mathrm{Q_{it}^{p}}$	amount of battery with SoC value of *p* at BSS *i* at time *t*; $\mathrm{p \in P, i \in M, t \in T}$
Q_{ift}	amount of battery that just becoming full 100%
C_{it}	1, if there is stockout at BSS *i* at time *t*; 0, otherwise
Z_{0s}	1, if the CBS is visited at shipment *s*; 0, otherwise
Z_{is}	1, if the BSS *i* is visited at shipment *s*; 0, otherwise; $\mathrm{i \in M}$
y_{ij}^{s}	1, if BSS *j* immediately follows *i* in the route traveled at shipment *s*; 0, otherwise.

4. Notation of the battery

$\mathrm{t_{UL}}$	loading/unloading time of battery at BSS i at time t; $\mathrm{i \in M, t \in T}$

5. Notation of the vehicle

$\mathrm{Z_k}$	capacity of vehicle k; $\mathrm{k \in K}$
$\mathrm{v_{ij}}$	velocity of vehicle
$\mathrm{W_{sk}}$	total loaded batteries to vehicle *k* at shipment *s*

6. Notation of decision variable

$\mathrm{X_{ijtk}}$	1, if vertex j is directly visited after vertex i at time t by vehicle k 0, otherwise

Y_{itk} 1, if BSS i is visited by vehicle k at time t

0, otherwise

Q_{itk} delivered quantity to BSS i at time t by vehicle k

4.2.2. Objective Function

There are three costs considered in the objective function, which are transportation cost, replenishment cost, and material handling cost. Each cost is explained below.

1. Transportation cost is the cost incurred by the vehicle when traveling from node *i* to node *j*.
2. Replenishment cost is the cost incurred by having the replenishment unit delivered from CBS.
3. Material handling cost is the cost incurred by loading/unloading a battery in the BSS.

These costs are represented in the mathematical model as follows.

Min Z =

$$\sum_{\forall i\in M}\sum_{\forall j\in M}\sum_{\forall t\in T}\sum_{\forall k\in K} C_T t_{ij} X_{ijtk} + \sum_{\forall i\in M}\sum_{\forall j\in M}\sum_{\forall t\in T}\sum_{\forall k\in K} C_M t_{UL} Y_{itk} + \sum_{\forall i\in M}\sum_{\forall j\in M}\sum_{\forall t\in T} C_R Q_{itk} \quad (4.1)$$

4.2.3. Constraints

Constraints that are considered in the IRP model are as follows.

Subject to :

1. Inventory at the BSS

$$I_{it} = I_{i(t-1)} + Q_{itk} + Q_{ift} - D_{it} \qquad \forall i \in M, \forall t \in T \qquad (4.2)$$

2. No stockout is allowed at the BSS

$$I_{it} \geq 0 \qquad \forall i \in M, \forall t \in T \qquad (4.3)$$

$$D_{it} \leq W_i \qquad \forall i \in M, \forall t \in T \qquad (4.4)$$

3. The inventory level at the BSS should be less than equal to BSS maximum capacity

$I_{it} \leq W_i \qquad \forall i \in M, \forall t \in T \qquad (4.5)$

4. Delivered quantity to BSS *i* should not exceed the capacity of BSS *i*

$Q_{itk} \leq W_i Y_{itk} + Q_{ift} \qquad \forall i \in M, \forall t \in T, \forall k \in K \qquad (4.6)$

5. Total quantity delivered by vehicle *k* should not exceed its maximum capacity

$\sum_{\forall i \in I} Q_{itk} \leq Z_k \qquad \forall t \in T, \forall k \in K \qquad (4.7)$

6. Delivered quantity to BSS *i* should be less than equal to loaded batteries to vehicle *k* at shipment *s*

$Q_{itk} \leq W_{sk} \qquad \forall i \in M, \forall t \in T, \forall k \in K \qquad (4.8)$

7. Total loaded batteries to vehicle *k* on shipment *s* should be less than equal to its capacity

$W_{sk} \leq Z_k \qquad \forall i \in M, \forall t \in T, \forall k \in K \qquad (4.9)$

8. Delivered quantity to BSS *i* at time *t* by vehicle *k* should not exceed the total amount of batteries with SoC under α on BSS *i* at time *t*

$$Q_{itk} \leq \sum_{p=0}^{p<\alpha} Q_{it}^{p} + (D_{it} - I_{i(t-1)} - Q_{ift})C_{it}$$

$\forall i \in M, \forall t \in T, \forall k \in K, \forall p \in P \qquad (4.10)$

9. The route traveled at shipment *s* should visit the CBS when there is at least a BSS visited at shipment *s*.

$\sum_{\forall i \in I} Q_{itk} \leq Z_k Z_{0s} \qquad \forall t \in T, \forall k \in K, \forall s \in S \qquad (4.11)$

10. The route traveled at shipment *s* should contain one arc entering every *i* of the route and one arc leaving every *i* if delivery is made at shipment *s*.

$\sum_{m \in I} y_{im}^{s} + \sum_{j \in I} y_{ji}^{s} = 2z_{is} \qquad \forall i \in M, \forall s \in S \qquad (4.12)$

11. Non-negativity and integrality constraints

$$X_{ijtk} \in \{0,1\} \quad (4.13)$$

$$Y_{itk} \in \{0,1\} \quad (4.14)$$

$$Q_{itk} \geq 0 \quad (4.15)$$

4.2.4. Inventory Model on Battery Swap Station

This model represents the inventory level of Battery Swap Station (BSS) from two points of view, which are the battery swapping system and battery charging system as in Ahmad (2019). However, in this model, all electric vehicles are assumed to finish the battery swapping process in the same time slot as the arrival time slot. Therefore a variable representing the number of EVs that have not finish swapping the battery is omitted.

a. Battery Swapping Model

$$N_{EV}(i) = N_{NEV}(i) \quad (4.16)$$

$$N_{EV}(i) = N_{SEV}(i) \quad (4.17)$$

$$N_A(i) = N_A(i-1) + N_{NA}(i) \quad (4.18)$$

$$N_C(i) = N_C(i-1) - N_{NA}(i) + N_{SEV}(i-1) \quad (4.19)$$

c. Battery Charging Model

$$N_A(i) \geq N_{EV}(i) \quad (4.20)$$

Notations:

$N_A(i)$ quantity of available battery to be swapped at time slot *t*

$N_C(i)$ quantity of charging battery at time slot *t*

$N_{NA}(i)$ quantity of finished charging battery at time slot *t*

$N_{EV}(i)$ quantity of electric vehicle waiting to swap its battery at time slot *t*

$N_{NEV}(i)$ quantity of electric vehicle arriving to swap its battery at time slot *t*

$N_{SEV}(i)$ quantity of electric vehicle finishing the battery swapping process at time slot *t*

4.3 Model Algorithm

The algorithm for IRP in this research begins with route determination using the shortest path algorithm of Traveling Salesman Problem (TSP) model. Before executing the route determination algorithm, the amount of BSS and its location coordinate in longitude and latitude format should be first determined. Then the route determination algorithm is started by calculating the distance matrix for each pair of nodes. The distance between two nodes is set to symmetrical and is calculated using the haversine formula. Haversine formula is used to obtain a more realistic distance between two nodes considering the earth as a sphere. Every route will depart from CBS (depot) and will return to CBS after all nodes have been included in the route. After creating the distance matrix and setting the departure node as CBS, the destination node is determined by choosing a node (BSS) with the closest distance to the departure node (CBS). The chosen node then is considered as a departure node and this searching process continues until all nodes have been included in the route.

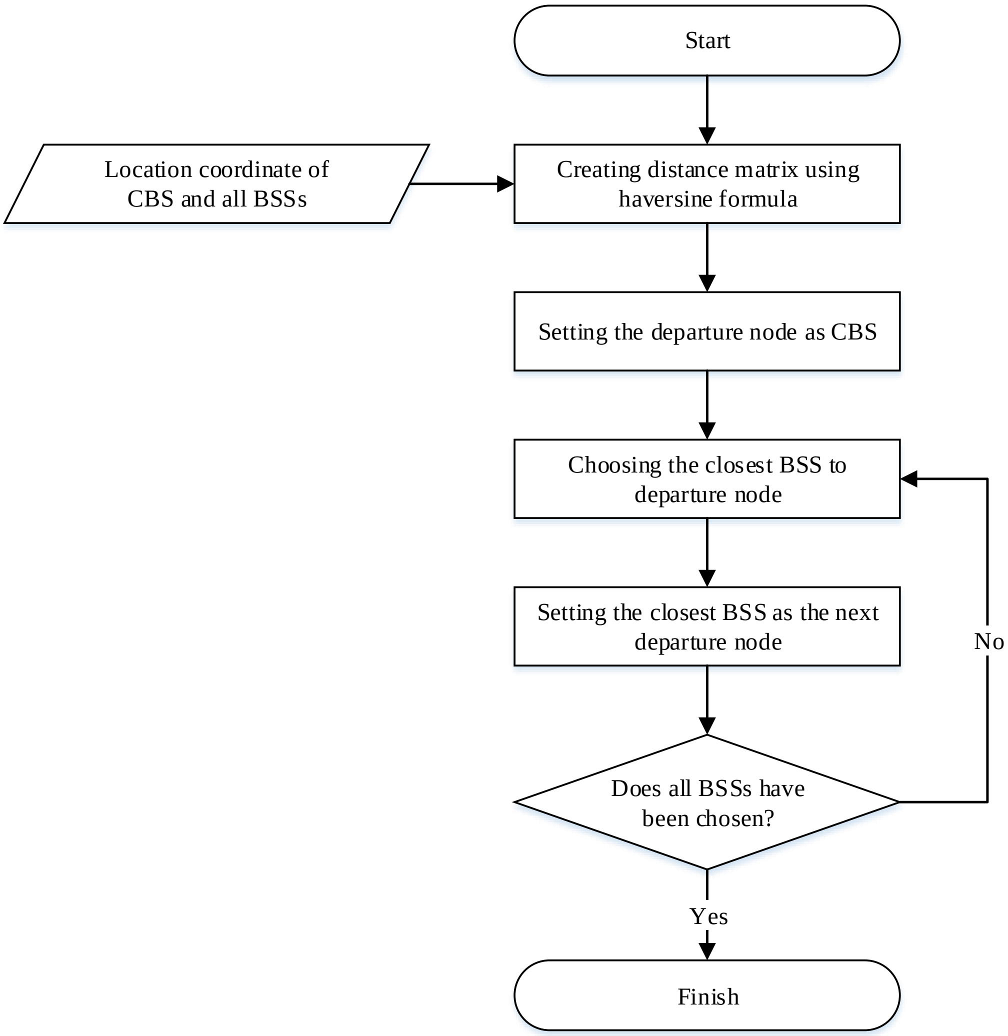

Figure 4.2 Flowchart of Route Determination using TSP

When the route has been determined, the next process is determining the delivered quantity and delivering time to each BSS consecutively as in the route. The first step is the vehicle departure time determination. If the shipment is considered as the first shipment in the period, intershipment time is not taken into account in determining the vehicle departure time. Intershipment time is the time duration between two consecutive shipments. The vehicle departure time for the first shipment in the period equals to the starting time of the vehicle operating in the period. If the vehicle departure time is bigger than the vehicle latest departure time in the period, the shipment will be canceled because no more shipment is allowed. The inventory level of all BSSs then will be updated until the end of the period and total lost sales during the period will be calculated. Another aspect to consider before determining the condition of each BSS is either the vehicle capacity is bigger than zero or not. When the vehicle capacity equals to zero, even though the vehicle departure time is less than the vehicle latest departure time, the shipment will also be canceled.

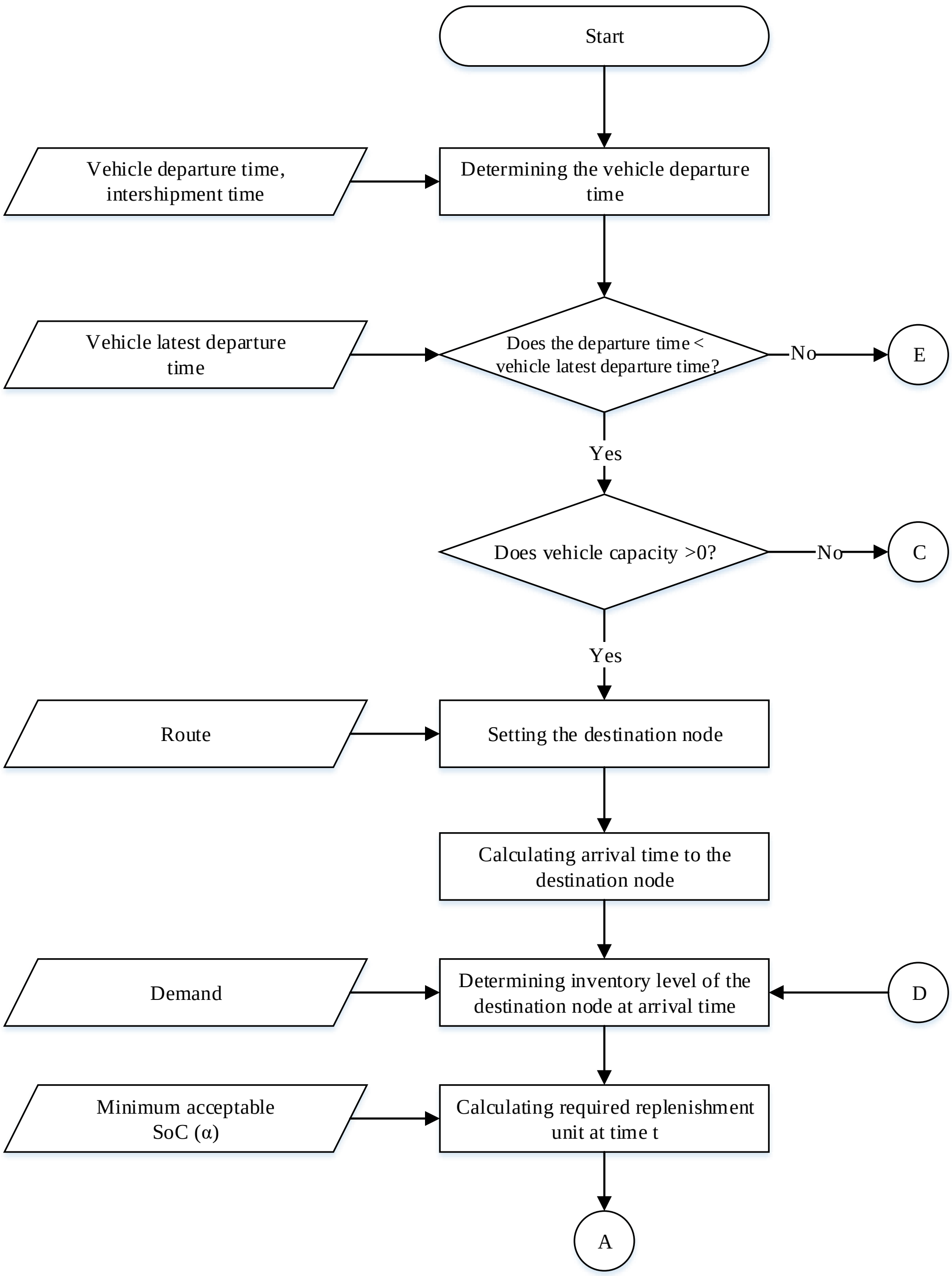

Figure 4.3 Flowchart of Replenishment Unit and Scheduling Determination (1)

If the constraints of vehicle departure time and vehicle capacity are satisfied, the destination node is set consecutively according to the route. Arrival time at the destination node then is calculated along with the inventory level of the destination node at arrival time. Not only calculating the number of fully charged battery but also the number of empty battery and charging battery as well as the state of charge (SoC) of each charging battery at that time. To determine the delivered quantity to the destination node, calculating the required replenishment unit of destination node at time t should be concerned. The required replenishment unit is the amount of battery that is eligible to be replaced with fully charged batteries delivered by the vehicle. Only batteries with SoC under the minimum acceptable SoC (α) that will be counted as required replenishment unit.

Before determining the actual replenishment unit or delivered quantity by the vehicle, it should be assured either the vehicle capacity if sufficient to load the required replenishment unit or not. If the vehicle capacity is less than the required replenishment unit, then the destination node changes to CBS, postponing the shipment to the node. Otherwise, the replenishment unit is set as equal to the required replenishment unit, and the left capacity on the vehicle is updated. In case that all BSSs can be visited within the same shipment, this shipment will be finished by calculating the arrival time at CBS and calculating the total cost.

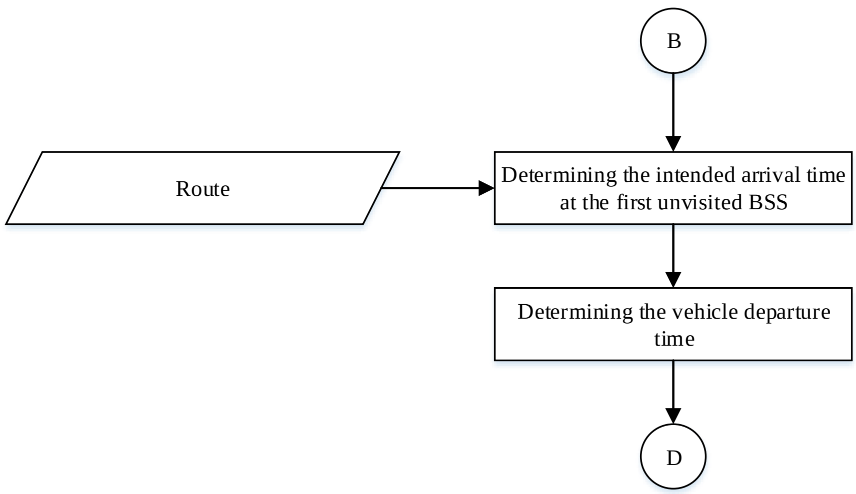

Figure 4.4 Flowchart of Vehicle Departure Time Calculation When Visiting The Postponed Node

When there is a condition of all BSSs can not be visited in the same shipment, additional shipment should be arranged to cover the postponed shipment to all BSSs that have not been visited by the previous shipment. This additional shipment should arrive at the unvisited node at the same time as if it is visited along in the previous shipment. Hence, the vehicle departure time should be calculated to assure the vehicle will arrive at the destination at the intended arrival time. After deciding the vehicle departure time, the inventory level at the destination node at arrival time is calculated and the process continues as in Figure 4.3. The process of scheduling shipments is repeated until the constraint of vehicle latest departure time is met. Furthermore, the last steps are updating the inventory level of all BSSs until the end of the period and calculating the total lost sales of all BSSs in the period.

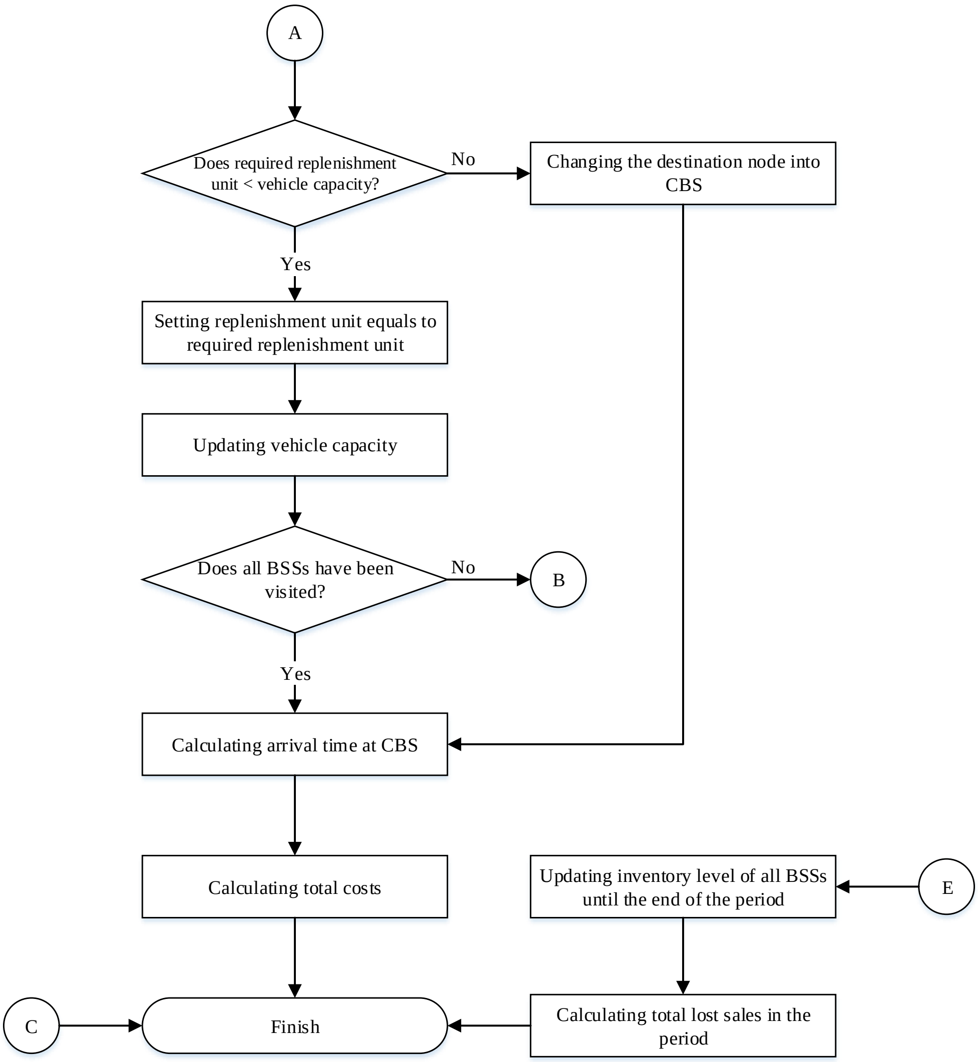

Figure 4.5 Flowchart of Replenishment Unit and Scheduling Determination (2)

4.4 Model Verification

In creating a model, verification is important to identify the model's mathematical accuracy and logical consistency. The validation process is not performed in this research because this model has not been implemented in real condition thus the accuracy of this model towards real condition could not be identified. This model will be verified by comparing the results of the VBA model with the results of manual computation. If there is no difference in the results, then the model is verified. Otherwise, the model should be adjusted until no difference is found.

In this subchapter will only be shown the representative data from the results of a data set. The detail of the data set and the overall results are available in Appendix A. According to the following calculations, there is no difference between the results of manual calculation and the results of the IRP model in VBA. Hence, this IRP model is considered as verified. The results generated by the IRP model with Microsoft Excel 2016 VBA and manual calculations are as follow.

Table 4.2 First Trip Result

Route	Departure Time (min)	Returning Time (min)	Total Traveling Cost	Total Replenishment Cost	Total Handling Cost	Total cost
0-5-4-1-3-2-0	480	600	Rp. 164.857,3	Rp. 470.250,-	Rp. 24.750,-	Rp. 659.857,3

Table 4.3 First Shipment Report

Cycle	0	5	4	1	3	2	0	Total	Total Cost
Period	0	1	4	6	8	9	12		
Time (min)	480	490	520	540	560	570	600		
Required Replenishment (unit)		5	31	20	24	15			
Actual Replenishment (unit)		5	31	20	24	15		95	Rp. 470.250
Vehicle Capacity (unit)	300	295	264	244	220	205	205		
Handling Time (min)		10	10	10	10	10		50	Rp. 24.750
Travelling Distance (km)		7,418282	13,29914	6,471945	5,546123	3,134386	17,30989	53,17976	Rp. 164.857,3
Travelling Time (min)		9	16	8	7	4	21		
Total Cost									Rp. 659.857,3

Table 4.4 Inventory Level of All BSSs at Vehicle Arrival Time

	BSS 1		BSS 2		BSS 3		BSS 4		BSS 5
Time Slot	Slot 5	Slot 6	Slot 8	Slot 9	Slot 7	Slot 8	Slot 3	Slot 4	Slot 1
Time (min)	530	540	560	570	550	560	510	520	490
Demand (unit)	10	11	8	6	7	11	13	8	5
Replenishment (unit)		25		15		25		31	5
Picked up (unit)		25		15		25		31	5
Rejected Demand (unit)		0			0	0			
Fully Charged Battery (unit)	2	20	15	33	2	24	10	33	40
Empty Battery (unit)	10	0	8	0	7	0	13	0	0
Charging Battery (unit)	28	20	17	7	31	16	17	7	0
1	100	Ready	50	75	25	Ready	50	75	
2	100	Ready	50	75	25	Ready	50	75	Ready
3	100	Ready	50	75	25	Ready	50	75	Ready
4	100	Ready	50	75	25	Ready	50	75	Ready
5	75	100	50	75	25	Ready	50	75	Ready
6	75	100	50	75	0	Ready	50	75	Ready
7	75	100	25	Ready	0	Ready	50	75	Ready
8	75	100	0	Ready	0	Ready	25	Ready	Ready
9	75	100	0	Ready	0	Ready	25	Ready	Ready
10	75	100	0	Ready	0	Ready	25	Ready	Ready
11	75	100	0	Ready	0	Ready	25	Ready	Ready
12	75	100	0	Ready	0	Ready	25	Ready	Ready
13	50	75	0	Ready	Ready	Ready	25	Ready	Ready
14	50	75	0	Ready	100	Ready	25	Ready	Ready

	BSS 1		BSS 2		BSS 3		BSS 4		BSS 5
Time Slot	Slot 5	Slot 6	Slot 8	Slot 9	Slot 7	Slot 8	Slot 3	Slot 4	Slot 1
Time (min)	530	540	560	570	550	560	510	520	490
15	50	75	0	Ready	100	Ready	25	Ready	Ready
16	50	75	Ready	Ready	100	Ready	25	Ready	Ready
17	50	75	Ready	Ready	100	Ready	25	Ready	Ready
18	50	75	Ready	Ready	100	Ready	0	Ready	Ready
19	50	75	Ready	Ready	100	Ready	0	Ready	Ready
20	50	75	Ready	Ready	100	Ready	0	Ready	Ready
21	50	75	Ready	Ready	100	Ready	0	Ready	Ready
22	50	75	Ready	Ready	75	100	0	Ready	Ready
23	50	75	Ready	Ready	75	100	0	Ready	Ready
24	50	75	Ready	Ready	75	100	0	Ready	Ready
25	25	Ready	Ready	Ready	75	100	0	Ready	Ready
26	25	Ready	Ready	Ready	75	100	0	Ready	Ready
27	25	Ready	Ready	Ready	75	100	0	Ready	Ready
28	25	Ready	Ready	Ready	75	100	0	Ready	Ready
29	0	Ready	Ready	Ready	50	75	0	Ready	Ready
30	0	Ready	Ready	Ready	50	75	0	Ready	Ready
31	0	Ready	100	Ready	50	75	Ready	Ready	Ready
32	0	Ready	100	Ready	50	75	Ready	Ready	Ready
33	0	Ready	100	Ready	50	75	Ready	Ready	Ready
34	0	Ready	100	Ready	50	75	Ready	Ready	Ready
35	0	Ready	100	Ready	50	75	Ready	Ready	Ready
36	0	Ready	100	Ready	50	75	Ready	Ready	Ready
37	0	Ready	100	Ready	50	75	Ready	Ready	Ready
38	0	Ready	100	Ready	25	Ready	Ready	Ready	Ready
39	Ready	Ready	100	Ready	25	Ready	Ready	Ready	Ready
40	Ready	Ready	75	100	Ready	Ready	Ready	Ready	Ready

The previous results are compared to the results of manual calculation on each constraint of the IRP model. The details are as follows.

1. Inventory at the BSS

$I_{it} = I_{i(t-1)} + Q_{itk} + Q_{ift} - D_{it}$

Manual calculation:

20 = 2 + 25 + 4 – 11 (BSS 1 at t = 540 (slot 6) in shipment 1)

33 = 15 + 15 + 9 – 6 (BSS 2 at t = 570 (slot 9) in shipment 1)

24 = 2 + 25 + 8 – 11 (BSS 3 at t = 560 (slot 8) in shipment 1)

33 = 10 + 31 + 0 – 8 (BSS 4 at t = 520 (slot 4) in shipment 1)

40 = 0 + 5 + 0 – 5 (BSS 5 at t = 490 (slot 1) in shipment 1)

2. No stock-out is allowed at the BSS

$I_{it} \geq 0$

Manual calculation:

20 (BSS 1 at t = 540 (slot 6) in shipment 1)

33 (BSS 2 at t = 570 (slot 9) in shipment 1)

24 (BSS 3 at t = 560 (slot 8) in shipment 1)

33 (BSS 4 at t = 520 (slot 4) in shipment 1)

40 (BSS 5 at t = 490 (slot 1) in shipment 1)

$D_{it} \leq W_i$

Manual calculation:

11 ≤ 40 (BSS 1 at t = 540 (slot 6) in shipment 1)

6 ≤ 40 (BSS 2 at t = 570 (slot 9) in shipment 1)

11 ≤ 40 (BSS 3 at t = 560 (slot 8) in shipment 1)

8 ≤ 40 (BSS 4 at t = 520 (slot 4) in shipment 1)

5 ≤ 40 (BSS 5 at t = 490 (slot 1) in shipment 1)

3. The inventory level at the BSS should be less than equal to BSS maximum capacity

$I_{it} \leq W_i$

Manual calculation:

20 ≤ 40 (BSS 1 at t = 540 (slot 6) in shipment 1)

33 ≤ 40 (BSS 2 at t = 570 (slot 9) in shipment 1)

24 ≤ 40 (BSS 3 at t = 560 (slot 8) in shipment 1)

33 ≤ 40 (BSS 4 at t = 520 (slot 4) in shipment 1)

40 ≤ 40 (BSS 5 at t = 490 (slot 1) in shipment 1)

4. Delivered quantity to BSS *i* should not exceed the capacity of BSS *i*

$Q_{itk} \leq W_i Y_{itk} + Q_{ift}$

25 ≤ 40(1) + 4 (BSS 1 at t = 540 (slot 6) in shipment 1)

15 ≤ 40(1) + 9 (BSS 2 at t = 570 (slot 9) in shipment 1)

25 ≤ 40(1) + 8 (BSS 3 at t = 560 (slot 8) in shipment 1)

31 ≤ 40(1) + 0 (BSS 4 at t = 520 (slot 4) in shipment 1)

5 ≤ 40(1) + 0 (BSS 5 at t = 490 (slot 1) in shipment 1)

5. Quantity loaded to vehicle *k* should not exceed its maximum capacity

$$\sum_{\forall i \in I} Q_{itk} \leq Z_k$$

Manual calculation:

25 + 15 + 25 + 31 + 5 ≤ 300 (Shipment 1)

101 ≤ 300

6. Delivered quantity to BSS *i* should less than equal to loaded capacity of vehicle *k* on shipment *s*

$Q_{itk} \leq W_{sk}$

25 ≤ 101 (BSS 1 in shipment 1)

15 ≤ 101 (BSS 2 in shipment 1)

25 ≤ 101 (BSS 3 in shipment 1)

31 ≤ 101 (BSS 4 in shipment 1)

5 ≤ 101 (BSS 5 in shipment 1)

7. Total delivered quantity by vehicle *k* on shipment *s* should less than equal to its capacity

$W_{sk} \leq Z_k$

Manual calculation:

101 ≤ 300 (Shipment 1)

8. Delivered quantity to BES *i* at time *t* by vehicle *k* should not exceed the total amount of batteries with SoC under α on BES *i* at time *t*

$$Q_{itk} \leq \sum_{p=0}^{p<\alpha} Q_{it}^{p} + (D_{it} - I_{i(t-1)} - Q_{ift})C_{it}$$

Manual calculation:

25 ≤ 20 + (11 – 2 – 4)(1) (BSS 1 at t = 540 (slot 6) in shipment 1 and *p* = 75%)

15 ≤ 15 + (6 – 15 – 9)(0) (BSS 2 at t = 570 (slot 9) in shipment 1 and *p* = 75%)

25 ≤ 24 + (11 – 2 – 8)(1) (BSS 3 at t = 560 (slot 8) in shipment 1 and *p* = 75%)

31 ≤ 31 + (8 – 10 – 0)(0) (BSS 4 at t = 520 (slot 4) in shipment 1 and *p* = 75%)

5 ≤ 5 + (0 – 0 – 0)(0) (BSS 5 at t = 490 (slot 1) in shipment 1 and *p* = 75%)

9. The route traveled at shipment *s* should visit the CBS when there is at least a BSS visited at shipment *s*

$$\sum_{\forall i \in I} Q_{itk} \leq Z_k Z_{0s}$$

Manual calculation:

25 + 15 + 25 + 31 + 5 ≤ 300(1) (Shipment 1)

101 ≤ 300

10. The route traveled at shipment *s* should contain one arc entering every vertex *i* of the route and one arc leaving every *i* if delivery is made at shipment *s*

$$\sum_{m \in I} y_{im}^{s} + \sum_{j \in I} y_{ji}^{s} = 2z_{is}$$

Manual calculation:

1 + 1 = 2(1) (Shipment 1, with i = 4, m = 1, and j = 5)

11. Non-negativity and integrality constraints

$X_{ijtk} \in \{0,1\}$

Manual calculation:

X_{054901} = 1 (visit BSS 5 directly from depot at t = 490 (slot 1) in shipment 1)

X_{545201} = 1 (visit BSS 4 directly from BSS 5 at t = 520 (slot 4) in shipment 1)

X_{415401} = 1 (visit BSS 1 directly from BSS 4 at t = 540 (slot 6) in shipment 1)

X_{135601} = 1 (visit BSS 3 directly from BSS 1 at t = 560 (slot 8) in shipment 1)

X_{325701} = 1 (visit BSS 2 directly from BSS 3 at t = 570 (slot 9) in shipment 1)

$Y_{itk} \in \{0,1\}$

Manual calculation:

Y_{54901} = 1 (BSS 5 is visited at t = 490 by vehicle 1)

Y_{45201} = 1 (BSS 4 is visited at t = 520 by vehicle 1)

Y_{15401} = 1 (BSS 1 is visited at t = 540 by vehicle 1)

Y_{35601} = 1 (BSS 3 is visited at t = 560 by vehicle 1)

Y_{25701} = 1 (BSS 2 is visited at t = 570 by vehicle 1)

$Q_{itk} \geq 0$

Manual calculation:

$25 \leq 0$ (BSS 1 at t = 540 (slot 6) in shipment 1)

$15 \leq 0$ (BSS 2 at t = 570 (slot 9) in shipment 1)

$25 \leq 0$ (BSS 3 at t = 560 (slot 8) in shipment 1)

$31 \leq 0$ (BSS 4 at t = 520 (slot 4) in shipment 1)

$5 \leq 0$ (BSS 5 at t = 490 (slot 1) in shipment 1)

12. $N_{EV}(i) = N_{NEV}(i)$

Manual calculation:

11 = 11 (BSS 1 at i = 540 (slot 6) in shipment 1)

6 = 6 (BSS 2 at i = 570 (slot 9) in shipment 1)

11 = 11 (BSS 3 at i = 560 (slot 8) in shipment 1)

8 = 8 (BSS 4 at i = 520 (slot 4) in shipment 1)

5 = 5 (BSS 5 at i = 490 (slot 1) in shipment 1)

13. $N_{EV}(i) = N_{SEV}(i)$

11 = 11 (BSS 1 at i = 540 (slot 6) in shipment 1)

6 = 6 (BSS 2 at i = 570 (slot 9) in shipment 1)

11 = 11 (BSS 3 at i = 560 (slot 8) in shipment 1)

8 = 8 (BSS 4 at i = 520 (slot 4) in shipment 1)

5 = 5 (BSS 5 at i = 490 (slot 1) in shipment 1)

14. $N_A(i) = N_A(i-1) + N_{NA}(i)$

Manual calculation:

12 = 12 + 0 (BSS 1 at t = 530 (slot 5))

23 = 11 + 12 (BSS 2 at t = 560 (slot 8))

9 = 1 + 8 (BSS 3 at t = 550 (slot 7))

23 = 23 + 0 (BSS 4 at t = 510 (slot 3))

40 = 40 + 0 (BSS 5 at t = 500 (slot 2))

15. $N_C(i) = N_C(i-1) - N_{NA}(i) + N_{SEV}(i-1)$

Manual calculation:

28 = 24 – 0 + 4 (BSS 1 at t = 530 (Slot 5))

17 = 28 – 12 + 1 (BSS 2 at t = 560 (slot 8))

31 = 32 – 8 + 7 (BSS 3 at t = 550 (slot 7))

17 = 7 – 0 + 10 (BSS 4 at t = 510 (slot 3))

6 = 0 – 0 + 6 (BSS 5 at t = 510 (slot 3))

16. $N_A(i) \geq N_{EV}(i)$

12 > 10 (BSS 1 at t = 530 (slot 5))

23 > 8 (BSS 2 at t = 560 (slot 8))

9 > 7 (BSS 3 at t = 550 (slot 7))

23 > 13 (BSS 4 at t = 510 (slot 3))

40 > 5 (BSS 5 at t = 500 (slot 2))

4.5 IRP model in Microsoft Excel VBA

This IRP model is built on Microsoft Excel 2016 using visual basic for application (VBA) feature. There are four processes conducted in the IRP computer model that are setting the value of the variables, creating distance matrix, generating demand, and generating the route, replenishment unit, and shipment time to each BSS in truck operational time.

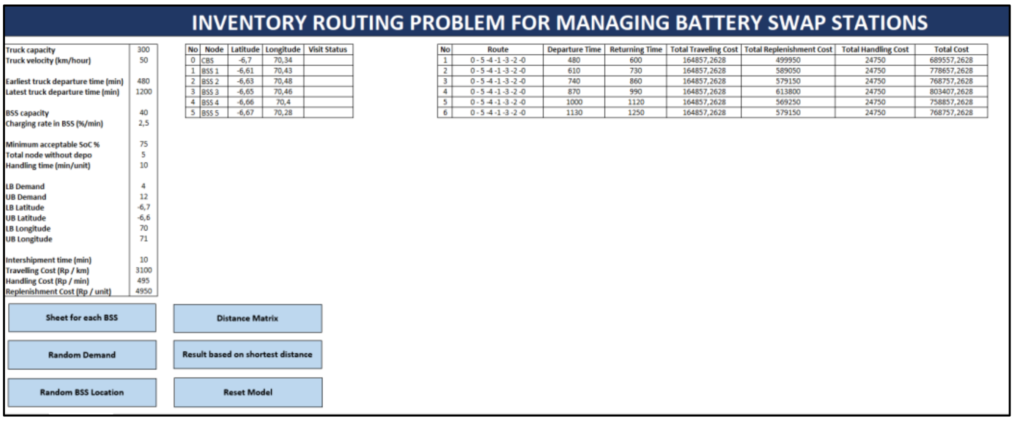

Figure 4.6 Homepage Sheet in IRP Computer Model

In Microsoft Excel, there are five types of sheet dedicated respectively for variables and final results, distance matrix, demand matrix, shipments report, and inventory level on each BSS. All input variables used in the model is declared in the homepage sheet. Hence, the distance matrix is generated as well as the demand matrix of each BSS. In the distance matrix, the distance for each pair of nodes of all nodes is stated as in Figure 4.7.

Total Node	6					
Distance Matrix						
	CBS	BSS 1	BSS 2	BSS 3	BSS 4	BSS 5
CBS	350104	14,1045	17,3099	14,3712	7,98035	7,41828
BSS 1	14,1045	350104	5,95334	5,54612	6,47194	17,8594
BSS 2	17,3099	5,95334	350104	3,13439	9,44411	22,5316
BSS 3	14,3712	5,54612	3,13439	350104	6,71906	20,0031
BSS 4	7,98035	6,47194	9,44411	6,71906	350104	13,2991
BSS 5	7,41828	17,8594	22,5316	20,0031	13,2991	350104

Figure 4.7 Distance Matrix Sheet

After creating the distance matrix, the demand matrix is also created on the demand matrix sheet. In this model, the time is discrete to 10 minutes starting from truck earliest departure time until the end of the day. The demand is set randomly in a normal distribution for each BSS. Moreover, the demand is used to calculate the inventory level on each BSS at each discrete time.

Random Demand														
Time	490	500	510	520	530	540	550	560	570	580	590	600	610	620
	6	5	6	8	7	4	9	7	6	6	12	7	11	5
	6	7	12	11	7	4	6	6	7	9	8	11	6	12
	12	7	12	12	11	11	10	10	11	8	11	6	11	6
	12	10	8	9	9	6	8	8	4	9	8	6	6	5
	5	7	7	10	10	4	10	11	10	5	9	8	8	9
	6	4	6	8	9	7	9	7	4	5	5	8	4	5
	4	7	4	7	6	9	5	6	5	6	5	6	5	9
Average	7,285714	6,714286	7,857143	9,285714	8,428571	6,428571	8,142857	7,857143	6,714286	6,857143	8,285714	7,428571	7,285714	7,285714
SD	3,302236	1,889822	3,078342	1,799471	1,812654	2,760262	1,9518	1,9518	2,811541	1,772811	2,690371	1,812654	2,811541	2,751623
Demand	5	6	7	8	7	10	9	6	7	6	9	8	10	10
BSS 1	4	8	12	4	10	11	4	12	7	10	11	9	10	5
BSS 2	7	11	12	9	11	6	1	8	6	4	7	12	10	13
BSS 3	5	8	8	7	9	7	7	11	6	10	3	9	10	14
BSS 4	7	10	13	8	8	10	4	10	8	10	10	6	6	7
BSS 5	5	6	7	8	7	10	9	6	7	6	9	8	10	10

Random Demand													
Time	630	640	650	660	670	680	690	700	710	720	730	740	750
	9	11	10	10	5	4	9	9	5	6	8	5	5
	7	6	9	11	8	10	11	9	9	9	7	9	11
	5	11	11	9	10	6	5	6	10	5	9	6	9
	11	10	11	4	9	4	4	5	5	4	8	6	9
	7	7	7	9	5	9	4	5	5	11	10	9	5
	5	12	11	12	9	8	9	11	5	5	12	10	6
	6	8	10	5	5	9	11	11	11	9	7	7	5
Average	7,142857	9,285714	9,857143	8,571429	7,285714	7,142857	7,571429	8	7,142857	7	8,714286	7,428571	7,142857
SD	2,193063	2,288689	1,46385	2,992053	2,21467	2,478479	3,154739	2,645751	2,734262	2,645751	1,799471	1,902379	2,478479
Demand	6	9	11	4	7	7	14	8	7	5	9	8	5
BSS 1	4	10	10	6	6	11	6	9	10	6	8	8	9
BSS 2	8	8	8	8	11	8	11	7	6	5	7	8	6
BSS 3	13	12	11	9	6	10	1	8	7	6	0	7	7
BSS 4	12	10	10	8	12	10	5	9	11	8	6	8	6
BSS 5	6	9	11	4	7	7	14	8	7	5	9	8	5

Figure 4.8 Demand Matrix

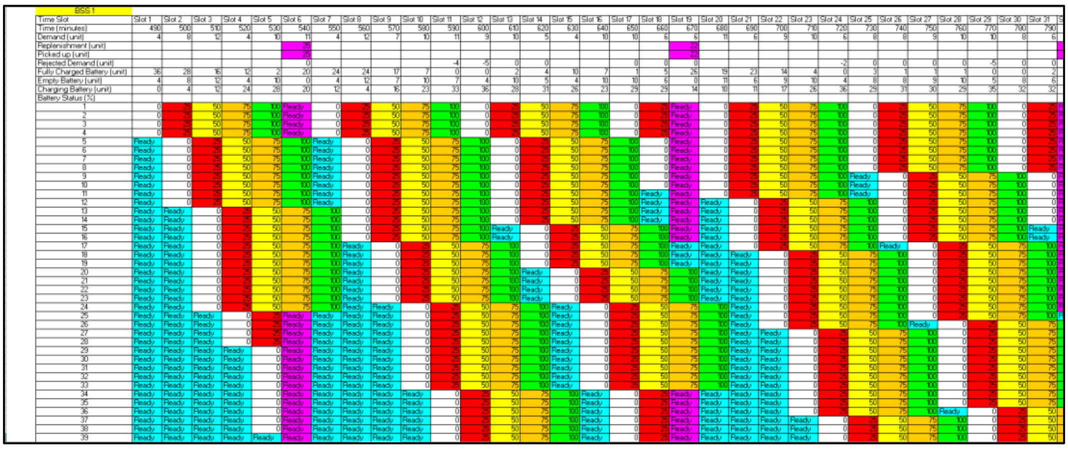

Figure 4.9 Inventory Level on each BSS

Each BSS has their sheet to depict the inventory level condition. The sheet displays the number of fully charged battery, empty battery, charging battery, as well as their SoC. The colors in the cell have their meaning. Red color indicates the battery with SoC under 25%, yellow color indicates the battery with SoC under 50%, orange color indicates the battery with SoC under 75%, and green color indicates the battery with SoC under 100%. The SoC stated in each cell represents a value to achieve by the battery at the end of the time slot. Hence, battery with SoC value equals to 100% at a time slot only can be used at the following time slot. The batter label of “Ready” indicates that the battery is ready for use. The purple color in the cells indicates the replenished battery by the truck according to the set α value.

Trip No.										
1	Cycle	0	5	4	1	3	2	0	Total	Total Cost
	Period	0	1	4	6	8	9	12		
	Time (min)	480	490	520	540	560	570	600		
	Required Replenishment (unit)		5	31	25	25	15			
	Actual Replenishment (unit)		5	31	25	25	15		101	499950
	Vehicle Capacity (unit)	300	295	264	239	214	199	199		
	Handling Time (min)		10	10	10	10	10		50	24750
	Travelling Distance (km)		7,41828	13,2991	6,47194	5,54612	3,13439	17,3099	53,1798	164857,2628
	Travelling Time (min)		9	16	8	7	4	21		
	Total Cost									689557,2628
2	Cycle	0	5	4	1	3	2	0	Total	Total Cost
	Period	13	14	17	19	21	22	25		
	Time (min)	610	620	650	670	690	700	730		
	Required Replenishment (unit)		28	32	22	17	20			
	Actual Replenishment (unit)		28	32	22	17	20		119	589050
	Vehicle Capacity (unit)	300	272	240	218	201	181	181		
	Handling Time (min)		10	10	10	10	10		50	24750
	Travelling Distance (km)		7,41828	13,2991	6,47194	5,54612	3,13439	17,3099	53,1798	164857,2628
	Travelling Time (min)		9	16	8	7	4	21		
	Total Cost									778657,2628
3	Cycle	0	5	4	1	3	2	0	Total	Total Cost
	Period	26	27	30	32	34	35	38		
	Time (min)	740	750	780	800	820	830	860		
	Required Replenishment (unit)		22	26	24	24	21			
	Actual Replenishment (unit)		22	26	24	24	21		117	579150
	Vehicle Capacity (unit)	300	278	252	228	204	183	183		
	Handling Time (min)		10	10	10	10	10		50	24750
	Travelling Distance (km)		7,41828	13,2991	6,47194	5,54612	3,13439	17,3099	53,1798	164857,2628

Figure 4.10 Shipments Report

In this model, demand value represents demand at the end of each time slot. The truck will visit the BSS before or at the same time as the demand arriving at the BSS. Hence, when at the time slot of the truck arriving, no stock-out will exists. The replenishment unit, arriving time, and other details of each shipment are recorded in the shipments report sheet. In this sheet, the report is dedicated to each shipment performed in the day. While the general results of shipment are presented in the homepage sheet.

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CHAPTER 5
NUMERICAL EXPERIMENT AND ANALYSIS

In this chapter will be discussed the numerical experiments conducted using the IRP model as well as the analysis of the results.

5.1 Basic Parameters of Numerical Experiment

In conducting the numerical experiments, several parameters have the same value for both numerical experiments, known as basic parameters. The basic parameters consist of truck capacity, truck velocity, earliest truck departure time, latest truck departure time, BSS capacity, handling time, charging rate in BSS, demand interval, latitude interval, longitude interval, traveling cost, handling cost, and replenishment cost. The details of these basic parameters are as follow.

Table 5.1 Basic Parameters of Numerical Experiment

No	Variable	Unit	Value
1	Truck capacity	item	300
2	Truck velocity	km/hour	30 and 50
3	Earliest truck departure time	minutes	480
4	Latest truck departure time	minutes	1200
5	BSS capacity	item	40
6	Charging rate in BSS	%/minute	2,5
7	Handling time	minutes	10
8	Demand (low)		[1,4]
9	Demand (medium)		[5,8]
10	Demand (high)		[9,12]
11	Demand (very high)		[13,21]
12	Latitude		[-6,7 , -6,6]
13	Longitude		[70,71]
14	Traveling cost	/minute	1
15	Handling cost	/minute	0,01
16	Replenishment cost	/item	2,4
17	Penalty cost	/item	8,4

1. Traveling cost referring to Shao, et.al (2017) represents the traveling cost incurred for every minute of traveling time.
2. Replenishment cost is obtained from the assumption that a battery has a capacity of 3 kWh. While for the electricity cost is considered as 0,8 / kWh (Verma, 2018). Therefore, the electricity cost of charging a battery from empty to full is 2,4.
3. Handling cost is set to 1% of traveling cost as in Battara, et. al (2010). Thus, the handling cost is 0,01 for moving batteries in 1 minute.
4. Penalty cost, a cost incurred for any lost sales in each BSS, refers to Verma (2018).
5. Truck capacity is set to 300 as in Ahmad (2019).
6. Truck velocity is set to 30 km/hour for numerical experiment 1 and 50 km/hour for numerical experiment 2.
7. BSS capacity is set to 40 as the common capacity of Gogoro's BSS.
8. The charging rate is set to 2,5 %/minute according to average EV battery charging time equals to 40 minutes (from empty to full) as in Dreyfuss & Giat (2017).
9. Demand, which is divided into four levels, are determined according to the BSS capacity and battery SoC type. In this research, the battery SoC while in charging is divided into four types; ¼ of full, 2/4 of full, ¾ of full, and 4/4 of full that if it is converted to charging percentage are 25%, 50%, 75%, and 100%. Besides, the empty battery has the SoC of 0%. Therefore, to avoid stockout, these five types of SoC should be at least satisfied. By considering the BSS capacity of 40, hence the maximum demand to avoid any stockout is 8. Otherwise, if the demand exceeds 8, there will be stockout thus the demand is considered as high and very high. On the other hand, if demand far below 8, stockout will not exist thus the demand is considered as low. The value of each level of demand is determined randomly that fit normal distribution.
10. Truck operational time, handling time, latitude, and longitude are set randomly.

5.2 Numerical Experiment 1

The objective of the first numerical experiment is to determine intershipment time and minimum acceptable SoC (α) that lead to the most minimum total cost in the period corresponding to each level of demand. In this experiment, total cost includes traveling cost, handling cost, replenishment cost, and penalty cost. This experiment is conducted only for a data set of five BSSs (n = 5). The overall results are as follows.

Table 5.2 Results of Low Demand

Demand	Min. Acceptable SoC (α)	Intershipment Time	Shipment Frequency	Replenishment Unit	Traveling Cost	Replenishment Cost	Material Handling Cost	Penalty Cost	Total cost	Lost Sales
Low	25	60	12	156	1284	374,4	6	0	1664,4	0
		90	8	97	856	232,8	4	0	1092,8	0
		120	6	74	642	177,6	3	0	822,6	0
	50	60	12	313	1284	751,2	6	0	2041,2	0
		90	8	192	856	460,8	4	0	1320,8	0
		120	6	150	642	360	3	0	1005	0
	75	60	12	462	1284	1108,8	6	0	2398,8	0
		90	8	291	856	698,4	4	0	1558,4	0
		120	6	226	642	542,4	3	0	1187,4	0
	100	60	12	600	1284	1440	6	0	2730	0
		90	8	392	856	940,8	4	0	1800,8	0
		120	6	287	642	688,8	3	0	1333,8	0

Table 5.3 Results of Medium Demand

Demand	Min. Acceptable SoC (α)	Intershipment Time	Shipment Frequency	Replenishment Unit	Traveling Cost	Replenishment Cost	Material Handling Cost	Penalty Cost	Total cost	Lost Sales
Medium	25	60	12	392	1284	940,8	6	0	2230,8	0
		90	8	262	856	628,8	4	0	1488,8	0
		120	6	194	642	465,6	3	0	1110,6	0
	50	60	12	775	1284	1860	6	0	3150	0
		90	8	511	856	1226,4	4	0	2086,4	0
		120	6	385	642	924	3	0	1569	0

Demand	Min. Acceptable SoC (α)	Intershipment Time	Shipment Frequency	Replenishment Unit	Traveling Cost	Replenishment Cost	Material Handling Cost	Penalty Cost	Total cost	Lost Sales
	75	60	12	1174	1284	2817,6	6	0	4107,6	0
		90	8	764	856	1833,6	4	0	2693,6	0
		120	6	582	642	1396,8	3	0	2041,8	0
	100	60	12	1554	1284	3729,6	6	0	5019,6	0
		90	8	1015	856	2436	4	0	3296	0
		120	6	770	642	1848	3	0	2493	0

Table 5.4 Results of High Demand

Demand	Min. Acceptable SoC (α)	Intershipment Time	Shipment Frequency	Replenishment Unit	Traveling Cost	Replenishment Cost	Material Handling Cost	Penalty Cost	Total cost	Lost Sales
High	25	60	12	625	1284	1500	6	8484	11274	1010
		90	8	416	856	998,4	4	7333,2	9191,6	873
		120	6	306	642	734,4	3	8904	10283,4	1060
	50	60	12	670	1284	1608	6	8391,6	11289,6	999
		90	8	813	856	1951,2	4	6955,2	9766,4	828
		120	6	582	642	1396,8	3	8811,6	10853,4	1049
	75	60	12	1162	1284	2788,8	6	8391,6	12470,4	999
		90	8	1193	856	2863,2	4	6955,2	10678,4	828
		120	6	621	642	1490,4	3	8811,6	10947	1049
	100	60	12	1787	1284	4288,8	6	8391,6	13970,4	999
		90	8	1587	856	3808,8	4	6955,2	11624	828
		120	6	901	642	2162,4	3	8811,6	11619	1049

Table 5.5 Results of Very High Demand

Demand	Min. Acceptable SoC (α)	Intershipment Time	Shipment Frequency	Replenishment Unit	Traveling Cost	Replenishment Cost	Material Handling Cost	Penalty Cost	Total cost	Lost Sales
Very High	25	60	12	888	1284	2131,2	6	26342,4	29763,6	3136
		90	8	469	856	1125,6	4	26871,6	28857,2	3199
		120	6	439	642	1053,6	3	27207,6	28906,2	3239
	50	60	12	944	1284	2265,6	6	26082	29637,6	3105
		90	8	1102	856	2644,8	4	22570,8	26075,6	2687
		120	6	830	642	1992	3	26804,4	29441,4	3191
	75	60	12	980	1284	2352	6	25964,4	29606,4	3091
		90	8	1569	856	3765,6	4	22360,8	26986,4	2662
		120	6	868	642	2083,2	3	26670	29398,2	3175
	100	60	12	1487	1284	3568,8	6	25964,4	30823,2	3091
		90	8	2113	856	5071,2	4	22360,8	28292	2662
		120	6	907	642	2176,8	3	26670	29491,8	3175

According to results of Table 5.2, when the demand is considered as low, the most efficient value for intershipment time and α is 120 minutes and 25%. It means that time between consecutive shipments is 120 minutes, which results in six shipments in a period. With α equals to 25% means that the replaced batteries are batteries with SoC less than 25%. Thus there are 74 replaced batteries during the period (six shipments). Since the demand is low, no lost sales existing.

For demand classified as medium, the most efficient intershipment time and α result in the same value as when the demand is low, which are 120 minutes and 25%. The replenishment unit in the period equals to 194 batteries and no lost sales is found due to the medium level of demand.

While for high demand, the most efficient intershipment time and α are 90 minutes and 25%. It means that time between two consecutive shipments are 90 minutes, resulting in eight total shipments during truck operational time in the period. The α value of 25% means that all batteries with SoC below 25% will be replaced by the truck, resulting in a total of 416 replenishment units in the period. Due to the high demand, lost sales equal to 873 batteries in the period.

For very high demand, the most efficient intershipment time and α are 90 minutes and 50%. It means that time between two consecutive shipments are 90 minutes, resulting in eight shipments during the period. The α value of 50% means that all batteries with SoC below 50% will be replaced by the truck, resulting in 1102 replaced batteries. Because the demand is considered as very high, there are 2687 lost sales in the period.

According to these results, when the demand level is considered as low and medium, the most economical options of intershipment time and α are the most minimum one, that are interhsipment time equals to 120 minutes and α equals to 25%. It is because the BSS will not experience stock-out concerning the demand level, hence the least frequent delivery and the most minimum value of α are still be considered as enough to maintain the service level of BSS. On the other hand, when the demand is considered as higher, this experiment shows that the required intershipment time will be shorter since more frequent shipment is needed. Besides, the value of α also increases due to higher probability of having lost sales. In this case, for high and very high demand, the most efficient intershipment time is 90 minutes while the value of α is 25% and 50% respectively.

From this experiment, it can be seen that when the demand is considered as low and medium, the least frequent supply of anticipation stock is considered as enough because stock-out will not happened in corresponding demand level. While as the demand level gets higher, delivery of fully charged batteries as anticipation stocks should be done more frequent to minimize or avoid stock-out. On the one hand, the value of α should be set higher to increase the amount of replaced battery in the BSSs. It will lead to higher stock of fully charged batteries in the BSSs.

5.3 Numerical Experiment 2

The second numerical experiment aims to determine either additional shipment is required or not in correspond to three levels of demand (low, medium, and high) between four data sets; n = 5, n = 10, n = 15, and n = 20. In this experiment, the vehicle velocity is set to 50 km/hour, the α value is 75%, and the intershipment time of 90 minutes that are applicable for all demands and all data sets. With intershipment time of 90 minutes, ideally there will be nine scheduled shipments during the truck operational time. Additional shipment is a shipment generated to visit node that is not yet been visited by the previous shipment. In this experiment, the additional shipment is assigned for only unvisited nodes. The scheduled shipment will not be performed if all nodes of previous shipment have not been visited. The objective of this experiment is to determine which data set at what demand level that requires additional shipment. The results of this experiment are as follow.

1. N = 5 with Low Demand

For a data set of BSSs equals to five and low demand, there are nine shipments generated during truck operational time. From Table 5.6, it could be seen that the intershipment time between two consecutive shipments for the whole period is static with a value of 90 minutes. The static value of intershipment time and the total shipments equal to nine indicates that there is no additional shipment in this case. All BSSs are visited within the same shipment.

Table 5.6 Intershipment Time when n = 5 with Low Demand

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
1	0-5-4-1-3-2-0	480	600		30
2	0-5-4-1-3-2-0	570	690	90	35
3	0-5-4-1-3-2-0	660	780	90	37
4	0-5-4-1-3-2-0	750	870	90	36
5	0-5-4-1-3-2-0	840	960	90	42
6	0-5-4-1-3-2-0	930	1050	90	37
7	0-5-4-1-3-2-0	1020	1140	90	41
8	0-5-4-1-3-2-0	1110	1230	90	37
9	0-5-4-1-3-2-0	1200	1320	90	37

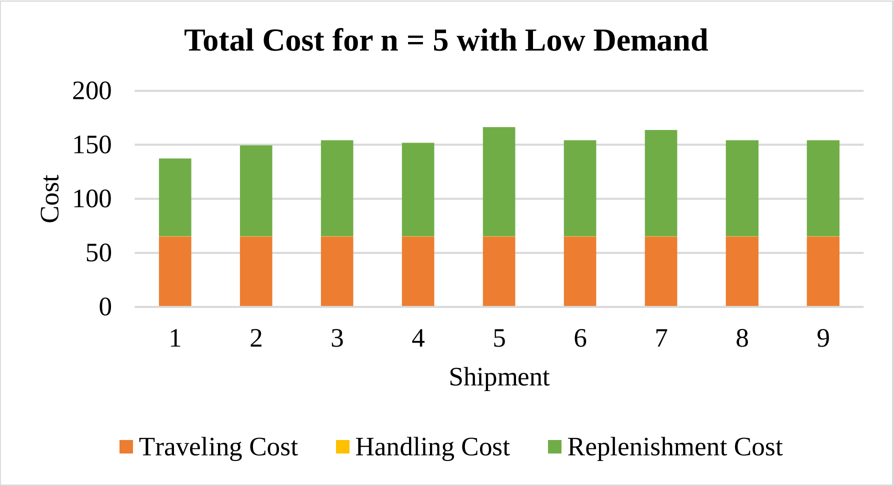

Figure 5.1 Total Cost when n = 5 with Low Demand

Table 5.7 Total Cost when n = 5 with Low Demand

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
1	0-5-4-1-3-2-0	65	0,5	72	137,5
2	0-5-4-1-3-2-0	65	0,5	84	149,5
3	0-5-4-1-3-2-0	65	0,5	88,8	154,3
4	0-5-4-1-3-2-0	65	0,5	86,4	151,9
5	0-5-4-1-3-2-0	65	0,5	100,8	166,3
6	0-5-4-1-3-2-0	65	0,5	88,8	154,3
7	0-5-4-1-3-2-0	65	0,5	98,4	163,9
8	0-5-4-1-3-2-0	65	0,5	88,8	154,3
9	0-5-4-1-3-2-0	65	0,5	88,8	154,3

Because all BSSs are visited in the same route for all shipments and none of the additional shipment performed, the traveling cost and handling cost of all shipments have the same value. On the other hand, the replenishment cost of each shipment is various as in Figure 5.1 and Table 5.7. It can be seen that the highest replenishment cost, as well as the total cost, is performed by the fifth shipment. While the least replenishment cost and total cost is performed by the first shipment. However, the replenishment costs of all shipments do not vary significantly since no additional shipment exists.

2. N = 5 with Medium Demand

According to Table 5.8, the intershipment value of all shipments is exactly the same as the previous result. Not only the intershipment time, but also the shipment frequency is exactly the same as in n = 5 with low demand. Hence, it means that none of additional shipment exist and all BSSs are visited within the same shipment.

Table 5.8 Intershipment Time when n = 5 with Medium Demand

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
1	0-5-4-1-3-2-0	480	600		84
2	0-5-4-1-3-2-0	570	690	90	99
3	0-5-4-1-3-2-0	660	780	90	94
4	0-5-4-1-3-2-0	750	870	90	93
5	0-5-4-1-3-2-0	840	960	90	98
6	0-5-4-1-3-2-0	930	1050	90	99
7	0-5-4-1-3-2-0	1020	1140	90	102
8	0-5-4-1-3-2-0	1110	1230	90	92
9	0-5-4-1-3-2-0	1200	1320	90	96

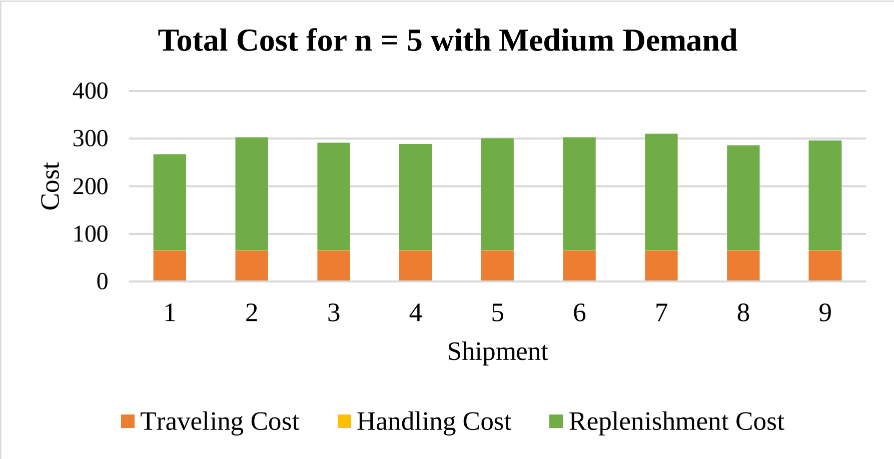

Figure 5.2 Total Cost when n = 5 with Medium Demand

Table 5.9 Total Cost when n = 5 with Medium Demand

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
1	0-5-4-1-3-2-0	65	0,5	201,6	267,1
2	0-5-4-1-3-2-0	65	0,5	237,6	303,1
3	0-5-4-1-3-2-0	65	0,5	225,6	291,1
4	0-5-4-1-3-2-0	65	0,5	223,2	288,7
5	0-5-4-1-3-2-0	65	0,5	235,2	300,7
6	0-5-4-1-3-2-0	65	0,5	237,6	303,1
7	0-5-4-1-3-2-0	65	0,5	244,8	310,3
8	0-5-4-1-3-2-0	65	0,5	220,8	286,3
9	0-5-4-1-3-2-0	65	0,5	230,4	295,9

While in terms of total cost, the total cost of all shipments vary less significant than the results of n = 5 with low demand. The least total cost belongs to first shipment and the highest total cost belongs to the seventh shipment. Compared to previous condition, the proportion of replenishment cost to total cost is bigger.

3. N = 5 with High Demand

The intershipment time of n = 5 with high demand indicates that a data set of five BSSs have all of the BSSs is visited within the same shipment. Regardless of the demand level, the required replenishment unit by all BSSs could be satisfied in one shipment for the whole period.

Table 5.10 Intershipment Time when n = 5 with High Demand

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
1	0-5-4-1-3-2-0	480	600		126
2	0-5-4-1-3-2-0	570	690	90	150
3	0-5-4-1-3-2-0	660	780	90	158
4	0-5-4-1-3-2-0	750	870	90	156
5	0-5-4-1-3-2-0	840	960	90	155
6	0-5-4-1-3-2-0	930	1050	90	153
7	0-5-4-1-3-2-0	1020	1140	90	152
8	0-5-4-1-3-2-0	1110	1230	90	151
9	0-5-4-1-3-2-0	1200	1320	90	154

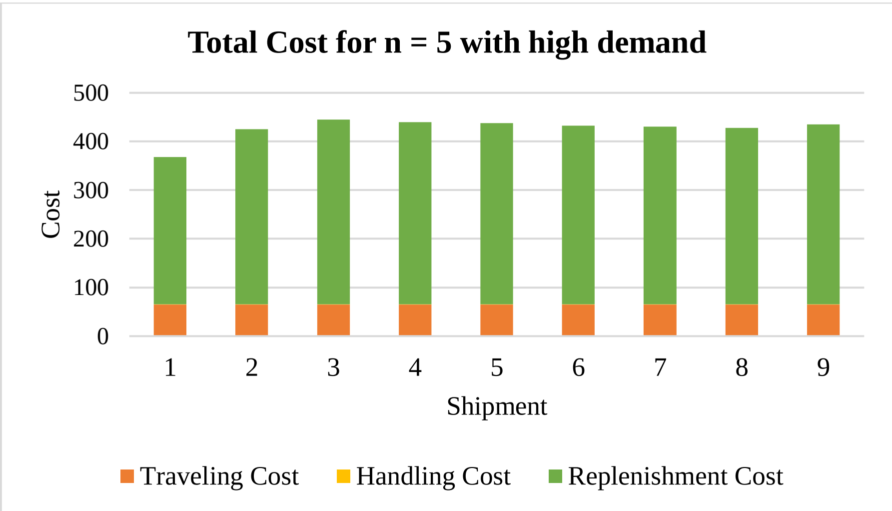

Figure 5.3 Total Cost when n = 5 with High Demand

Table 5.11 Total Cost when n = 5 with High Demand

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
1	0-5-4-1-3-2-0	65	0,5	302,4	367,9
2	0-5-4-1-3-2-0	65	0,5	360	425,5
3	0-5-4-1-3-2-0	65	0,5	379,2	444,7
4	0-5-4-1-3-2-0	65	0,5	374,4	439,9
5	0-5-4-1-3-2-0	65	0,5	372	437,5
6	0-5-4-1-3-2-0	65	0,5	367,2	432,7
7	0-5-4-1-3-2-0	65	0,5	364,8	430,3
8	0-5-4-1-3-2-0	65	0,5	362,4	427,9
9	0-5-4-1-3-2-0	65	0,5	369,6	435,1

According to Figure 5.3 and Table 5.11, it could be seen that the total cost of all shipments, except for the first shipment, is slightly different. The first shipment incurred the lowest total cost and the highest total cost is performed by the third shipment. Compared to other demand levels of the same data set, this condition has the biggest proportion of replenishment cost to total cost.

4. N = 10 with Low Demand

For a data set of 10 BSSs with low demand, the intershipment time is static to the value of 90 minutes. During the truck operational time, there are nine shipments generated with a duration of one shipment visiting all BSSs equals to 200 minutes. Hence, in this condition, none of the additional shipment is performed and all BSSs are visited in the same shipment.

Table 5.12 Intershipment Time when n = 10 with Low Demand

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
1	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	480	680		66
2	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	570	770	90	71
3	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	660	860	90	68
4	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	750	950	90	71
5	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	840	1040	90	64

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
6	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	930	1130	90	80
7	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	1020	1220	90	64
8	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	1110	1310	90	76
9	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	1200	1400	90	77

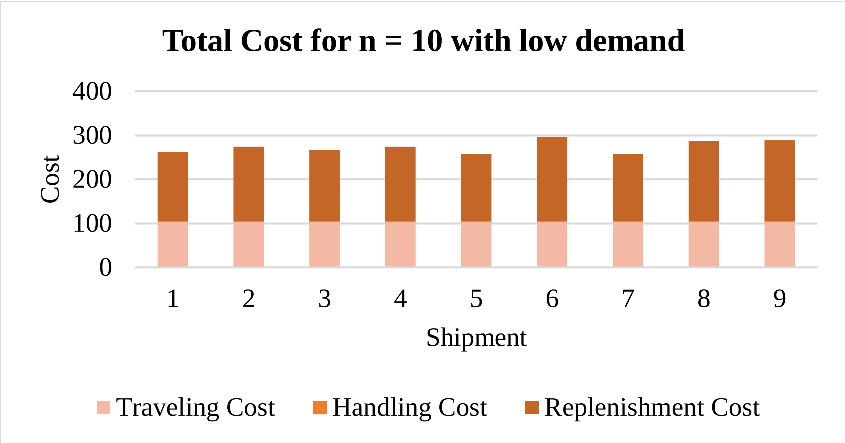

Figure 5.4 Total Cost when n = 10 with Low Demand

Table 5.13 Total Cost when n = 10 with Low Demand

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
1	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	158,4	262,4
2	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	170,4	274,4
3	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	163,2	267,2
4	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	170,4	274,4
5	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	153,6	257,6
6	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	192	296
7	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	153,6	257,6
8	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	182,4	286,4
9	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	184,8	288,8

For the total cost, there is no significant difference in all shipments. The difference in total cost between shipments is influenced only by the replenishment cost because none of the additional shipment is performed and all BSSs are visited in the same shipment for all shipments. Hence, the handling cost and traveling cost are the same for all shipments. The highest total cost is generated by the sixth shipment while the least total cost is generated by the fifth shipment and the seventh shipment with the same value.

5. N = 10 with Medium Demand

The intershipment time pattern for a data set of 10 BSSs with medium demand is static, performing the same value as in the same data set with low demand. Not only the variety of intershipment time, but also the shipment frequency in the whole period is the same as in the previous section. It means that in this condition none of BSS is visited in different shipment with the others.

Table 5.14 Intershipment Time when n = 10 with Medium Demand

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
1	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	480	680		177
2	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	570	770	90	197
3	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	660	860	90	192
4	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	750	950	90	187
5	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	840	1040	90	196
6	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	930	1130	90	200
7	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	1020	1220	90	195
8	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	1110	1310	90	190
9	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	1200	1400	90	197

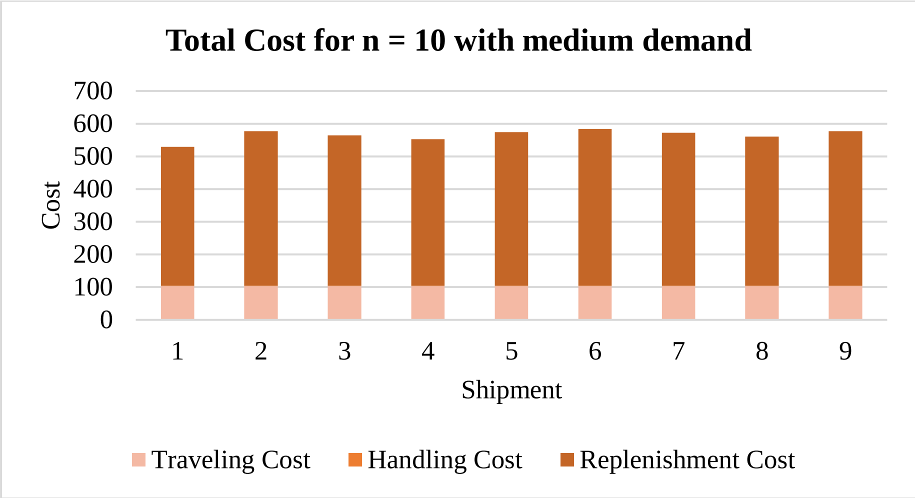

Figure 5.5 Total Cost when n = 10 with Medium Demand

Table 5.15 Total Cost when n = 10 with Medium Demand

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
1	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	424,8	528,8
2	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	472,8	576,8
3	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	460,8	564,8
4	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	448,8	552,8
5	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	470,4	574,4
6	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	480	584
7	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	468	572
8	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	456	560
9	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	472,8	576,8

While for the total cost, even though there is no significant difference in all shipments, it could be seen that the replenishment cost dominates more of total cost compared to the previous conditions. The highest total cost is incurred in the sixth shipment while the least total cost is incurred in the first shipment.

6. N = 10 with High Demand

In this condition, the intershipment time between two consecutive shipments of all shipments in the period is various. It indicates that there is a condition where some BSSs could not visit in the same shipment, which results in generating additional shipment. From 14 shipments generated, there are six additional shipments generated that are highlighted in blue color. Besides, the scheduled shipment performed in this condition is only eight from nine shipments (ideal amount of shipment) because there is one BSS that could not be visited corresponding to the eighth scheduled shipment due to truck operational time constraint.

Table 5.16 Intershipment Time when n = 10 with High Demand

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
1	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -8 -0	480	680		250
2	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -0	570	750	90	283
3	0 - 8 -0	680	770	110	29
4	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -0	660	840	(20)	277
5	0 - 8 -0	770	860	110	35
6	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -0	750	930	(20)	279
7	0 - 8 -0	860	950	110	31
8	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -0	840	1020	(20)	272
9	0 - 8 -0	950	1040	110	29
10	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -0	930	1110	(20)	278
11	0 - 8 -0	1040	1130	110	31
12	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -0	1020	1200	(20)	278
13	0 - 8 -0	1130	1220	110	30
14	0 - 10 -6 -4 -2 -5 - 9 -3 -7 -1 -0	1110	1290	(20)	283

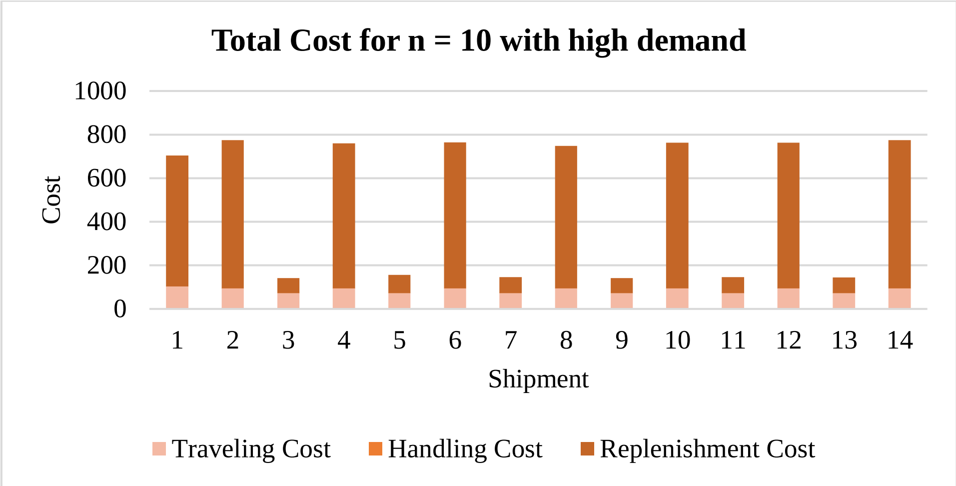

Figure 5.6 Total Cost when n = 10 with High Demand

Table 5.17 Total Cost when n = 10 with High Demand

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
1	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -8 -0	103	1	600	704
2	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -0	94	0,9	679,2	774,1
3	0 - 8 -0	72	0,1	69,6	141,7
4	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -0	94	0,9	664,8	759,7
5	0 - 8 -0	72	0,1	84	156,1
6	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -0	94	0,9	669,6	764,5
7	0 - 8 -0	72	0,1	74,4	146,5
8	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -0	94	0,9	652,8	747,7
9	0 - 8 -0	72	0,1	69,6	141,7
10	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -0	94	0,9	667,2	762,1
11	0 - 8 -0	72	0,1	74,4	146,5
12	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -0	94	0,9	667,2	762,1
13	0 - 8 -0	72	0,1	72	144,1
14	0 - 10 -6 -4 -2 -5 -9 -3 -7 -1 -0	94	0,9	679,2	774,1

Referring to Table 5.16, the intershipment time of additional shipment to previous shipment equals to 110 minutes. While the intershipment time of scheduled shipment to previous shipment is (20) minutes, meaning that it is generated 20 minutes earlier from the additional shipment. Because additional shipment exists in this case, total cost of additional shipments differs significantly to the total cost of scheduled shipments. The most minimum total cost performed in this period belongs to the third shipment and the ninth shipment with the same value while the highest total cost belongs to the second shipment and the fourteenth shipment.

7. N = 15 with Low Demand

For a data set of 15 BSSs with low demand, the intershipment time is static with a value of 90 minutes. While the traveling time performed by the truck in one shipment until it returns to CBS equals to 250 minutes. Within the truck operational time, there are nine shipments performed.

Table 5.18 Intershipment Time when n = 15 with Low Demand

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
1	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	480	730		116
2	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	570	820	90	102
3	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	660	910	90	122
4	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	750	1000	90	124
5	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	840	1090	90	126
6	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	930	1180	90	118
7	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	1020	1270	90	109

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
8	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	1110	1360	90	119
9	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	1200	1450	90	118

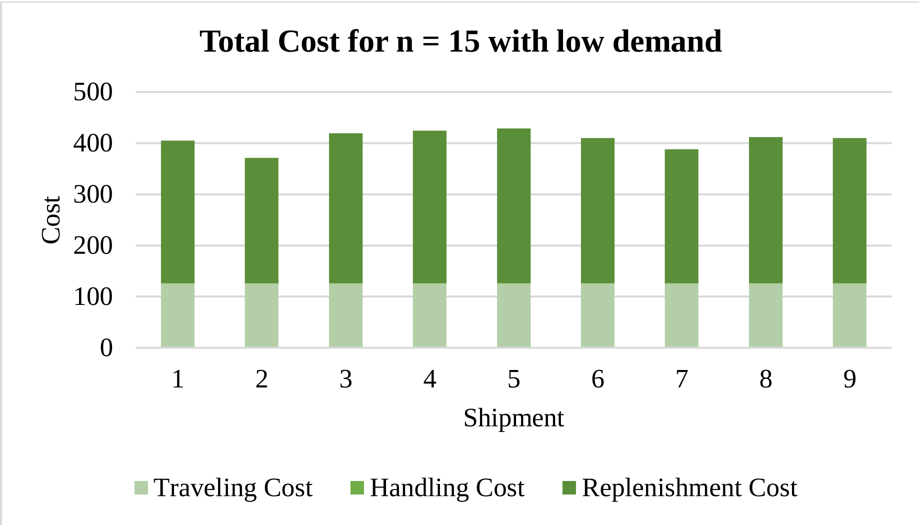

Figure 5.7 Total Cost when n = 15 with Low Demand

Table 5.19 Total Cost when n = 15 with Low Demand

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
1	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	278,4	404,9
2	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	244,8	371,3
3	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	292,8	419,3
4	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12	125	1,5	297,6	424,1

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
	-14 -9 -11 -5 -2 - 0				
5	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	302,4	428,9
6	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	283,2	409,7
7	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	261,6	388,1
8	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	285,6	412,1
9	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	283,2	409,7

In the aspect of total cost, the total cost of all shipments are slightly different. Between these nine shipments, the highest total cost belongs to the fifth shipment while the least total cost belongs to the second shipment.

8. N = 15 with Medium Demand

The intershipment time of this data set with medium demand is exactly the same as in the same data set with low demand, with a value of 90 minutes. Not only the intershipment time, but also the number of shipment performed in the period is equal to nine shipments.

Table 5.20 Intershipment Time when n = 15 with Medium Demand

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
1	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	480	730		282
2	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	570	820	90	291

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
3	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	660	910	90	292
4	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	750	1000	90	291
5	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	840	1090	90	280
6	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	930	1180	90	285
7	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	1020	1270	90	293
8	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	1110	1360	90	288
9	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -11 -5 -2 -0	1200	1450	90	299

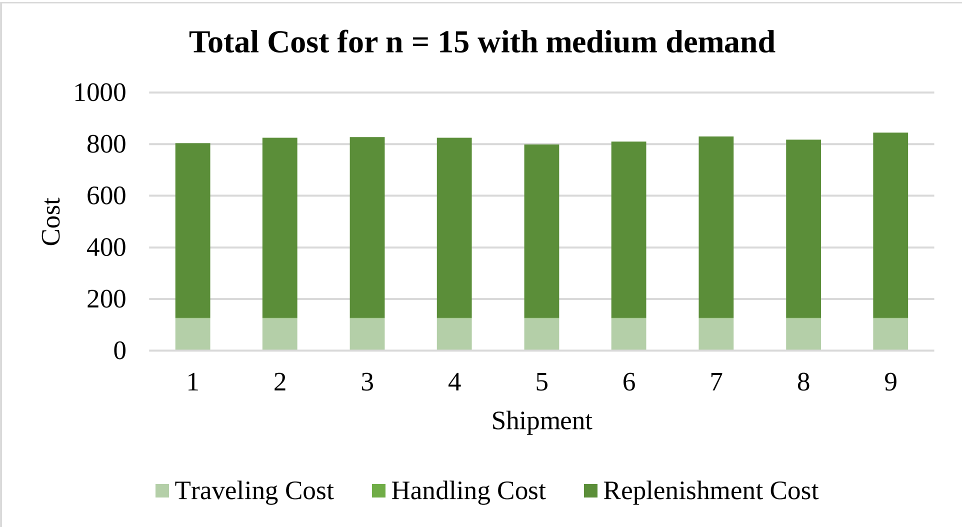

Figure 5.8 Total Cost when n = 15 with Medium Demand

Table 5.21 Total Cost when n = 15 with Medium Demand

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
1	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	676,8	803,3
2	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	698,4	824,9
3	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	700,8	827,3
4	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	698,4	824,9
5	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	672	798,5
6	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	684	810,5
7	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	703,2	829,7
8	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	691,2	817,7
9	0 - 8 -7 -6 -3 -15 -10 -13 -4 -1 -12 -14 -9 -11 -5 -2 - 0	125	1,5	717,6	844,1

While for the total cost, in this condition the replenishment cost becomes more dominant to total cost compared to as in the same data set with low demand. The total cost between shipments is also not varying significantly. The highest total cost is performed by the last shipment while the least total cost is performed by the fifth shipment.

9. N = 15 with High Demand

Different to the two previous conditions, in this condition there are total fifteen shipments generated in the period. All of the intershipment time has value not equal to 90 minutes, indicating that there are some BSSs not visited in the same shipment. From fifteen shipments, there are seven additional shipments and eight scheduled shipments.

Table 5.22 Intershipment Time when n = 15 for High Demand

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
1	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 14 -9 -0	480	670		300
2	0 - 11 -5 -2 -0	630	730	150	79
3	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -0	570	730	(60)	281
4	0 - 12 -14 -9 -11 - 5 -2 -0	690	820	120	188
5	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -0	660	820	(30)	282
6	0 - 12 -14 -9 -11 - 5 -2 -0	780	910	120	187
7	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -0	750	910	(30)	277
8	0 - 12 -14 -9 -11 - 5 -2 -0	870	1000	120	181
9	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -0	840	1000	(30)	280
10	0 - 12 -14 -9 -11 - 5 -2 -0	960	1090	120	180
11	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -12 - 0	930	1100	(30)	300
12	0 - 14 -9 -11 -5 -2 -0	1060	1180	130	150
13	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -0	1020	1180	(40)	280
14	0 - 12 -14 -9 -11 - 5 -2 -0	1140	1270	120	188
15	0 - 8 -7 -6 -3 -15 - 10 -13 -4 -1 -0	1110	1270	(30)	279

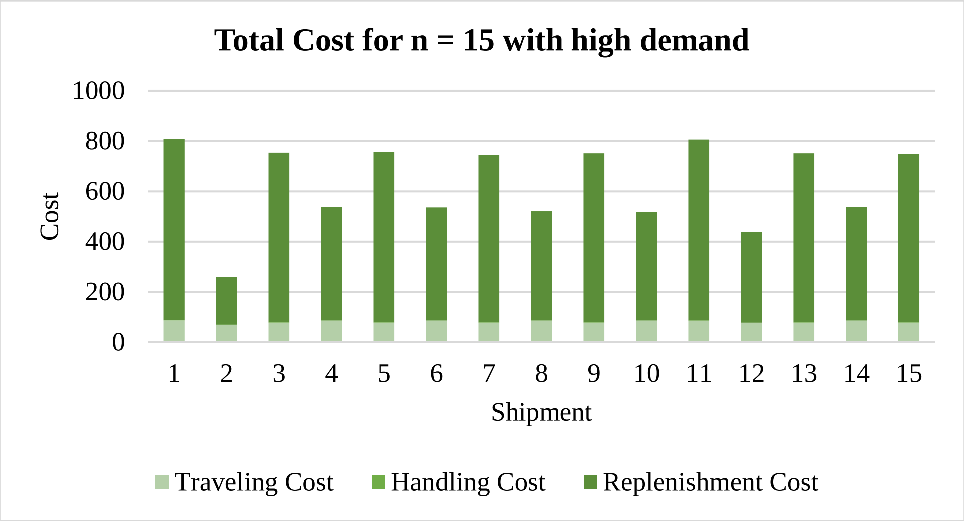

Figure 5.9 Total Cost when n = 15 with High Demand

Table 5.23 Total Cost when n = 15 with High Demand

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
1	0 - 8 -7 -6 -3 - 15 -10 -13 -4 -1 -12 -14 -9 -0	87	1,2	720	808,2
2	0 - 11 -5 -2 -0	70	0,3	189,6	259,9
3	0 - 8 -7 -6 -3 - 15 -10 -13 -4 -1 -0	78	0,9	674,4	753,3
4	0 - 12 -14 -9 - 11 -5 -2 -0	86	0,6	451,2	537,8
5	0 - 8 -7 -6 -3 - 15 -10 -13 -4 -1 -0	78	0,9	676,8	755,7
6	0 - 12 -14 -9 - 11 -5 -2 -0	86	0,6	448,8	535,4
7	0 - 8 -7 -6 -3 - 15 -10 -13 -4 -1 -0	78	0,9	664,8	743,7
8	0 - 12 -14 -9 - 11 -5 -2 -0	86	0,6	434,4	521
9	0 - 8 -7 -6 -3 - 15 -10 -13 -4 -1 -0	78	0,9	672	750,9
10	0 - 12 -14 -9 - 11 -5 -2 -0	86	0,6	432	518,6
11	0 - 8 -7 -6 -3 - 15 -10 -13 -4 -1 -12 -0	85	1	720	806

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
12	0 - 14 -9 -11 -5 -2 -0	77	0,5	360	437,5
13	0 - 8 -7 -6 -3 - 15 -10 -13 -4 -1 -0	78	0,9	672	750,9
14	0 - 12 -14 -9 - 11 -5 -2 -0	86	0,6	451,2	537,8
15	0 - 8 -7 -6 -3 - 15 -10 -13 -4 -1 -0	78	0,9	669,6	748,5

Due to the existence of additional shipments, the total cost of all shipments varies significantly. Between seven additional shipments, the second shipment or the first additional shipment has the lowest total cost compared to others additional shipments due to the least number of BSS to visit by the shipment. The most minimum total cost of all shipments is performed by the second shipment while the highest shipment is performed by the first shipment.

10. N = 20 with Low Demand

For a data set of 20 BSSs with low demand, there are three shipments generated in the period. The intershipment time is static with a value of 90 minutes. In the data set of 20 BSSs to visit, the duration of performing a shipment to visit all BSSs requires 330 minutes.

Table 5.24 Intershipment Time when n = 20 with Low Demand

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
1	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -1 -16 -19 -13 -15 -0	480	810		138
2	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -1 -16 -19 -13 -15 -0	570	900	90	149
3	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -1 -16 -19 -13 -15 -0	660	990	90	142

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
4	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -1 -16 -19 -13 -15 -0	750	1080	90	145
5	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -1 -16 -19 -13 -15 -0	840	1170	90	155
6	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -1 -16 -19 -13 -15 -0	930	1260	90	151
7	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -1 -16 -19 -13 -15 -0	1020	1350	90	168
8	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -1 -16 -19 -13 -15 -0	1110	1440	90	141
9	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -1 -16 -19 -13 -15 -0	1200	1530	90	129

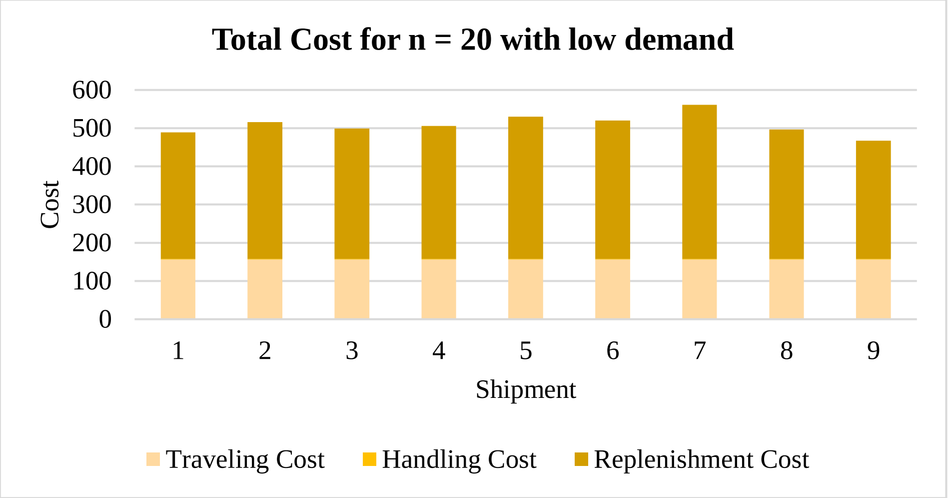

Figure 5.10 Total Cost when n = 20 with Low Demand

Table 5.25 Total Cost when n = 20 with Low Demand

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
1	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -1 -16 -19 -13 -15 -0	156	2	331,2	489,2
2	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -1 -16 -19 -13 -15 -0	156	2	357,6	515,6
3	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -1 -16 -19 -13 -15 -0	156	2	340,8	498,8
4	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -1 -16 -19 -13 -15 -0	156	2	348	506
5	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -1 -16 -19 -13 -15 -0	156	2	372	530
6	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -1 -16 -19 -13 -15 -0	156	2	362,4	520,4
7	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -1 -16 -19 -13 -15 -0	156	2	403,2	561,2
8	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -1 -16 -19 -13 -15 -0	156	2	338,4	496,4
9	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -1 -16 -19 -13 -15 -0	156	2	309,6	467,6

The total cost of all shipments does not vary significantly since it has a very similar value between one and another and no additional shipment exists in this condition. The most minimum total cost of all shipments is generated by the last shipment while the highest total cost is generated by the seventh shipment.

11. N = 20 with Medium Demand

In this condition, the intershipment time has a value not equals to 90 minutes. It indicates that there are additional shipments in this condition, determining that due to vehicle capacity constraint, not all BSSs could be visited in the same shipment. Total shipments performed in this condition is 13 shipments with six of it are additional shipments and the rest are scheduled shipments.

Table 5.26 Intershipment Time when n = 20 with Medium Demand

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
1	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -1 -0	480	730		287
2	0 - 16 -19 -13 -15 -0	710	810	230	78
3	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -0	570	790	(140)	296
4	0 - 1 -16 -19 -13 -15 -0	790	900	220	97
5	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -0	660	880	(130)	291
6	0 - 1 -16 -19 -13 -15 -0	880	990	220	93
7	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -0	750	970	(130)	288
8	0 - 1 -16 -19 -13 -15 -0	970	1080	220	96
9	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -0	840	1060	(130)	299
10	0 - 1 -16 -19 -13 -15 -0	1060	1170	220	101
11	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -0	930	1150	(130)	290

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
12	0 - 1 -16 -19 -13 -15 -0	1150	1260	220	95
13	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -0	1020	1240	(130)	295

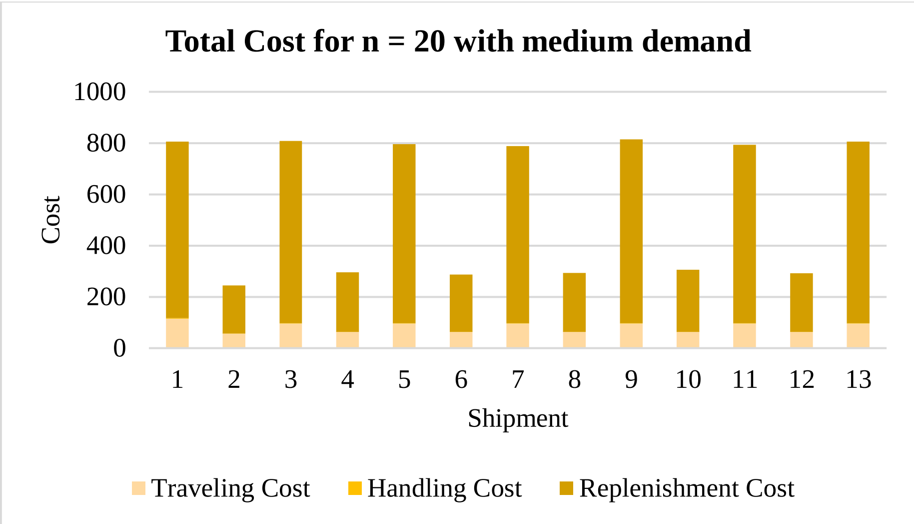

Figure 5.11 Total Cost when n = 20 with Medium Demand

Table 5.27 Total Cost when n = 20 with Medium Demand

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
1	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -1 -0	115	1,6	688,8	805,4
2	0 - 16 -19 -13 -15 -0	57	0,4	187,2	244,6
3	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -0	96	1,5	710,4	807,9
4	0 - 1 -16 -19 -13 -15 -0	63	0,5	232,8	296,3
5	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -20 -2 -17 -7 -5 -14 -0	96	1,5	698,4	795,9

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
6	0 - 1 -16 -19 -13 -15 -0	63	0,5	223,2	286,7
7	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -0	96	1,5	691,2	788,7
8	0 - 1 -16 -19 -13 -15 -0	63	0,5	230,4	293,9
9	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -0	96	1,5	717,6	815,1
10	0 - 1 -16 -19 -13 -15 -0	63	0,5	242,4	305,9
11	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -0	96	1,5	696	793,5
12	0 - 1 -16 -19 -13 -15 -0	63	0,5	228	291,5
13	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -17 -7 -5 - 14 -0	96	1,5	708	805,5

When considering the total cost of all shipments in the period, it could be seen that the total cost of additional shipments is significantly lower than the others. Hence, it means that additional shipments visit less amount of BSSs compared to other shipments. The most minimum total cost of all shipments belongs to the second shipment while the highest total cost belongs to the third shipment.

12. N = 20 with High Demand

Not different from the intershipment time of previous condition, in this condition, there are also additional shipments. With total shipment of 19 shipments, none of the visits all BSSs in the same shipment. There are 12 additional shipments and seven scheduled shipments performed in this condition.

Table 5.28 Intershipment Time when n = 20 with High Demand

No	Route	Departure Time	Returning Time	Intershipment Time	Replenishment unit
1	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -20 -2 -0	480	660		272
2	0 - 17 -7 -5 -14 -1 -16 -19 -13 -15 -0	600	810	120	236
3	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -0	570	730	(30)	282
4	0 - 20 -2 -17 -7 -5 -14 -1 -16 -19 -0	670	860	100	283
5	0 - 13 -15 -0	820	900	150	64
6	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -0	660	820	(160)	288
7	0 - 20 -2 -17 -7 -5 -14 -1 -16 -19 -0	760	950	100	275
8	0 - 13 -15 -0	910	990	150	64
9	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -0	750	910	(160)	284
10	0 - 20 -2 -17 -7 -5 -14 -1 -16 -19 -0	850	1040	100	274
11	0 - 13 -15 -0	1000	1080	150	62
12	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -0	840	1000	(160)	281
13	0 - 20 -2 -17 -7 -5 -14 -1 -16 -19 -0	940	1130	100	279
14	0 - 13 -15 -0	1090	1170	150	62
15	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -0	930	1090	(160)	280
16	0 - 20 -2 -17 -7 -5 -14 -1 -16 -19 -0	1030	1220	100	285
17	0 - 13 -15 -0	1180	1260	150	63
18	0 - 10 -9 -6 -4 -8 - 12 -18 -11 -3 -0	1020	1180	(160)	278
19	0 - 20 -2 -17 -7 -5 -14 -1 -16 -19 -0	1120	1310	100	272

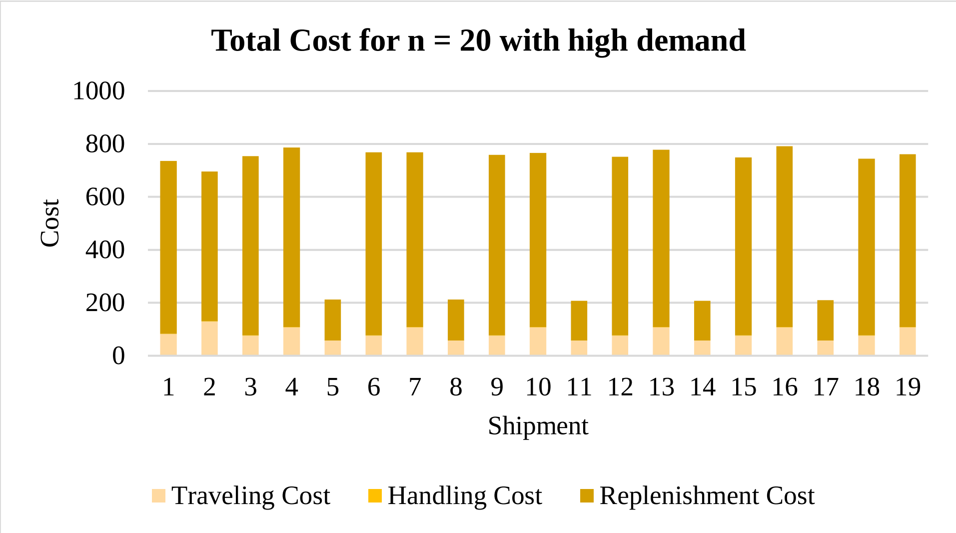

Figure 5.12 Total Cost when n = 20 with High Demand

Table 5.29 Total Cost when n = 20 with High Demand

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
1	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 - 20 -2 -0	82	1,1	652,8	735,9
2	0 - 17 -7 -5 -14 - 1 -16 -19 -13 -15 -0	129	0,9	566,4	696,3
3	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -0	76	0,9	676,8	753,7
4	0 - 20 -2 -17 -7 - 5 -14 -1 -16 -19 - 0	107	0,9	679,2	787,1
5	0 - 13 -15 -0	58	0,2	153,6	211,8
6	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -0	76	0,9	691,2	768,1
7	0 - 20 -2 -17 -7 - 5 -14 -1 -16 -19 - 0	107	0,9	660	767,9
8	0 - 13 -15 -0	58	0,2	153,6	211,8
9	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -0	76	0,9	681,6	758,5
10	0 - 20 -2 -17 -7 - 5 -14 -1 -16 -19 - 0	107	0,9	657,6	765,5
11	0 - 13 -15 -0	58	0,2	148,8	207
12	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -0	76	0,9	674,4	751,3

No	Route	Total Traveling Cost	Total Handling Cost	Total Replenishment Cost	Total Cost
13	0 - 20 -2 -17 -7 - 5 -14 -1 -16 -19 - 0	107	0,9	669,6	777,5
14	0 - 13 -15 -0	58	0,2	148,8	207
15	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -0	76	0,9	672	748,9
16	0 - 20 -2 -17 -7 - 5 -14 -1 -16 -19 - 0	107	0,9	684	791,9
17	0 - 13 -15 -0	58	0,2	151,2	209,4
18	0 - 10 -9 -6 -4 -8 -12 -18 -11 -3 -0	76	0,9	667,2	744,1
19	0 - 20 -2 -17 -7 - 5 -14 -1 -16 -19 - 0	107	0,9	652,8	760,7

In this condition, there are some shipments having significantly different amount of total costs to other shipments. Between 12 additional shipments, five of them generate a significantly lower amount of total costs compared to others. Apart from these five additional shipments, the rest shipments perform not significant difference of total cost. The highest total cost of all shipments is generated by the sixteenth shipment while the lowest total cost is generated by the fourteenth shipment.

CHAPTER 6
CONCLUSION AND SUGGESTION

In this chapter is shown the conclusion of this research and the suggestion for further research.

6.1 Conclusion

The conclusions of this research are as follows.

1. In this research, a model called Inventory Routing Problem (IRP) considering stochastic demand and state of charge (SoC) of batteries in Battery Swap Stations (BSSs) is developed. This model has a decision over time only, meaning that it only determines the delivered quantity or replenishment unit and the shipment time to each BSS. The route is pre-determined using the Traveling Salesman Problem (TSP) model. In determining the number of replenishment units at each BSS, it is required to set the minimum acceptable SoC (α) at each BSS. This IRP model is developed using Microsoft Excel VBA that is considered robust and can be used to experiment with various values of the variables.
2. There are two types of numerical experiments conducted in this research. According to the first numerical experiment, it could be concluded that the efficient value of intershipment time decreases as the demand gets higher, meaning that more frequent shipment is requires for a condition with high demand. While the efficient value of α increases as the demand gets higher, meaning that more batteries need to be replaced to minimize stock-out. While according to the second numerical experiment, with the same vehicle capacity of all data sets, a data set with a higher amount of BSS to be visited and with a higher level of demand have a higher probability of generating additional shipment. The additional shipment is generated for a condition where the demand is high, according to three data sets of four; n = 10, n = 15, and n = 20. On the one hand, in a data set of 20 BSSs, the condition

with medium demand also requires additional shipment. Due to these condition, having vehicle with bigger capacity or multi capacity vehicle for the shipment might be considered.

6.2 Suggestion

The suggestions for further research are as follow.

1. To develop an IRP model with other heuristic algorithm that generates better performance and less greedy.
2. To develop an IRP model with decision over time and space.
3. To elaborate the mathematical model of IRP so that it could capture the real condition more accurately.

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APPENDIX

APPENDIX A

A data set for model verification process and its results

Variables used for the verification process

No	Variable	Unit	Value
1	Number of BSS		5
2	Truck capacity	item	300
3	Truck velocity	km/hour	50
4	Earliest truck departure time	minutes	480
5	Latest truck departure time	minutes	1200
6	BSS capacity	item	40
7	Charging rate in BSS	%/minute	2,5
8	Minimum acceptable SoC	%	75
9	Handling time	minutes	10
10	Lower bound of demand		4
11	Upper bound of demand		12
12	Lower bound of latitude		-6,7
13	Upper bound of latitude		-6,6
14	Lower bound of longitude		70
15	Upper bound of longitude		71
16	Intershipment time	minutes	10
17	Travelling cost	Rp/km	3.100
18	Handling cost	Rp/minute	495
19	Replenishment cost	Rp/unit	4.950

Coordinates of CBS and BSSs

No	**Node**	**Latitude**	**Longitude**
0	CBS	-6,7	70,34
1	BSS 1	-6,61	70,43
2	BSS 2	-6,63	70,48
3	BSS 3	-6,65	70,46
4	BSS 4	-6,66	70,4
5	BSS 5	-6,67	70,28

Distance Matrix

	CBS	BSS 1	BSS 2	BSS 3	BSS 4	BSS 5
CBS	350104,5	14,10452	17,30989	14,3712	7,98035	7,418282
BSS 1	14,10452	350104,5	5,953342	5,546123	6,471945	17,8594
BSS 2	17,30989	5,953342	350104,5	3,134386	9,444113	22,53162
BSS 3	14,3712	5,546123	3,134386	350104,5	6,719062	20,00306
BSS 4	7,98035	6,471945	9,444113	6,719062	350104,5	13,29914
BSS 5	7,418282	17,8594	22,53162	20,00306	13,29914	350104,5

Demand Matrix

Time	BSS 1	BSS 2	BSS 3	BSS 4	BSS 5
490	4	7	5	7	5
500	8	11	8	10	6
510	12	12	8	13	7
520	4	9	7	8	8
530	10	11	9	8	7
540	11	6	7	10	10
550	4	1	7	4	9
560	12	8	11	10	6
570	7	6	6	8	7
580	10	4	10	10	6
590	11	7	3	10	9
600	9	12	9	6	8
610	10	10	10	6	10
620	5	13	14	7	10
630	4	8	13	12	6
640	10	8	12	10	9
650	10	8	11	10	11
660	6	8	9	8	4
670	6	11	6	12	7
680	11	8	10	10	7
690	6	11	1	5	14
700	9	7	8	9	8
710	10	6	7	11	7
720	6	5	6	8	5
730	8	7	0	6	9
740	8	8	7	8	8
750	9	6	7	6	5
760	10	5	6	10	10
770	10	9	7	10	9

Time	BSS 1	BSS 2	BSS 3	BSS 4	BSS 5
780	8	7	3	6	10
790	6	6	6	10	9
800	10	7	8	7	7
810	11	7	7	7	7
820	9	7	9	11	5
830	8	7	9	9	7
840	7	12	10	5	11
850	9	8	4	8	8
860	8	11	7	8	8
870	5	3	9	5	11
880	8	10	3	6	6
890	6	9	9	5	4
900	4	8	10	10	9
910	11	8	7	6	9
920	10	10	7	6	12
930	14	10	7	9	9
940	6	10	9	8	6
950	5	5	10	1	12
960	11	8	12	6	11
970	9	10	7	10	10
980	5	6	10	12	13
990	8	9	8	6	5
1000	10	8	12	5	5
1010	10	8	6	8	14
1020	7	4	8	7	10
1030	5	2	8	9	8
1040	8	11	7	7	10
1050	8	5	5	7	7
1060	5	13	4	9	8
1070	10	14	10	11	6
1080	6	7	11	10	9
1090	10	12	8	7	6
1100	8	7	10	10	8
1110	7	7	6	7	8
1120	7	8	6	10	10
1130	9	7	6	10	7
1140	9	11	7	7	9
1150	9	7	3	10	6
1160	6	7	11	11	8
1170	6	9	6	6	7

Time	BSS 1	BSS 2	BSS 3	BSS 4	BSS 5
1180	8	13	5	4	4
1190	8	7	7	8	10
1200	9	10	3	8	8
1210	9	15	6	7	6
1220	6	16	8	7	7
1230	3	9	11	12	6
1240	10	7	10	8	9
1250	9	8	5	7	8
1260	8	9	8	8	8
1270	4	9	10	8	8
1280	9	10	6	11	4
1290	13	10	8	8	9
1300	9	7	10	7	9
1310	10	3	11	6	6
1320	13	7	8	5	9
1330	6	8	8	9	3
1340	12	8	5	9	5
1350	9	12	8	7	9
1360	8	8	7	6	8
1370	10	6	10	14	7
1380	7	12	7	3	8
1390	11	10	9	11	6
1400	9	6	15	8	13
1410	6	10	6	8	14
1420	9	5	6	6	6
1430	11	7	7	5	7
1440	10	11	11	4	12

Results

No	Route	Departure Time (min)	Returning Time (min)	Total Traveling Cost (Rp)	Total Replenishment Cost (Rp)	Total Handling Cost (Rp)	Total Cost (Rp)
1	0 - 5 -4 -1 -3 -2 -0	480	600	164.857,2628	470.250	24.750	659.857,2628
2	0 - 5 -4 -1 -3 -2 -0	610	730	164.857,2628	549.450	24.750	739.057,2628
3	0 - 5 -4 -1 -3 -2 -0	740	860	164.857,2628	579.150	24.750	768.757,2628
4	0 - 5 -4 -1 -3 -2 -0	870	990	164.857,2628	589.050	24.750	778.657,2628
5	0 - 5 -4 -1 -3 -2 -0	1000	1120	164.857,2628	559.350	24.750	748.957,2628
6	0 - 5 -4 -1 -3 -2 -0	1130	1250	164.857,2628	534.600	24.750	724.207,2628

Report of each shipment

1	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	0	1	4	6	8	9	12		
	Time (min)	480	490	520	540	560	570	600		
	Required Replenishment(unit)		5	31	20	24	15			
	Actual Replenishment (unit)		5	31	20	24	15		95	470250
	Vehicle Capacity (unit)	300	295	264	244	220	205	205		
	Handling Time (min)		10	10	10	10	10		50	24750
	Travelling Distance (km)		7,418282	13,29914	6,471945	5,546123	3,134386	17,30989	53,17976	164857,2628
	Travelling Time (min)		9	16	8	7	4	21		
	Total Cost									659857,2628
2	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	13	14	17	19	21	22	25		

	Time (min)	610	620	650	670	690	700	730		
	Required Replenishment(unit)		25	27	22	17	20			
	Actual Replenishment (unit)		25	27	22	17	20		111	549450
	Vehicle Capacity (unit)	300	275	248	226	209	189	189		
	Handling Time (min)		10	10	10	10	10		50	24750
	Travelling Distance (km)		7,418282	13,29914	6,471945	5,546123	3,134386	17,30989	53,17976	164857,2628
	Travelling Time (min)		9	16	8	7	4	21		
	Total Cost									739057,2628
3	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	26	27	30	32	34	35	38		
	Time (min)	740	750	780	800	820	830	860		
	Required Replenishment(unit)		22	26	24	24	21			
	Actual Replenishment (unit)		22	26	24	24	21		117	579150
	Vehicle Capacity (unit)	300	278	252	228	204	183	183		
	Handling Time (min)		10	10	10	10	10		50	24750
	Travelling Distance (km)		7,418282	13,29914	6,471945	5,546123	3,134386	17,30989	53,17976	164857,2628
	Travelling Time (min)		9	16	8	7	4	21		
	Total Cost									768757,2628
4	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	39	40	43	45	47	48	51		
	Time (min)	870	880	910	930	950	960	990		
	Required Replenishment(unit)		20	21	30	26	22			
	Actual Replenishment (unit)		20	21	30	26	22		119	589050
	Vehicle Capacity (unit)	300	280	259	229	203	181	181		
	Handling Time (min)		10	10	10	10	10		50	24750

	Travelling Distance (km)		7,418282	13,29914	6,471945	5,546123	3,134386	17,30989	53,17976	164857,2628
	Travelling Time (min)		9	16	8	7	4	21		
	Total Cost									778657,2628
5	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	52	53	56	58	60	61	64		
	Time (min)	1000	1010	1040	1060	1080	1090	1120		
	Required Replenishment(unit)		22	23	21	25	22			
	Actual Replenishment (unit)		22	23	21	25	22		113	559350
	Vehicle Capacity (unit)	300	278	255	234	209	187	187		
	Handling Time (min)		10	10	10	10	10		50	24750
	Travelling Distance (km)		7,418282	13,29914	6,471945	5,546123	3,134386	17,30989	53,17976	164857,2628
	Travelling Time (min)		9	16	8	7	4	21		
	Total Cost									748957,2628
6	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	65	66	69	71	73	74	77		
	Time (min)	1130	1140	1170	1190	1210	1220	1250		
	Required Replenishment(unit)		24	20	22	16	26			
	Actual Replenishment (unit)		24	20	22	16	26		108	534600
	Vehicle Capacity (unit)	300	276	256	234	218	192	192		
	Handling Time (min)		10	10	10	10	10		50	24750
	Travelling Distance (km)		7,418282	13,29914	6,471945	5,546123	3,134386	17,30989	53,17976	164857,2628
	Travelling Time (min)		9	16	8	7	4	21		
	Total Cost									724207,2628

Inventory level at BSS 1 (Example)

Time Slot	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6	Slot 7	Slot 8	Slot 9	Slot 10	Slot 11	Slot 12	Slot 13	Slot 14	Slot 15
Time (minutes)	490	500	510	520	530	540	550	560	570	580	590	600	610	620	630
Demand (unit)	4	8	12	4	10	11	4	12	7	10	11	9	10	5	4
Replenishment (unit)						20									
Picked up (unit)						20									
Rejected Demand (unit)						0					-4	-5	0	0	
Fully Charged Battery (unit)	36	28	16	12	2	20	24	24	17	7	0	0	2	4	10
Empty Battery (unit)	4	8	12	4	10	0	4	12	7	10	7	4	10	5	4
Charging Battery (unit)	0	4	12	24	28	20	12	4	16	23	33	36	28	31	26
Battery Status (%)															
1	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50	75
2	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50	75
3	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50	75
4	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50	75
5	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50
6	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50
7	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50
8	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50
9	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50
10	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50
11	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50
12	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50
13	Ready	Ready	0	25	50	75	100	0	25	50	75	100	0	25	50

Time Slot	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6	Slot 7	Slot 8	Slot 9	Slot 10	Slot 11	Slot 12	Slot 13	Slot 14	Slot 15
Time (minutes)	490	500	510	520	530	540	550	560	570	580	590	600	610	620	630
Demand (unit)	4	8	12	4	10	11	4	12	7	10	11	9	10	5	4
Replenishment (unit)						20									
Picked up (unit)						20									
Rejected Demand (unit)						0					-4	-5	0	0	
Fully Charged Battery (unit)	36	28	16	12	2	20	24	24	17	7	0	0	2	4	10
Empty Battery (unit)	4	8	12	4	10	0	4	12	7	10	7	4	10	5	4
Charging Battery (unit)	0	4	12	24	28	20	12	4	16	23	33	36	28	31	26
Battery Status (%)															
14	Ready	Ready	0	25	50	75	100	0	25	50	75	100	0	25	50
15	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	0	25
16	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	0	25
17	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	25
18	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	25
19	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	25
20	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready	0
21	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready	0
22	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready	0
23	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready	0
24	Ready	Ready	0	25	50	75	100	Ready	Ready	0	25	50	75	100	Ready
25	Ready	Ready	Ready	0	25	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready
26	Ready	Ready	Ready	0	25	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready
27	Ready	Ready	Ready	0	25	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready

Time Slot	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6	Slot 7	Slot 8	Slot 9	Slot 10	Slot 11	Slot 12	Slot 13	Slot 14	Slot 15
Time (minutes)	490	500	510	520	530	540	550	560	570	580	590	600	610	620	630
Demand (unit)	4	8	12	4	10	11	4	12	7	10	11	9	10	5	4
Replenishment (unit)						20									
Picked up (unit)						20									
Rejected Demand (unit)						0					-4	-5	0	0	
Fully Charged Battery (unit)	36	28	16	12	2	20	24	24	17	7	0	0	2	4	10
Empty Battery (unit)	4	8	12	4	10	0	4	12	7	10	7	4	10	5	4
Charging Battery (unit)	0	4	12	24	28	20	12	4	16	23	33	36	28	31	26
Battery Status (%)															
28	Ready	Ready	Ready	0	25	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready
29	Ready	Ready	Ready	Ready	0	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready
30	Ready	Ready	Ready	Ready	0	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready
31	Ready	Ready	Ready	Ready	0	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready
32	Ready	Ready	Ready	Ready	0	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready
33	Ready	Ready	Ready	Ready	0	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready
34	Ready	Ready	Ready	Ready	0	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100
35	Ready	Ready	Ready	Ready	0	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100
36	Ready	Ready	Ready	Ready	0	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100
37	Ready	Ready	Ready	Ready	0	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100
38	Ready	Ready	Ready	Ready	0	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100
39	Ready	Ready	Ready	Ready	Ready	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100
40	Ready	Ready	Ready	Ready	Ready	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100

Time Slot	Slot 16	Slot 17	Slot 18	Slot 19	Slot 20	Slot 21	Slot 22	Slot 23	Slot 24	Slot 25	Slot 26	Slot 27	Slot 28	Slot 29	Slot 30
Time (minutes)	640	650	660	670	680	690	700	710	720	730	740	750	760	770	780
Demand (unit)	10	10	6	6	11	6	9	10	6	8	8	9	10	10	8
Replenishment (unit)				22											
Picked up (unit)				22											
Rejected Demand (unit)		0	0	0					-2	0	0	0	0	-5	0
Fully Charged Battery (unit)	7	1	5	26	19	23	14	4	0	3	1	1	1	0	0
Empty Battery (unit)	10	10	6	0	11	6	9	10	4	8	8	9	10	5	8
Charging Battery (unit)	23	29	29	14	10	11	17	26	36	29	31	30	29	35	32
Battery Status (%)															
1	100	0	25	Ready	0	25	50	75	100	0	25	50	75	100	0
2	100	0	25	Ready	0	25	50	75	100	0	25	50	75	100	0
3	100	0	25	Ready	0	25	50	75	100	0	25	50	75	100	0
4	100	0	25	Ready	0	25	50	75	100	0	25	50	75	100	0
5	75	100	0	Ready	0	25	50	75	100	0	25	50	75	100	0
6	75	100	0	Ready	0	25	50	75	100	0	25	50	75	100	0
7	75	100	0	Ready	0	25	50	75	100	0	25	50	75	100	0
8	75	100	0	Ready	0	25	50	75	100	0	25	50	75	100	0
9	75	100	0	Ready	0	25	50	75	100	Ready	0	25	50	75	100
10	75	100	0	Ready	0	25	50	75	100	Ready	0	25	50	75	100
11	75	100	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100
12	75	100	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100
13	75	100	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100
14	75	100	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100

Time Slot	Slot 16	Slot 17	Slot 18	Slot 19	Slot 20	Slot 21	Slot 22	Slot 23	Slot 24	Slot 25	Slot 26	Slot 27	Slot 28	Slot 29	Slot 30
Time (minutes)	640	650	660	670	680	690	700	710	720	730	740	750	760	770	780
Demand (unit)	10	10	6	6	11	6	9	10	6	8	8	9	10	10	8
Replenishment (unit)				22											
Picked up (unit)				22											
Rejected Demand (unit)		0	0	0					-2	0	0	0	0	-5	0
Fully Charged Battery (unit)	7	1	5	26	19	23	14	4	0	3	1	1	1	0	0
Empty Battery (unit)	10	10	6	0	11	6	9	10	4	8	8	9	10	5	8
Charging Battery (unit)	23	29	29	14	10	11	17	26	36	29	31	30	29	35	32
Battery Status (%)															
15	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50	75	100
16	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50	75	100
17	50	75	100	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75
18	50	75	100	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75
19	50	75	100	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75
20	25	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50	75
21	25	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50	75
22	25	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50	75
23	25	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50	75
24	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50	75
25	0	25	50	75	100	Ready	0	25	50	75	100	0	25	50	75
26	0	25	50	75	100	Ready	0	25	50	75	100	Ready	0	25	50
27	0	25	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50
28	0	25	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50

Time Slot	Slot 16	Slot 17	Slot 18	Slot 19	Slot 20	Slot 21	Slot 22	Slot 23	Slot 24	Slot 25	Slot 26	Slot 27	Slot 28	Slot 29	Slot 30
Time (minutes)	640	650	660	670	680	690	700	710	720	730	740	750	760	770	780
Demand (unit)	10	10	6	6	11	6	9	10	6	8	8	9	10	10	8
Replenishment (unit)				22											
Picked up (unit)				22											
Rejected Demand (unit)		0	0	0					-2	0	0	0	0	-5	0
Fully Charged Battery (unit)	7	1	5	26	19	23	14	4	0	3	1	1	1	0	0
Empty Battery (unit)	10	10	6	0	11	6	9	10	4	8	8	9	10	5	8
Charging Battery (unit)	23	29	29	14	10	11	17	26	36	29	31	30	29	35	32
Battery Status (%)															
29	0	25	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50
30	0	25	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50
31	0	25	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50
32	0	25	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50
33	0	25	50	75	100	Ready	Ready	0	25	50	75	100	0	25	50
34	Ready	0	25	Ready	Ready	Ready	Ready	0	25	50	75	100	0	25	50
35	Ready	0	25	Ready	Ready	Ready	Ready	0	25	50	75	100	0	25	50
36	Ready	0	25	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready	0	25
37	Ready	0	25	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100	0	25
38	Ready	0	25	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100	0	25
39	Ready	0	25	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100	0	25
40	Ready	Ready	Ready	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100	0	25

Time Slot	Slot 31	Slot 32	Slot 33	Slot 34	Slot 35	Slot 36	Slot 37	Slot 38	Slot 39	Slot 40	Slot 41	Slot 42	Slot 43	Slot 44	Slot 45
Time (minutes)	790	800	810	820	830	840	850	860	870	880	890	900	910	920	930
Demand (unit)	6	10	11	9	8	7	9	8	5	8	6	4	11	10	14
Replenishment (unit)		24													30
Picked up (unit)		24													30
Rejected Demand (unit)	0	0					-4	0	0	0			0	0	0
Fully Charged Battery (unit)	2	25	24	20	12	5	0	3	7	7	8	9	6	1	30
Empty Battery (unit)	6	0	11	9	8	7	5	8	5	8	6	4	11	10	0
Charging Battery (unit)	32	15	5	11	20	28	35	29	28	25	26	27	23	29	10
Battery Status (%)															
1	25	Ready	0	25	50	75	100	0	25	50	75	100	0	25	Ready
2	25	Ready	0	25	50	75	100	0	25	50	75	100	0	25	Ready
3	25	Ready	0	25	50	75	100	0	25	50	75	100	0	25	Ready
4	25	Ready	0	25	50	75	100	0	25	50	75	100	0	25	Ready
5	25	Ready	0	25	50	75	100	0	25	50	75	100	0	25	Ready
6	25	Ready	0	25	50	75	100	0	25	50	75	100	0	25	Ready
7	25	Ready	0	25	50	75	100	0	25	50	75	100	0	25	Ready
8	25	Ready	0	25	50	75	100	0	25	50	75	100	0	25	Ready
9	0	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	Ready
10	0	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	Ready
11	0	Ready	0	25	50	75	100	Ready	0	25	50	75	100	0	Ready
12	0	Ready	Ready	0	25	50	75	100	0	25	50	75	100	0	Ready
13	0	Ready	Ready	0	25	50	75	100	0	25	50	75	100	0	Ready
14	0	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready

Time Slot	Slot 31	Slot 32	Slot 33	Slot 34	Slot 35	Slot 36	Slot 37	Slot 38	Slot 39	Slot 40	Slot 41	Slot 42	Slot 43	Slot 44	Slot 45
Time (minutes)	790	800	810	820	830	840	850	860	870	880	890	900	910	920	930
Demand (unit)	6	10	11	9	8	7	9	8	5	8	6	4	11	10	14
Replenishment (unit)		24													30
Picked up (unit)		24													30
Rejected Demand (unit)	0	0					-4	0	0	0			0	0	0
Fully Charged Battery (unit)	2	25	24	20	12	5	0	3	7	7	8	9	6	1	30
Empty Battery (unit)	6	0	11	9	8	7	5	8	5	8	6	4	11	10	0
Charging Battery (unit)	32	15	5	11	20	28	35	29	28	25	26	27	23	29	10
Battery Status (%)															
15	Ready	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready
16	Ready	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready
17	100	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready
18	100	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready
19	100	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready
20	100	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready
21	100	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready
22	100	Ready	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100
23	100	Ready	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100
24	100	Ready	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100
25	100	Ready	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100
26	75	100	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100
27	75	100	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100
28	75	100	Ready	Ready	0	25	50	75	100	Ready	Ready	0	25	50	75

Time Slot	Slot 31	Slot 32	Slot 33	Slot 34	Slot 35	Slot 36	Slot 37	Slot 38	Slot 39	Slot 40	Slot 41	Slot 42	Slot 43	Slot 44	Slot 45
Time (minutes)	790	800	810	820	830	840	850	860	870	880	890	900	910	920	930
Demand (unit)	6	10	11	9	8	7	9	8	5	8	6	4	11	10	14
Replenishment (unit)		24													30
Picked up (unit)		24													30
Rejected Demand (unit)	0	0					-4	0	0	0			0	0	0
Fully Charged Battery (unit)	2	25	24	20	12	5	0	3	7	7	8	9	6	1	30
Empty Battery (unit)	6	0	11	9	8	7	5	8	5	8	6	4	11	10	0
Charging Battery (unit)	32	15	5	11	20	28	35	29	28	25	26	27	23	29	10
Battery Status (%)															
29	75	100	Ready	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75
30	75	100	Ready	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75
31	75	100	Ready	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75
32	75	100	Ready	Ready	Ready	0	25	50	75	100	Ready	Ready	0	25	Ready
33	75	100	Ready	Ready	Ready	0	25	50	75	100	Ready	Ready	0	25	Ready
34	75	100	Ready	Ready	Ready	0	25	50	75	100	Ready	Ready	0	25	Ready
35	75	100	Ready	Ready	Ready	0	25	50	75	100	Ready	Ready	Ready	0	Ready
36	50	75	100	Ready	Ready	Ready	0	25	50	75	100	Ready	Ready	0	Ready
37	50	75	100	Ready	Ready	Ready	0	25	50	75	100	Ready	Ready	0	Ready
38	50	75	100	Ready	Ready	Ready	0	25	50	75	100	Ready	Ready	0	Ready
39	50	75	100	Ready	Ready	Ready	0	25	50	75	100	Ready	Ready	0	Ready
40	50	75	100	Ready	Ready	Ready	0	25	50	75	100	Ready	Ready	Ready	Ready

Time Slot	Slot 46	Slot 47	Slot 48	Slot 49	Slot 50	Slot 51	Slot 52	Slot 53	Slot 54	Slot 55	Slot 56	Slot 57	Slot 58	Slot 59	Slot 60
Time (minutes)	940	950	960	970	980	990	1000	1010	1020	1030	1040	1050	1060	1070	1080
Demand (unit)	6	5	11	9	5	8	10	10	7	5	8	8	5	10	6
Replenishment (unit)													21		
Picked up (unit)													21		
Rejected Demand (unit)						0	-3	0	0	0	0	0	0		
Fully Charged Battery (unit)	30	29	18	9	4	2	0	1	3	3	3	2	28	25	24
Empty Battery (unit)	6	5	11	9	5	8	7	10	7	5	8	8	0	10	6
Charging Battery (unit)	4	6	11	22	31	30	33	29	30	32	29	30	12	5	10
Battery Status (%)															
1	0	25	50	75	100	0	25	50	75	100	0	25	Ready	0	25
2	0	25	50	75	100	0	25	50	75	100	0	25	Ready	0	25
3	0	25	50	75	100	0	25	50	75	100	0	25	Ready	0	25
4	0	25	50	75	100	0	25	50	75	100	0	25	Ready	0	25
5	0	25	50	75	100	0	25	50	75	100	0	25	Ready	0	25
6	0	25	50	75	100	0	25	50	75	100	0	25	Ready	0	25
7	Ready	0	25	50	75	100	0	25	50	75	100	0	Ready	0	25
8	Ready	0	25	50	75	100	0	25	50	75	100	0	Ready	0	25
9	Ready	0	25	50	75	100	0	25	50	75	100	0	Ready	0	25
10	Ready	0	25	50	75	100	0	25	50	75	100	0	Ready	0	25
11	Ready	0	25	50	75	100	0	25	50	75	100	0	Ready	Ready	0
12	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	0
13	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	0
14	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	0

Time Slot	Slot 46	Slot 47	Slot 48	Slot 49	Slot 50	Slot 51	Slot 52	Slot 53	Slot 54	Slot 55	Slot 56	Slot 57	Slot 58	Slot 59	Slot 60
Time (minutes)	940	950	960	970	980	990	1000	1010	1020	1030	1040	1050	1060	1070	1080
Demand (unit)	6	5	11	9	5	8	10	10	7	5	8	8	5	10	6
Replenishment (unit)													21		
Picked up (unit)													21		
Rejected Demand (unit)						0	-3	0	0	0	0	0	0		
Fully Charged Battery (unit)	30	29	18	9	4	2	0	1	3	3	3	2	28	25	24
Empty Battery (unit)	6	5	11	9	5	8	7	10	7	5	8	8	0	10	6
Charging Battery (unit)	4	6	11	22	31	30	33	29	30	32	29	30	12	5	10
Battery Status (%)															
15	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	0
16	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	0
17	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready
18	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready
19	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready
20	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready
21	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready
22	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready	Ready
23	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready
24	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready
25	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready
26	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready
27	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready
28	100	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready

Time Slot	Slot 46	Slot 47	Slot 48	Slot 49	Slot 50	Slot 51	Slot 52	Slot 53	Slot 54	Slot 55	Slot 56	Slot 57	Slot 58	Slot 59	Slot 60
Time (minutes)	940	950	960	970	980	990	1000	1010	1020	1030	1040	1050	1060	1070	1080
Demand (unit)	6	5	11	9	5	8	10	10	7	5	8	8	5	10	6
Replenishment (unit)													21		
Picked up (unit)													21		
Rejected Demand (unit)						0	-3	0	0	0	0	0	0		
Fully Charged Battery (unit)	30	29	18	9	4	2	0	1	3	3	3	2	28	25	24
Empty Battery (unit)	6	5	11	9	5	8	7	10	7	5	8	8	0	10	6
Charging Battery (unit)	4	6	11	22	31	30	33	29	30	32	29	30	12	5	10
Battery Status (%)															
29	100	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready
30	100	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready
31	100	Ready	Ready	0	25	50	75	100	Ready	0	25	50	75	100	Ready
32	Ready	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready
33	Ready	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready
34	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready	0	25	Ready	Ready	Ready
35	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready	0	25	Ready	Ready	Ready
36	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready	Ready	0	Ready	Ready	Ready
37	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready	0	Ready	Ready	Ready
38	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready	0	Ready	Ready	Ready
39	Ready	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready	Ready	Ready	Ready
40	Ready	Ready	Ready	Ready	Ready	Ready	0	25	50	75	100	Ready	Ready	Ready	Ready

Time Slot	Slot 61	Slot 62	Slot 63	Slot 64	Slot 65	Slot 66	Slot 67	Slot 68	Slot 69	Slot 70	Slot 71	Slot 72	Slot 73	Slot 74	Slot 75
Time (minutes)	1090	1100	1110	1120	1130	1140	1150	1160	1170	1180	1190	1200	1210	1220	1230
Demand (unit)	10	8	7	7	9	9	9	6	6	8	8	9	9	6	3
Replenishment (unit)											22				
Picked up (unit)											22				
Rejected Demand (unit)			-1	0	0	0	0	0	0	0	0				
Fully Charged Battery (unit)	14	6	0	3	0	1	0	0	1	2	25	25	22	16	13
Empty Battery (unit)	10	8	6	7	9	9	9	6	6	8	0	9	9	6	3
Charging Battery (unit)	16	26	34	30	31	30	31	34	33	30	15	6	9	18	24
Battery Status (%)															
1	50	75	100	0	25	50	75	100	0	25	Ready	0	25	50	75
2	50	75	100	0	25	50	75	100	0	25	Ready	0	25	50	75
3	50	75	100	0	25	50	75	100	0	25	Ready	0	25	50	75
4	50	75	100	0	25	50	75	100	0	25	Ready	0	25	50	75
5	50	75	100	0	25	50	75	100	0	25	Ready	0	25	50	75
6	50	75	100	0	25	50	75	100	0	25	Ready	0	25	50	75
7	50	75	100	0	25	50	75	100	Ready	0	Ready	0	25	50	75
8	50	75	100	Ready	0	25	50	75	100	0	Ready	0	25	50	75
9	50	75	100	Ready	0	25	50	75	100	0	Ready	0	25	50	75
10	50	75	100	Ready	0	25	50	75	100	0	Ready	Ready	0	25	50
11	25	50	75	100	0	25	50	75	100	0	Ready	Ready	0	25	50
12	25	50	75	100	0	25	50	75	100	0	Ready	Ready	0	25	50
13	25	50	75	100	0	25	50	75	100	0	Ready	Ready	0	25	50
14	25	50	75	100	0	25	50	75	100	0	Ready	Ready	0	25	50

Time Slot	Slot 61	Slot 62	Slot 63	Slot 64	Slot 65	Slot 66	Slot 67	Slot 68	Slot 69	Slot 70	Slot 71	Slot 72	Slot 73	Slot 74	Slot 75
Time (minutes)	1090	1100	1110	1120	1130	1140	1150	1160	1170	1180	1190	1200	1210	1220	1230
Demand (unit)	10	8	7	7	9	9	9	6	6	8	8	9	9	6	3
Replenishment (unit)											22				
Picked up (unit)											22				
Rejected Demand (unit)			-1	0	0	0	0	0	0	0	0				
Fully Charged Battery (unit)	14	6	0	3	0	1	0	0	1	2	25	25	22	16	13
Empty Battery (unit)	10	8	6	7	9	9	9	6	6	8	0	9	9	6	3
Charging Battery (unit)	16	26	34	30	31	30	31	34	33	30	15	6	9	18	24
Battery Status (%)															
15	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	0	25	50
16	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	0	25	50
17	0	25	50	75	100	0	25	50	75	100	Ready	Ready	0	25	50
18	0	25	50	75	100	0	25	50	75	100	Ready	Ready	0	25	50
19	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	0	25
20	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	0	25
21	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	0	25
22	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	0	25
23	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	0	25
24	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	0	25
25	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	Ready	0
26	0	25	50	75	100	Ready	0	25	50	75	100	Ready	Ready	Ready	0
27	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	0
28	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	Ready

Time Slot	Slot 61	Slot 62	Slot 63	Slot 64	Slot 65	Slot 66	Slot 67	Slot 68	Slot 69	Slot 70	Slot 71	Slot 72	Slot 73	Slot 74	Slot 75
Time (minutes)	1090	1100	1110	1120	1130	1140	1150	1160	1170	1180	1190	1200	1210	1220	1230
Demand (unit)	10	8	7	7	9	9	9	6	6	8	8	9	9	6	3
Replenishment (unit)											22				
Picked up (unit)											22				
Rejected Demand (unit)			-1	0	0	0	0	0	0	0	0				
Fully Charged Battery (unit)	14	6	0	3	0	1	0	0	1	2	25	25	22	16	13
Empty Battery (unit)	10	8	6	7	9	9	9	6	6	8	0	9	9	6	3
Charging Battery (unit)	16	26	34	30	31	30	31	34	33	30	15	6	9	18	24
Battery Status (%)															
29	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	Ready
30	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	Ready
31	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	Ready
32	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	Ready
33	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	Ready
34	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	Ready
35	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready
36	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready
37	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready
38	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready
39	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready
40	Ready	Ready	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready

Time Slot	Slot 76	Slot 77	Slot 78	Slot 79	Slot 80	Slot 81	Slot 82	Slot 83	Slot 84	Slot 85	Slot 86	Slot 87	Slot 88	Slot 89	Slot 90
Time (minutes)	1240	1250	1260	1270	1280	1290	1300	1310	1320	1330	1340	1350	1360	1370	1380
Demand (unit)	10	9	8	4	9	13	9	10	13	6	12	9	8	10	7
Replenishment (unit)															
Picked up (unit)															
Rejected Demand (unit)		0	0		0	-3	0	-2	-9	0	0	0	0	-5	-1
Fully Charged Battery (unit)	3	3	4	6	0	0	0	0	0	3	1	1	1	0	0
Empty Battery (unit)	10	9	8	4	9	10	9	8	4	6	12	9	8	5	6
Charging Battery (unit)	27	28	28	30	31	30	31	32	36	31	27	30	31	35	34
Battery Status (%)															
1	100	0	25	50	75	100	0	25	50	75	100	0	25	50	75
2	100	0	25	50	75	100	0	25	50	75	100	0	25	50	75
3	100	0	25	50	75	100	0	25	50	75	100	0	25	50	75
4	100	0	25	50	75	100	0	25	50	75	100	0	25	50	75
5	100	0	25	50	75	100	0	25	50	75	100	0	25	50	75
6	100	0	25	50	75	100	0	25	50	75	100	0	25	50	75
7	100	0	25	50	75	100	0	25	50	75	100	0	25	50	75
8	100	0	25	50	75	100	0	25	50	75	100	0	25	50	75
9	100	0	25	50	75	100	0	25	50	75	100	0	25	50	75
10	75	100	0	25	50	75	100	0	25	50	75	100	0	25	50
11	75	100	0	25	50	75	100	0	25	50	75	100	0	25	50
12	75	100	0	25	50	75	100	0	25	50	75	100	0	25	50
13	75	100	0	25	50	75	100	0	25	50	75	100	0	25	50
14	75	100	0	25	50	75	100	0	25	50	75	100	0	25	50

Time Slot	Slot 76	Slot 77	Slot 78	Slot 79	Slot 80	Slot 81	Slot 82	Slot 83	Slot 84	Slot 85	Slot 86	Slot 87	Slot 88	Slot 89	Slot 90
Time (minutes)	1240	1250	1260	1270	1280	1290	1300	1310	1320	1330	1340	1350	1360	1370	1380
Demand (unit)	10	9	8	4	9	13	9	10	13	6	12	9	8	10	7
Replenishment (unit)															
Picked up (unit)															
Rejected Demand (unit)		0	0		0	-3	0	-2	-9	0	0	0	0	-5	-1
Fully Charged Battery (unit)	3	3	4	6	0	0	0	0	0	3	1	1	1	0	0
Empty Battery (unit)	10	9	8	4	9	10	9	8	4	6	12	9	8	5	6
Charging Battery (unit)	27	28	28	30	31	30	31	32	36	31	27	30	31	35	34
Battery Status (%)															
15	75	100	0	25	50	75	100	0	25	50	75	100	0	25	50
16	75	100	0	25	50	75	100	0	25	50	75	100	0	25	50
17	75	100	0	25	50	75	100	0	25	50	75	100	0	25	50
18	75	100	Ready	0	25	50	75	100	0	25	50	75	100	0	25
19	50	75	100	Ready	0	25	50	75	100	0	25	50	75	100	0
20	50	75	100	Ready	0	25	50	75	100	0	25	50	75	100	0
21	50	75	100	Ready	0	25	50	75	100	0	25	50	75	100	0
22	50	75	100	Ready	0	25	50	75	100	0	25	50	75	100	0
23	50	75	100	Ready	0	25	50	75	100	0	25	50	75	100	0
24	50	75	100	Ready	0	25	50	75	100	0	25	50	75	100	0
25	25	50	75	100	0	25	50	75	100	Ready	0	25	50	75	100
26	25	50	75	100	0	25	50	75	100	Ready	0	25	50	75	100
27	25	50	75	100	0	25	50	75	100	Ready	0	25	50	75	100
28	0	25	50	75	100	0	25	50	75	100	0	25	50	75	100

Time Slot	Slot 76	Slot 77	Slot 78	Slot 79	Slot 80	Slot 81	Slot 82	Slot 83	Slot 84	Slot 85	Slot 86	Slot 87	Slot 88	Slot 89	Slot 90
Time (minutes)	1240	1250	1260	1270	1280	1290	1300	1310	1320	1330	1340	1350	1360	1370	1380
Demand (unit)	10	9	8	4	9	13	9	10	13	6	12	9	8	10	7
Replenishment (unit)															
Picked up (unit)															
Rejected Demand (unit)		0	0		0	-3	0	-2	-9	0	0	0	0	-5	-1
Fully Charged Battery (unit)	3	3	4	6	0	0	0	0	0	3	1	1	1	0	0
Empty Battery (unit)	10	9	8	4	9	10	9	8	4	6	12	9	8	5	6
Charging Battery (unit)	27	28	28	30	31	30	31	32	36	31	27	30	31	35	34
Battery Status (%)															
29	0	25	50	75	100	0	25	50	75	100	0	25	50	75	100
30	0	25	50	75	100	0	25	50	75	100	0	25	50	75	100
31	0	25	50	75	100	0	25	50	75	100	0	25	50	75	100
32	0	25	50	75	100	0	25	50	75	100	0	25	50	75	100
33	0	25	50	75	100	0	25	50	75	100	0	25	50	75	100
34	0	25	50	75	100	0	25	50	75	100	0	25	50	75	100
35	0	25	50	75	100	0	25	50	75	100	0	25	50	75	100
36	0	25	50	75	100	0	25	50	75	100	0	25	50	75	100
37	0	25	50	75	100	0	25	50	75	100	Ready	Ready	Ready	0	25
38	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100	0	25
39	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100	0	25
40	Ready	Ready	Ready	0	25	50	75	100	0	25	50	75	100	0	25

Time Slot	Slot 91	Slot 92	Slot 93	Slot 94	Slot 95	Slot 96
Time (minutes)	1390	1400	1410	1420	1430	1440
Demand (unit)	11	9	6	9	11	10
Replenishment (unit)						
Picked up (unit)						
Rejected Demand (unit)	0	0	0	-1	-5	0
Fully Charged Battery (unit)	1	1	3	0	0	1
Empty Battery (unit)	11	9	6	8	6	10
Charging Battery (unit)	28	30	31	32	34	29
Battery Status (%)						
1	100	0	25	50	75	100
2	100	0	25	50	75	100
3	100	0	25	50	75	100
4	100	0	25	50	75	100
5	100	0	25	50	75	100
6	100	0	25	50	75	100
7	100	0	25	50	75	100
8	100	0	25	50	75	100
9	100	0	25	50	75	100
10	75	100	0	25	50	75
11	75	100	0	25	50	75
12	75	100	0	25	50	75
13	75	100	0	25	50	75
14	75	100	0	25	50	75
15	75	100	0	25	50	75
16	75	100	Ready	0	25	50
17	75	100	Ready	0	25	50
18	50	75	100	0	25	50
19	25	50	75	100	0	25
20	25	50	75	100	0	25
21	25	50	75	100	0	25
22	25	50	75	100	0	25
23	25	50	75	100	0	25
24	25	50	75	100	0	25
25	0	25	50	75	100	0
26	0	25	50	75	100	0
27	0	25	50	75	100	0
28	0	25	50	75	100	0
29	0	25	50	75	100	0
30	0	25	50	75	100	0
31	0	25	50	75	100	0

Time Slot	Slot 91	Slot 92	Slot 93	Slot 94	Slot 95	Slot 96
Time (minutes)	1390	1400	1410	1420	1430	1440
Demand (unit)	11	9	6	9	11	10
Replenishment (unit)						
Picked up (unit)						
Rejected Demand (unit)	0	0	0	-1	-5	0
Fully Charged Battery (unit)	1	1	3	0	0	1
Empty Battery (unit)	11	9	6	8	6	10
Charging Battery (unit)	28	30	31	32	34	29
Battery Status (%)						
32	0	25	50	75	100	0
33	0	25	50	75	100	0
34	0	25	50	75	100	0
35	0	25	50	75	100	Ready
36	Ready	Ready	Ready	0	25	50
37	50	75	100	0	25	50
38	50	75	100	0	25	50
39	50	75	100	0	25	50
40	50	75	100	0	25	50

APPENDIX B - The results of Second Numerical Experiment (Report of each shipment)

Example for n = 5

N = 5 with low demand

1	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	0	1	4	6	8	9	12		
	Time (min)	480	490	520	540	560	570	600		
	Required Replenishment(unit)		1	7	10	4	8			
	Actual Replenishment (unit)		1	7	10	4	8		30	72
	Vehicle Capacity (unit)	300	299	292	282	278	270	270		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									137,5
2	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	9	10	13	15	17	18	21		
	Time (min)	570	580	610	630	650	660	690		
	Required Replenishment(unit)		6	9	7	7	6			
	Actual Replenishment (unit)		6	9	7	7	6		35	84
	Vehicle Capacity (unit)	300	294	285	278	271	265	265		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									149,5
3	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	18	19	22	24	26	27	30		

	Time (min)	660	670	700	720	740	750	780		
	Required Replenishment(unit)		9	6	6	8	8			
	Actual Replenishment (unit)		9	6	6	8	8		37	88,8
	Vehicle Capacity (unit)	300	291	285	279	271	263	263		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									154,3
4	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	27	28	31	33	35	36	39		
	Time (min)	750	760	790	810	830	840	870		
	Required Replenishment(unit)		6	6	7	8	9			
	Actual Replenishment (unit)		6	6	7	8	9		36	86,4
	Vehicle Capacity (unit)	300	294	288	281	273	264	264		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									151,9
5	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	36	37	40	42	44	45	48		
	Time (min)	840	850	880	900	920	930	960		
	Required Replenishment(unit)		9	9	8	9	7			
	Actual Replenishment (unit)		9	9	8	9	7		42	100,8
	Vehicle Capacity (unit)	300	291	282	274	265	258	258		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65

	Total Cost									166,3
6	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	45	46	49	51	53	54	57		
	Time (min)	930	940	970	990	1010	1020	1050		
	Required Replenishment(unit)		10	8	7	5	7			
	Actual Replenishment (unit)		10	8	7	5	7		37	88,8
	Vehicle Capacity (unit)	300	290	282	275	270	263	263		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									154,3
7	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	54	55	58	60	62	63	66		
	Time (min)	1020	1030	1060	1080	1100	1110	1140		
	Required Replenishment(unit)		9	8	8	7	9			
	Actual Replenishment (unit)		9	8	8	7	9		41	98,4
	Vehicle Capacity (unit)	300	291	283	275	268	259	259		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									163,9
8	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	63	64	67	69	71	72	75		
	Time (min)	1110	1120	1150	1170	1190	1200	1230		
	Required Replenishment(unit)		6	11	8	7	5			
	Actual Replenishment (unit)		6	11	8	7	5		37	88,8
	Vehicle Capacity (unit)	300	294	283	275	268	263	263		

	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									154,3
9	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	72	73	76	78	80	81	84		
	Time (min)	1200	1210	1240	1260	1280	1290	1320		
	Required Replenishment(unit)		8	7	7	7	8			
	Actual Replenishment (unit)		8	7	7	7	8		37	88,8
	Vehicle Capacity (unit)	300	292	285	278	271	263	263		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									154,3

N = 5 with medium demand

1	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	0	1	4	6	8	9	12		
	Time (min)	480	490	520	540	560	570	600		
	Required Replenishment(unit)		8	21	20	17	18			
	Actual Replenishment (unit)		8	21	20	17	18		84	201,6
	Vehicle Capacity (unit)	300	292	271	251	234	216	216		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65

	Total Cost									267,1
2	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	9	10	13	15	17	18	21		
	Time (min)	570	580	610	630	650	660	690		
	Required Replenishment(unit)		20	22	18	21	18			
	Actual Replenishment (unit)		20	22	18	21	18		99	237,6
	Vehicle Capacity (unit)	300	280	258	240	219	201	201		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									303,1
3	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	18	19	22	24	26	27	30		
	Time (min)	660	670	700	720	740	750	780		
	Required Replenishment(unit)		21	18	17	20	18			
	Actual Replenishment (unit)		21	18	17	20	18		94	225,6
	Vehicle Capacity (unit)	300	279	261	244	224	206	206		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									291,1
4	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	27	28	31	33	35	36	39		
	Time (min)	750	760	790	810	830	840	870		
	Required Replenishment(unit)		19	19	17	17	21			
	Actual Replenishment (unit)		19	19	17	17	21		93	223,2
	Vehicle Capacity (unit)	300	281	262	245	228	207	207		

	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									288,7
5	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	36	37	40	42	44	45	48		
	Time (min)	840	850	880	900	920	930	960		
	Required Replenishment(unit)		19	20	20	20	19			
	Actual Replenishment (unit)		19	20	20	20	19		98	235,2
	Vehicle Capacity (unit)	300	281	261	241	221	202	202		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									300,7
6	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	45	46	49	51	53	54	57		
	Time (min)	930	940	970	990	1010	1020	1050		
	Required Replenishment(unit)		18	23	19	20	19			
	Actual Replenishment (unit)		18	23	19	20	19		99	237,6
	Vehicle Capacity (unit)	300	282	259	240	220	201	201		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									303,1
7	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	54	55	58	60	62	63	66		
	Time (min)	1020	1030	1060	1080	1100	1110	1140		
	Required Replenishment(unit)		21	21	19	20	21			

	Actual Replenishment (unit)		21	21	19	20	21		102	244,8
	Vehicle Capacity (unit)	300	279	258	239	219	198	198		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									310,3
8	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	63	64	67	69	71	72	75		
	Time (min)	1110	1120	1150	1170	1190	1200	1230		
	Required Replenishment(unit)		18	21	18	18	17			
	Actual Replenishment (unit)		18	21	18	18	17		92	220,8
	Vehicle Capacity (unit)	300	282	261	243	225	208	208		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									286,3
9	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	72	73	76	78	80	81	84		
	Time (min)	1200	1210	1240	1260	1280	1290	1320		
	Required Replenishment(unit)		21	20	19	19	17			
	Actual Replenishment (unit)		21	20	19	19	17		96	230,4
	Vehicle Capacity (unit)	300	279	259	240	221	204	204		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									295,9

N = 5 with high demand

1	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	0	1	4	6	8	9	12		
	Time (min)	480	490	520	540	560	570	600		
	Required Replenishment(unit)		11	35	20	30	30			
	Actual Replenishment (unit)		11	35	20	30	30		126	302,4
	Vehicle Capacity (unit)	300	289	254	234	204	174	174		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									367,9
2	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	9	10	13	15	17	18	21		
	Time (min)	570	580	610	630	650	660	690		
	Required Replenishment(unit)		30	32	31	28	29			
	Actual Replenishment (unit)		30	32	31	28	29		150	360
	Vehicle Capacity (unit)	300	270	238	207	179	150	150		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									425,5
3	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	18	19	22	24	26	27	30		
	Time (min)	660	670	700	720	740	750	780		
	Required Replenishment(unit)		33	31	30	31	33			
	Actual Replenishment (unit)		33	31	30	31	33		158	379,2

	Vehicle Capacity (unit)	300	267	236	206	175	142	142		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									444,7
4	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	27	28	31	33	35	36	39		
	Time (min)	750	760	790	810	830	840	870		
	Required Replenishment(unit)		31	29	32	33	31			
	Actual Replenishment (unit)		31	29	32	33	31		156	374,4
	Vehicle Capacity (unit)	300	269	240	208	175	144	144		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									439,9
5	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	36	37	40	42	44	45	48		
	Time (min)	840	850	880	900	920	930	960		
	Required Replenishment(unit)		32	30	33	31	29			
	Actual Replenishment (unit)		32	30	33	31	29		155	372
	Vehicle Capacity (unit)	300	268	238	205	174	145	145		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									437,5
6	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	45	46	49	51	53	54	57		
	Time (min)	930	940	970	990	1010	1020	1050		

	Required Replenishment(unit)		31	30	31	31	30			
	Actual Replenishment (unit)		31	30	31	31	30		153	367,2
	Vehicle Capacity (unit)	300	269	239	208	177	147	147		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									432,7
7	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	54	55	58	60	62	63	66		
	Time (min)	1020	1030	1060	1080	1100	1110	1140		
	Required Replenishment(unit)		31	29	30	30	32			
	Actual Replenishment (unit)		31	29	30	30	32		152	364,8
	Vehicle Capacity (unit)	300	269	240	210	180	148	148		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									430,3
8	**Cycle**	**0**	**5**	**4**	**1**	**3**	**2**	**0**	**Total**	**Total Cost**
	Period	63	64	67	69	71	72	75		
	Time (min)	1110	1120	1150	1170	1190	1200	1230		
	Required Replenishment(unit)		30	30	34	29	28			
	Actual Replenishment (unit)		30	30	34	29	28		151	362,4
	Vehicle Capacity (unit)	300	270	240	206	177	149	149		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									427,9

9	Cycle	0	5	4	1	3	2	0	Total	Total Cost
	Period	72	73	76	78	80	81	84		
	Time (min)	1200	1210	1240	1260	1280	1290	1320		
	Required Replenishment(unit)		29	30	32	31	32			
	Actual Replenishment (unit)		29	30	32	31	32		154	369,6
	Vehicle Capacity (unit)	300	271	241	209	178	146	146		
	Handling Time (min)		10	10	10	10	10		50	0,5
	Travelling Distance (km)		7,4183	13,2992	6,47195	5,54612	3,13439	17,3099	35,8699	
	Travelling Time (min)		9	16	8	7	4	21		65
	Total Cost									435,1

AUTHOR'S BIOGRAPHY

Fitri Annisaaulkarimah was born in Tegal on January 22nd, 2000. Author is the only daughter from three children of Muhamad Abdul Haris and Ida Nur Ismatun. During elementary schools, author had moved to several cities both in Hava and outside Java. Author continued her study in SMP Negeri 20 Malang and MA Negeri 3 Malang.

After finished with the 12 years of school education, author continued her study as an undergraduate student of Industrial Systems and Engineering at Institut Teknologi Sepuluh Nopember (ITS) Surabaya. During her college life, author was a staff of MSI Ulul Ilmi (2017 – 2019) and a staff of ITS Team Sapuangin (2019/2020). Besides, author also experienced an internship at PT. Ternaknesia Farm Innovation on 2019. For further information regarding this research, author is able to be reached via email fitriannisaau@gmail.com.