MATHEMATICAL MODELING APPROACH
FOR MULTIPLE TRIP VEHICLE ROUTING PROBLEM
WITH TIME WINDOWS AND WORKLOAD BALANCE

BY

NATHAYA THANYAPHOBPHAT

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF MASTER OF
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ENGINEERING)
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A Thesis Presented

By

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Abstract

MATHEMATICAL MODELING APPROACH FOR MULTIPLE TRIP VEHICLE ROUTING PROBLEM WITH TIME WINDOWS AND WORKLOAD BALANCE

by

NATHAYA THANYAPHOBPHAT

Bachelor of Engineering, King Mongkut’s University of Technology North Bangkok, 2016

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This research presents the multi-trip vehicle routing problem with time windows and manual material handling in which all customer is served by heterogeneous fleet with limited number of vehicle. Moreover, each delivery worker has their own energy capacity to unload product during service time. The objectives are to determine utilized vehicles, routes by minimizing operating cost consisted of fixed cost, variable cost and waiting cost, moreover, to match vehicle with worker so that fairly and evenly distribute workload among worker. The single optimization and sequential optimization model is developed in transportation problem and executed by IBM ILOG CPLEX Optimization program. Three pre-assignment policies and a post-assignment are proposed: (1) random assignment (2) low energy capacity workers to small vehicles assignment (3) low energy capacity workers to large vehicles assignment and (4) post-assignment using the workload balance model. The standard deviation of residual energy among worker is indicator for selecting policy. The results show that the sequential optimization is the best method because its running time is faster twenty times than single optimization under the same solution and post-assignment is help to decrease workload bias better than other policies within nine small data sets.

Keywords: Vehicle Routing Problem, Time Windows, Manual Material Handling, Multi-trip. Workforce balance.
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Chapter 1
Introduction

1.1 Overview of Vehicle Routing Problem

The Vehicle Routing Problem (VRP) is well studied in the transportation aspect of logistics management in which each of vehicle rapidly delivers goods from supply location (e.g., depot, warehouse) to customer locations (e.g., retail store). Generally basic objective is to find out the optimal set of routes, a fleet of vehicle within minimizing travelling cost.

The VRP started with a well-known the Traveling Salesman Problem (TSP) to determine a fleet of gasoline delivery trucks (Dantzig & Ramser, 1959). TSP is a well-known combinatorial optimization classified as a NP-hard problem. During the last decades, VRP has been applied widely in many areas such as the Capacitated Vehicle Routing Problem (CVRP) is to define a maximum number product of vehicle, Open Multi-Depot Vehicle Routing Problem (OMDVRP) in which vehicle is no return to depots is contributed by Tarantilis & Kiranoudis (2002) at a Greek industry distributing fresh meat, Vehicle Routing Problem with Pickup and Delivery (VRPPD) is different to Vehicle Routing Problem with Backhauls (VRPB) because VRPB applies to delivery product completely before pickup, Vehicle Routing Problem with Time Windows (VRPTW) is to address interval time of location to handle arrival time where aim to be inside opening time called earliest time and after ending time called latest time and so on.

In practice, the size of problems in the industries is too big to solve for optimal solutions using available optimization software such as ILOG CPLEX or LINGO. Hence, it is more practical to adopt approximating methods which typically solves faster than the exact method but produces a bit poorer solution. There are two main approximating methods: (1) heuristic method and (2) metaheuristic method such as Tabu Search (TS), Simulated Annealing (SA), Ant Colony Optimization (ACO), Particle Swarm Optimization (PSO), and Genetic Algorithms (GA).
1.2 Problem Statement

For trend of recent years, the human behavior is likely to consume goods promptly due to a variety of commodity, of promotion, of sales channel (e.g. online shopping). If the quality product among company are not different. The delivery sector is the necessary part to boost their chance of winning a business competition.

Because the ineffective infrastructures basically lead to many people decide to use their own private car instead of public services; the number of vehicle is increased; the traffic congestion will be occurred which affects a long-term transportation such as customer may receive product delay and delivery vehicle may obtain utilization poorer; vehicle struck on the road. Hence, customer time window is arisen to be an importance factor to compromise distribution schedule between service provider and customer. Due to a narrow lane, a complex road and a rush-hour large truck restriction. The small truck should be operated instead of a large truck to provide flexible and proactive traveling.

Besides, many researches solely dealt with a single-trip. They did not consider while the case of customer demand is higher and closer to vehicle capacity. The reason causes single trip which routing time is shorter than working time, so multiple trip is performed to improve utilization and helps handle condition due to the number of vehicle limitation either.

Moreover, when a truck arrives at customer sites, the workers assigned to the truck will need to unload the shipping and use their energy expenditure according to The National Institute for Occupational Safety and Health of ergonomic recommendation announced energy expenditure of any worker should not exceed 33% of energy capacity during working daily time (NIOSH, 1981). The worker does not deserve work too hard or too light that affect to his own and among the others. Therefore, Manual Material Handling (MMH) is considered to assign workload appropriately.

Thus, this research aims to determine a set of routes and a fleet of vehicles while minimizing fixed cost and traveling cost and balancing workload to assign worker fairly and evenly. The consequence of workload confliction is subsequent the risk of long-term injury and poor mental health such as the more hours people worked, the greater
their risk for back pain. As the above mentioned, this is a good opportunity to deduct gap and achieve transportation problem and ergonomic consideration simultaneously.

1.3 Objectives

The purpose of this thesis is to develop mathematical models in transportation and ergonomic consideration problem. For distribution problem, it consists of two main approaches: single-objective and sequential objectives to determine a set of delivery vehicles, routes and vehicle starting time under time windows, manual material handling service and allowed multi-trip travelling, moreover, MILP is also launched in the workload assignment used energy expenditure in the transportation problem to determine available worker who should be assigned to utilized vehicle.

1.4 Scopes of Thesis

The scopes of thesis are deterministic situation, which concerns in congestion areas (e.g. a city) that the small vehicle can be operated to serve product directly. The vehicle is a heterogeneous fleet and limited number of vehicle. In numerical example and computational experiment, the six vehicles are imposed: three type of number delivery worker, load capacity and vehicle speed except the fixed cost and variable cost of each vehicle are different throughout available vehicles. The number of worker is twenty with their own energy capacity. The number of customer is twelve in numerical example with their own demand, and time windows. Besides, each vehicle accompanies only one driver who is negligible and number of delivery worker which vary as vehicle capacity size as mentioned before.

The multiple trip is considered within working daily day (8 hours/day), which is not usually concerning driver and delivery worker’ lunch break, so the number of travelling can be two round mostly. In term of loading time, the first trip is negligible because the job is allocated by warehouse worker before transportation planning. However, when vehicle serve product and return depot, the vehicle must increase 60 minutes for re-loading product. The reason of constant re-loading time because the automatic machine is operated instead of manual warehouse worker.

In part of energy, the energy expenditure of vehicle is computed by average of unloading time per unit (2 mins/unit), energy expenditure per a minute (6 kcal/min) and
number of carried product. Then, it will share workload equally to worker in the same team. Moreover, the energy capacity of each vehicle is derived by aggregating the individual energy capacity of worker as vehicle requires.

1.5 Overview of Thesis

The thesis distinguished into six chapters, described as follows:

Chapter 1 introduces the overview of the research including general of VRP problem, statement of problem, objectives and scopes of thesis.

Chapter 2 reviews the VRP literature under many physical characteristics such as multi-trip, time windows and manual material handling related to delivery worker.

Chapter 3 designs the mathematical model divided into the two main problem as transportation model and workload balance model.

Chapter 4 stimulates the nine small data set of the numerical example.

Chapter 5 address the more computational experiment.

Chapter 6 express the conclusion research and recommendation.

Chapter 7 describes the significant of study.
Chapter 2
Literature Review

This chapter investigates many physical characteristics subject to a heterogeneous fleet with limited number of vehicle, multiple trip, time windows and manual material handling for realistic practical.

2.1 Multiple Trip (MTVRP)

Fleischmann (1990) is a first researcher for presenting Multi-Trip Vehicle Routing Problem (MTVRP) who constructed the saving (Clarke & Wright, 1964) and Bin Packing (BP) algorithm. Ayadi & Benadada (2013) represented the minimization of maximum overtime as infeasible solution and of routing cost as feasible solution in MTVRP. Memetic Algorithm (MA) is a technique to solve their problem called Hybrid Genetic Algorithm (HGA) because MA evolves population chromosome like GA but it augments local search to obtain diversity offspring. As the comparison of both results, their method is superior to Salhi & Petch (2007) who firstly present population search as GA in VRPMT, however, received inferior to Olivera & Viera (2007) who recommended enhancement of Tabu Search (TS) called adaptive memory procedure. However, Cattaruzza, Absi, Feillet, & Vidal (2014) contributed MA in which adapted of the split procedure (Prins, 2004) and introduced a new local search operator called Combined Local Search (CLS). For result comparison in feasible solution, MA+CLS is better average gap values than Olivera & Viera (2007) but is slower than them in term of computing time. In 2016, they have gathered the number of multiple trip publication which have gradually increased reconsideration (Cattaruzza, Absi, & Feillet, 2016b) as shown in Figure 2.1 They surveyed mathematical formulation base regarding trip or non-trip index, exact and heuristic method for approach. MTVRP extensions with additional variants as follows: (1) general VRP conducted with time windows, service-dependent loading time, limited trip duration and profit (2) distribution process combined with production and inventory (3) maritime transportation applied to minimize sailing and charter cost. Moreover, standard instances are shown to compare result when future researcher will perform to competitive running time.
2.2 Multiple Trip with Time Windows (MTVRPTW)

Vehicle Routing Problem with Time Windows (VRPTW) can be discriminated into two types. The first one is VRP with Hard Time Windows (VRPHTW); vehicles arriving too early must wait until the customer is ready as well as vehicles must deliver before the allowed closing time. The second one is VRP with Soft Time Windows (VRPSTW); it allows the violated specified windows with penalty cost. For more VRPTW review, El-Sherbeny (2010) provided variant of method to solve problem so far.

(Cattaruzza, Absi, & Feillet, 2016a) Release date is a time which product is available at the depot. In this paper, planning transportation time is important between the time which receive final product from supplier (release date), and the time which serve product to customer (time window) to increase the effective flow throughout supply chain under number of vehicle limitation (multiple trip). Hybrid genetic algorithm and split algorithm were purposed to compare result with exact instances Hernandez, Feillet, Giroudeau, & Naud (2011) which has a small size: 25 customers 2 vehicles, a medium size: 50 customers 4 vehicles and a large size: 100 customers 8 vehicles. In the conclusion, 100 customers with 8 vehicles was found average gap only 0.03% of all feasible solution instances.

(Anggodo, 2016) Multiple Trip VRP was adapted tourism city in Indonesia and implemented genetic algorithm to solve. The problem set the central location as hotel

![Figure 2.1 Number of multi trip publication](image)
and the others node as tourism to find out tourist route within 3 days while each of tourist and each of tourist attraction also had time window.

### 2.3 Heterogeneous Fleets with a Fixed Number of Vehicles (HFVRP)

For heterogeneous fleets VRP with a fixed number of vehicles and performing multi-trip (HFVRPMT), Prins (2002) considered bi-objective of minimum the total duration of trips and minimum the number of truck used for implementing real case of a French furniture manufacturer with 775 stores. They developed saving method to be a new Merge heuristic (MER) in single-trip and MER2 in multi-trip replaced by PackTrips procedure. Their local searches have steepest descent local search and TS to carry out. The solution found MER2 with TS saved 1 trip, 4 trucks and 7491 min (-11.7%) while compare with the experienced dispatcher of the company. Caceres-Cruz, Grasas, Ramalhinho, & Juan (2014) adopted objective of minimum total distance with a Randomized version of the MER heuristic (Rand-MER) based on additional two LS: cache and splitting techniques for implementing real case of a Spin distribution company with more than 370 stores. The result showed Rand-MER outperformed than MER on single-trip and multi-trip case. (Coelho et al., 2016) included docking constraints to be practical in objective function: fixed utilized vehicles, distance-based costs and a cost per customer visited. They designed GILS-VND that combines Iterated Local Search (ILS), Greedy Randomized Adaptive Search Procedure (GRASP) and Variable Neighborhood Descent (VND) procedures. The result expressed GILS-VND that is superior to Rand-MER in best gap solution with reducing computational time 5 minutes. Furthermore, their research yearly saved over € 70,000 and better routing indicators.

### 2.4 Manual Materials Handling (VRPMMH)

Boonprasurt & Nanthavanij (2012) considered Vehicle Routing Problem with Manual Materials Handling (VRPMMH). They considered two types of assignments: Fixed Workforce Assignment (FXW) and Flexible Workforce Assignment (FLX). The FXW policy randomly assigned a worker team to a vehicle without knowing vehicle paths (or it is called a pre-assignment policy). The FLX policy assigned the workers after...
knowing the vehicle paths. (or it is called a post-assignment policy). In 2017, they
developed hybrid genetic algorithm to solve a large scale FXW problem. The random
procedure and nearest neighborhood search were techniques to run initial population
and the new heuristic was developed in crossover and mutation operation (Boonprasurt

Rattanamanee, Nanthavanij, & Dumrongsiri (2014) studied a Multi-Workday
VRP (MW-VRP) with an objective to determine vehicle routing and worker allocation
over multi-day planning periods.
3.1 Problem Description

MTVRPTW-MMH proposes two main policies which consist of (1) fixed-workforce assignment (aka pre-assignment) and (2) flexible-workforce assignment (aka post-assignment). Pre-assignment is to assign worker into vehicle before determining delivery routes. Therefore, it merely computes once. Post-assignment is not to assign worker into vehicle. So, the first objective is to operate average instead of individual energy capacity, then the second objective is to act workforce allocate after obtaining routes and utilized vehicles as Figure 3.1 shows overall mathematical model framework to understand clearly.

Figure 3.1 Overall mathematical model framework
Our problem situation provides condition as follows:

1. The distribution situation is deterministic including only single depot and one product type along service.
2. The vehicle is non-identical fleet which three capacity difference.
3. Each vehicle has one driver (excluding in ergonomic consideration) and number of delivery worker depend on vehicle capacity.
4. In case vehicle waiting time is occurred, it is assumed that vehicle must travel to wait the opening time (or it is called waiting cost), which cannot stop the engine due to narrow lane, and the rule traffic in a city
5. The sum of individual energy capacity of worker in the same team is formed to energy capacity of vehicle.
6. The energy expenditure of vehicle will share workload equally to delivery worker in the same team.
7. The unloading time per unit, energy expenditure per min and re-loading time are known and fixed.

3.2 MTVRPTW-MMH for transportation problem

The transportation problem is divided into (1) Sequential optimization, which concerns only the actual operating cost excluding vehicle waiting cost in the first model (or it is called the synchronized departure time) and tries to reduce the waiting time in the second model afterward (or it is called the flexible departure time). (2) Single optimization, which considers fixed, variable and waiting cost altogether only one model. Both method approach can execute in pre-assignment and post-assignment policies.

Noted that the distribution assumption is taken into account the same throughout the different method, moreover, the main notation and model which apply a similar constraint are declared before beginning each of technique heading in order to reduce indices, parameters, decision variables, and equation duplication.

3.2.1 Assumption

1. The variable cost in each vehicle is not only adopted in actual travelling distance but is also applied travelling for waiting cost.
2. Each customer is served only one time by one vehicle.
3. Each vehicle must departure from depot and return at the same depot.
4. Each vehicle loads products and serves customer demands, but it will not exceed the vehicle load capacity.
5. Each vehicle spends energy expenditure when it serves customer, but it will not exceed the vehicle energy capacity.
6. Service time (unloading time) must operate inside time window range, and it will uncertain depend on carried product and number of worker in each utilized vehicle.
7. The re-loading product time will be considered when vehicle returns to re-load product
8. All utilized vehicles must travel during the working daily time.

3.2.2 Notation

Indices:

\( r \) Index for delivery trips; \( r = 1, \ldots, R \)
\( k \) Index for delivery vehicles; \( k = 1, \ldots, K \)
\( i, j \) \(i = 0\) for depot and \(i, j = 1, \ldots, N\) for customer locations

Parameters:

\( R \) Number of delivery trips
\( K \) Number of delivery vehicles
\( N \) Number of customer locations
\( NW_k \) Number worker of vehicle \( k \)
\( s_k \) Average traveling speed of the vehicle \( k \) (km/min)
\( FC_k \) Fixed cost of the selected vehicle (baht)
\( VC_k \) Variable cost of the selected vehicle (baht/km)
$EV_k$ Energy capacity of the vehicle $k$ for pre-assignment (kcal/day)

$Q_k$ Load capacity of vehicle $k$ (units)

$D_j$ Demand of customer $j$ (units)

$E_j$ Opening time window of customer $j$ (min)

$L_j$ Ending time window of customer $j$ (min)

$d_{ij}$ Traveling distance from location $i$ to location $j$ (km)

$avgEC$ Average energy capacity of available worker for post-assignment (kcal/day)

$ET$ Average energy expenditure (kcal/min)

$TU$ Average time of unloading a unit (min/unit)

$TR$ Average time of re-loading unit into vehicle at depot (min/times)

$TMAX$ Maximum working daily time (min/day)

**Decision Variables:**

$U_i$ Variables used to avoid sub tours,

$X_{ijk}^r$ 1 if vehicle $k$ travels from location $i$ to location $j$ in $r$ trip, 0 otherwise

$Y_k$ 1 if vehicle $k$ is selected, 0 otherwise

$S_{jk}^r$ 1 if vehicle $k$ serves location $j$ in trip $r$, 0 otherwise

$ST_{ik}^r$ Starting time of location $i$ vehicle $k$ in trip $r$

$ET_k$ Ending time of vehicle $k$

**3.2.3 Model**

subject to
\[
\sum_{k=1}^{K} \sum_{r=1}^{R} S'_{jk} = 1 \quad \forall i = 1, \ldots, N \tag{1}
\]
\[
\sum_{j=1}^{N} X'_{0jk} \leq Y_k \quad \forall k, \forall r \tag{2}
\]
\[
\sum_{i=1}^{N} X'_{ijk} \leq S'_k \quad \forall j, \forall k, \forall r \tag{3}
\]
\[
X'_{ijk} = 0 \quad \forall i, \forall k, \forall r \tag{4}
\]
\[
\sum_{i=0}^{N} X'_{0ik} - \sum_{j=0}^{N} X'_{j0k} = 0 \quad \forall h = 1, \ldots, N; i \neq j \neq h, \forall k, \forall r \tag{5}
\]
\[
\sum_{i=1}^{N} X'_{0ik} - \sum_{j=1}^{N} X'_{0jk} = 0 \quad \forall k, \forall r \tag{6}
\]
\[
\sum_{i=0}^{N} \sum_{j=0}^{N} D_j X'_{ijk} \leq Q_k \quad \forall k, \forall r \tag{7}
\]
\[
EU \cdot TU \sum_{i=0}^{N} \sum_{j=0}^{N} \sum_{r=1}^{R} D_j X'_{ijk} \leq EV_k \quad \forall k \tag{8}
\]
\[
U_j \geq U_i + 1 - N(1 - \sum_{k=1}^{K} X'_{ijk}) \quad \forall i, \forall j; i \neq j, \forall r \tag{9}
\]
\[
\sum_{j=1}^{N} X'_{0jk} \geq \sum_{j=1}^{N} X_{0jk} \quad \forall k, \forall r = 1 \ldots R-1 \tag{10}
\]
\[
X'_{ijk} \in \{0,1\} \quad \forall i, \forall j, \forall k, \forall r \tag{11}
\]
\[
Y_k \in \{0,1\} \quad \forall k \tag{12}
\]
\[
S'_{jk} \in \{0,1\} \quad \forall i, \forall k, \forall r \tag{13}
\]
\[
ST'_{ik} = \left( D_j \cdot TU \frac{d_{ij}}{NW_k} \right) + \left( \frac{d_{ij}}{s_k} \right) + M(X'_{ijk} - 1) \leq ST'_{jk} \quad \forall i, \forall j = 1, \ldots, N; i \neq j, \forall k, \forall r \tag{14}
\]
\[
ST'_{0j} = \left( \frac{d_{0j}}{s_k} \right) + M(X_{0jk} - 1) \leq ST'_{jk} \quad \forall j, \forall k \tag{15}
\]
\[ ST'_{0k} + TR + \left( \frac{d_{0l}}{s_k} \right) + M (X'_{0jk} - 1) \leq ST'_{jk} \quad \forall j, \forall k, \forall r = 2, ..., R \quad (16) \]

\[ ST'_{ik} + \left( \frac{d_{i0}}{TU_{NW_k}} \right) + \left( \frac{d_{0l}}{s_k} \right) + M (X'_{i0k} - 1) \leq ST'_{0k} + 1 \quad \forall i, \forall k, \forall r = 1, ..., R - 1 \quad (17) \]

\[ ST'_{ik} + \left( \frac{d_{i0}}{TU_{NW_k}} \right) + \left( \frac{d_{0l}}{s_k} \right) + M (X'_{i0k} - 1) \leq ET_k \quad \forall i, \forall k, \forall r \quad (18) \]

\[ E_i \leq ST'_{ik} \leq L_i \quad \forall i, \forall k, \forall r \quad (19) \]

\[ ET_k \leq TMAX \quad \forall k \quad (20) \]

\[ ST'_{0k} \leq ET_k \quad \forall k, \forall r \quad (21) \]

Constraints (1) ensures that each customer will be visited certainly once. Constraint (2) counts utilized vehicle while leaving from depot. Constraint (3) connects between two decision variables. Constraint (4) bans traveling in the same location. Constraint (5) conserves the inflow and outflow. Constraint (6) forces that if a vehicle leaves the depot, it must return to the depot. Constraint (7) requires that if a vehicle leaves the depot, it must return to the depot. Constraint (8) conserves the inflow and outflow. Constraint (6) forces that if a vehicle leaves the depot, it must return to the depot. Constraint (7) satisfies load capacity. Constraint (8) satisfies energy capacity. Constraint (9) prevents sub-tour. Constraints (10) establishes trip sequences. Constraint (11), (12), and (13) are binary variables. Constraint (14) determines that along service between customer must contain service time and travelling time. Constraint (15) addresses that only travelling time is considered in the first trip. Constraint (16) refers that re-loading time is occurred in the second trip onwards. Constraint (17) confirms trip time sequence. Constraint (18) approves the actual operating time of vehicle. Constraint (19) limits the arrival time of a location to be within allowed time window. Constraint (20) limits the arrival time to be within a time limit of a day. Constraint (21) restricts all the arrival time in any trip to be within the actual operating time of vehicle.

For post-assignment, it replaces constraint (8) to be constraint (22) due to without pairing worker and vehicle before.

\[ EU \cdot TU \sum_{i=0}^{N} \sum_{j=0}^{N} \sum_{r=1}^{R} D_{ij} X'_{ijk} \leq \text{avgEC} \cdot NW_k \quad \forall k \quad (22) \]
3.2.4 MTVRPTW-MMH in Sequential optimization for transportation problem

It can divide into the synchronized departure time and flexible departure time as describes below.

5.2.4.1 Synchronized departure time

This model is interested only the actual operating cost (fixed cost and variable cost of all utilized vehicles) which is the objective function in the first phase of sequential optimization (23) applied with equation (1) – (22) as constraint. Because it does not concern vehicle waiting time, so, the departure time of every utilized vehicle always start at 8:00:00 a.m. or (it is called synchronized departure time). However, this model is still weakness when waiting time have travelling cost because vehicle cannot stop to wait opening time due to a narrow lane and traffic rule as mention in assumption earlier. So, the total cost will be higher than actual operating cost that we found.

\[
\text{Minimize } \sum_{k=1}^{K} FC_k Y_k + \sum_{i=0}^{N} \sum_{j=0}^{N} \sum_{k=1}^{K} \sum_{r=1}^{R} VC_k d_{ij} X_{r}^{ijk}
\]  

(23)

5.2.4.2 Flexible departure time

This model is helped to reduce waiting cost by using the same set of operated vehicles in the previous model because it is a major cost of total cost, which forces decision variable \( Y_k \) to be parameter (1 if vehicle k is selected, 0 otherwise) and also applies equation (1) – (22) to be constraint. As the objective function (24) is to minimize variable cost and vehicle waiting cost. The waiting cost also applies the same value of variable cost because of fuel consumption expense for travelling to wait. Therefore, the vehicle must be flexible departure time to strict and reduce vehicle waiting time, however, we noted that the vehicle waiting time will be computed within actual starting time until actual ending time. So, the time from 8:00:00 a.m. to departure time is not waiting cost.
Minimize \[ \sum_{i=0}^{N} \sum_{j=0}^{N} \sum_{k=1}^{R} \sum_{r=1}^{R} V C \cdot d_{ij} \cdot X'_{ijk} + \]
\[ [ V C \cdot s_{k} \cdot \{ \sum_{k=1}^{K} E T_{k} - S T_{0 i k} \} - \left( \sum_{j=0}^{N} \sum_{j=0}^{N} \sum_{k=1}^{K} \sum_{r=1}^{R} X'_{ijk} \cdot d_{ij} \right) - \left( \sum_{r=0}^{R} \sum_{r=1}^{R} S'_{j} \cdot D_{j} \cdot T U \cdot N W_{k} \right) - \left( \sum_{j=0}^{N} \sum_{j=0}^{N} X'_{0 jk} \cdot T R \right) ] \]

\[ (24) \]

3.2.5 MTVRPTW-MMH in Single optimization for transportation problem

In the single optimization, we try to minimize actual operating cost and waiting cost altogether to obtain the optimal total cost as the objective function (25) with constraints (1) – (22) (or it is called flexible departure time as well).

Minimize \[ \{ \sum_{k=1}^{K} E T_{k} - S T_{0 i k} \} - \left( \sum_{j=0}^{N} \sum_{j=0}^{N} \sum_{k=1}^{K} \sum_{r=1}^{R} X'_{ijk} \cdot d_{ij} \right) - \left( \sum_{r=0}^{R} \sum_{r=1}^{R} S'_{j} \cdot D_{j} \cdot T U \cdot N W_{k} \right) - \left( \sum_{j=0}^{N} \sum_{j=0}^{N} X'_{0 jk} \cdot T R \right) ] \]

\[ (25) \]

3.3 MTVRPTW-MMH for worker assignment problem

This section, it is executed for post-assignment only. After we calculated transportation solution successfully, the delivery worker assignment is active to employ delivery worker (excluding driver). Firstly, we are supposed to determine the residual energy because each worker has his/her own energy capacity; the amount of energy capacity is non-identical. If only focus the energy consumption, it might not be fair when female worker is assigned as amount of work as male worker. Noted that worker’s energy consumption derives from utilized vehicle whose energy expenditure will be shared workload evenly to worker in the same team. Secondly, the standard deviation percent of residual energy among employed worker is indicator to represent how better allocate worker to vehicle. The consequence of workload confliction is subsequent the risk of long-term injury and poor mental health. However, this model cannot determine standard deviation directly, so we consider minimax decision concept instead in this model’s objective.

3.3.1 Assumption

1. Each worker can accompany one vehicle.
2. Each operated vehicle must assign number worker as vehicle needs.
3. Each worker spends energy expenditure when it serves customer, but it will not exceed his own energy capacity.
4. Energy expenditure of vehicle is consistent with unloading time a unit, energy expenditure per min, and actual loads.
5. Energy expenditure of operated vehicle is shared workload evenly to worker in the same team.

3.3.2 Notation

Indices:

- \( r \) Index for delivery trips; \( r = 1, \ldots, R \)
- \( k \) Index for delivery vehicles; \( k = 1, \ldots, K \)
- \( l \) Index for delivery workers; \( l = 1, \ldots, L \)

Parameters:

- \( R \) Number of delivery trips
- \( K \) Number of delivery vehicles
- \( L \) Number of delivery workers
- \( NW_k \) Number worker of vehicle \( k \)
- \( AD_{kr} \) Actual loaded demand of vehicle \( k \) in trip \( r \) (units)
- \( EC_l \) Individual energy capacity in worker \( l \) (kcal/day)
- \( TU \) Average time of unloading a unit (min/unit)
- \( ET \) Average energy expenditure (kcal/min)

Decision Variables:

- \( Z \) Maximum residual energy among workers
- \( W_{lk} \) 1 if worker \( l \) is assigned to vehicle \( k \), 0 otherwise
3.3.3 Model

Minimize \( Z \) \hspace{1cm} (26)

subject to

\[
\sum_{k=1}^{K} W_{lk} \leq 1 \quad \forall l \hspace{1cm} (27)
\]

\[
\sum_{l=1}^{L} W_{lk} = NW_k \quad \forall k \hspace{1cm} (28)
\]

\[
W_{lk} \cdot \left( 1 - \left( \frac{ET\cdot TU \cdot \sum_{r} AD_{kr}}{NW_k} \right) \right) \leq Z \quad \forall l, \forall k \hspace{1cm} (29)
\]

\[
W_{lk} \in \{0,1\} \quad \forall l, \forall k \hspace{1cm} (30)
\]

\[
Z > 0 \hspace{1cm} (31)
\]

The objective function (26) is to minimize the maximum percent residual energies. Constraints (27) states employed worker can be assigned only one vehicle. Constraints (28) fulfills number worker based on vehicle’s requirement. Constraint (29) designs residual energies of each employed worker that must not exceed the upper bound. Constraint (30) is to define worker decision to be binary. Constraint (31) prevents residual energies that becomes negative.
Chapter 4
Numerical Examples

At the beginning, the 9 small data sets are announced in which impose the six non-
identical vehicles (V1-V6) leaving from one depot (D) to serve twelve customers (C1-
C12) under the available twenty workers (W1-W20). These instances derived from
pairing between the small (1), medium (2) and large size (3) of demand (D) and vehicle
load capacity (L) modification. All of size are formed by random range as follows:

1. The demand size is 0-100 boxes, 0-150 boxes, and 0-200 boxes respectively
2. The load capacity size is 100 boxes in V1 and V2; 200 boxes in V3 and V4; 300
   boxes in V5 and V6 for small size, 150;300;450 for medium size, and
   200;400;600 for large size

Noted that the other parameter is the same, so these data can represent the list
as sorting the demand firstly: D1L1, D1L2, D1L3, D2L1, D2L2, D2L3, D3L1, D3L2,
D3L3.

For the initial data (D1L1) is a representative demonstration, Table 4.1 shows
the information of each delivery vehicle: fixed cost, variable cost, speed, number of
delivery worker and load capacity. With the maximum working daily time is 8
hours/day, average time of unloading a unit is 2 mins/unit, average energy expenditure
is 6 kcal/min and average time of re-loading is 60 mins/time.
Table 4.1 The information of six vehicles

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Delivery vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V1</td>
</tr>
<tr>
<td>Fixed cost (baht/day)</td>
<td>1,500</td>
</tr>
<tr>
<td>Variable cost (baht/km)</td>
<td>5.0</td>
</tr>
<tr>
<td>Number of delivery workers (persons/vehicle)</td>
<td>2</td>
</tr>
<tr>
<td>Load capacity (units)</td>
<td>100</td>
</tr>
<tr>
<td>Speed (km/min)</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Table 4.2 shows the demand, opening time and ending time of each customer.

Table 4.2 Customer demand (units) and time windows (mins)

<table>
<thead>
<tr>
<th></th>
<th>D</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
<th>C8</th>
<th>C9</th>
<th>C10</th>
<th>C11</th>
<th>C12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand</td>
<td>0</td>
<td>65</td>
<td>52</td>
<td>76</td>
<td>80</td>
<td>28</td>
<td>64</td>
<td>72</td>
<td>36</td>
<td>44</td>
<td>56</td>
<td>40</td>
<td>24</td>
</tr>
<tr>
<td>Earliest time</td>
<td>0</td>
<td>240</td>
<td>150</td>
<td>30</td>
<td>150</td>
<td>240</td>
<td>60</td>
<td>0</td>
<td>400</td>
<td>330</td>
<td>150</td>
<td>60</td>
<td>270</td>
</tr>
<tr>
<td>Latest time</td>
<td>480</td>
<td>360</td>
<td>450</td>
<td>120</td>
<td>300</td>
<td>450</td>
<td>210</td>
<td>240</td>
<td>480</td>
<td>480</td>
<td>480</td>
<td>100</td>
<td>360</td>
</tr>
</tbody>
</table>

The symmetrical distances between depot and all customers are shown in Table 4.3.
Table 4.3 The distances (km) between depot and all customers

<table>
<thead>
<tr>
<th></th>
<th>D</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
<th>C8</th>
<th>C9</th>
<th>C10</th>
<th>C11</th>
<th>C12</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>0.0</td>
<td>2.4</td>
<td>5.4</td>
<td>11.4</td>
<td>4.6</td>
<td>12.7</td>
<td>7.0</td>
<td>4.6</td>
<td>7.6</td>
<td>3.6</td>
<td>10.5</td>
<td>5.2</td>
<td>14.6</td>
</tr>
<tr>
<td>C1</td>
<td>0.0</td>
<td>13.0</td>
<td>6.2</td>
<td>7.7</td>
<td>5.7</td>
<td>10.8</td>
<td>8.8</td>
<td>6.7</td>
<td>15.0</td>
<td>5.6</td>
<td>9.6</td>
<td>13.2</td>
<td></td>
</tr>
<tr>
<td>C2</td>
<td>0.0</td>
<td>1.0</td>
<td>4.1</td>
<td>10.0</td>
<td>13.5</td>
<td>8.9</td>
<td>12.4</td>
<td>8.6</td>
<td>12.5</td>
<td>4.8</td>
<td>8.6</td>
<td>12.6</td>
<td></td>
</tr>
<tr>
<td>C3</td>
<td>0.0</td>
<td>5.5</td>
<td>6.9</td>
<td>9.9</td>
<td>4.9</td>
<td>3.1</td>
<td>14.8</td>
<td>5.8</td>
<td>11.2</td>
<td>12.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C4</td>
<td>0.0</td>
<td>4.4</td>
<td>13.2</td>
<td>5.4</td>
<td>9.8</td>
<td>10.8</td>
<td>2.0</td>
<td>7.1</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>0.0</td>
<td>5.0</td>
<td>13.6</td>
<td>9.5</td>
<td>14.6</td>
<td>11.5</td>
<td>2.8</td>
<td>5.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C6</td>
<td>0.0</td>
<td>8.0</td>
<td>10.9</td>
<td>10.8</td>
<td>10.0</td>
<td>2.5</td>
<td>5.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C7</td>
<td>0.0</td>
<td>3.0</td>
<td>5.3</td>
<td>12.4</td>
<td>4.3</td>
<td>11.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C8</td>
<td>0.0</td>
<td>7.1</td>
<td>13.2</td>
<td>1.7</td>
<td>10.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C9</td>
<td>0.0</td>
<td>13.1</td>
<td>13.0</td>
<td>13.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C10</td>
<td>0.0</td>
<td>13.5</td>
<td>6.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C11</td>
<td>0.0</td>
<td>14.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C12</td>
<td>0.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.4 shows individual energy capacities of twenty delivery workers (W1-W20) with random sequences. The energy range is from 1,500 kcal/day to 2,500 kcal/day.

Table 4.4 The individual energy capacities of twenty workers (kcal/day)

<table>
<thead>
<tr>
<th>Worker</th>
<th>Energy capacity</th>
<th>Worker</th>
<th>Energy capacity</th>
<th>Worker</th>
<th>Energy capacity</th>
<th>Worker</th>
<th>Energy capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>W1</td>
<td>2,154</td>
<td>W6</td>
<td>2,345</td>
<td>W11</td>
<td>1,692</td>
<td>W16</td>
<td>2,422</td>
</tr>
<tr>
<td>W2</td>
<td>1,900</td>
<td>W7</td>
<td>2,174</td>
<td>W12</td>
<td>2,283</td>
<td>W17</td>
<td>2,341</td>
</tr>
<tr>
<td>W3</td>
<td>2,161</td>
<td>W8</td>
<td>2,109</td>
<td>W13</td>
<td>1,923</td>
<td>W18</td>
<td>2,395</td>
</tr>
<tr>
<td>W4</td>
<td>2,183</td>
<td>W9</td>
<td>2,101</td>
<td>W14</td>
<td>2,355</td>
<td>W19</td>
<td>1,679</td>
</tr>
<tr>
<td>W5</td>
<td>2,234</td>
<td>W10</td>
<td>2,217</td>
<td>W15</td>
<td>1,648</td>
<td>W20</td>
<td>2,045</td>
</tr>
</tbody>
</table>

Besides, all models are executed on IBM ILOG CPLEX Optimization program.
4.1 Transportation problem for the initial data

We divide the transportation problem under (1) synchronized departure time lacking vehicle waiting time, which is executed in the first phase of sequential optimization and (2) flexible departure time including vehicle waiting time in the objective, which can perform in single optimization or run in the first phase to the second phase of sequential optimization to detect where is different between both of them and which one should be applied to ergonomic consideration problem later.

4.1.1 Transportation problem under synchronized departure time

For transportation problem of the initial data to determine the utilized vehicles and routes while concerning the optimal operating cost consisted of fixed and variable cost. The result is run within 68.75 seconds. Vehicles V3 and V4 are operated twice to deliver 200 and 180 units in V3, 104 and 153 units in V4 respectively. The total cost is 6,139.1 baht: fixed cost is 5,500 baht and the variable cost is 639.1 baht, which optimal routing can display in Table 4.5.

Table 4.5 The utilized vehicles and routes for the initial data

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Delivery route</th>
<th>Load capacity (units)</th>
<th>Carried load (units)</th>
<th>Fixed cost (baht)</th>
<th>Variable cost (baht)</th>
<th>Total (baht)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V3</td>
<td>D→C7→C3→C2→D</td>
<td>200</td>
<td>200</td>
<td>2,500</td>
<td>313.6</td>
<td>2,813.6</td>
</tr>
<tr>
<td></td>
<td>D→C4→C10→C9→D</td>
<td></td>
<td>180</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V4</td>
<td>D→C11→C6→D</td>
<td>200</td>
<td>104</td>
<td>3,000</td>
<td>325.5</td>
<td>3,325.5</td>
</tr>
<tr>
<td></td>
<td>D→C1→C5→C12 C8→D</td>
<td></td>
<td>153</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5,500</td>
<td>639.1</td>
<td>6,139.1</td>
</tr>
</tbody>
</table>

Assumes that the working hours is 8:00:00 a.m. until 4:00:00 p.m. without the legal break (0 min-480mins). Reader can see that Table 4.6 represents the beginning and ending time and also summarizes the total time of traveling, unloading and waiting with unit of minute in each trip of utilized vehicles. From the detail, all utilized vehicles
work on time, however, the total waiting of V3 and V4 are occurred as 12.4 mins and 48.6 min. Moreover, the starting time in trip 2 is derived from the ending time in trip1 and re-loading time e.g. V3: 12:24:36 p.m. (204.6+60 = 264.6 mins). The total travelling and unloading time is 145.2 mins, 253.3 mins in V3 and 172.2 mins, 171.3 mins in V4 respectively.

Table 4.6 Time schedule (mins.) under departure on time

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Trip</th>
<th>Starting time (mins)</th>
<th>Traveling time (mins)</th>
<th>Unloading time (mins)</th>
<th>Waiting time (mins)</th>
<th>Ending time (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V3</td>
<td>1</td>
<td>(0) 8:00:00 AM</td>
<td>(58.9)</td>
<td>(133.3)</td>
<td>(12.4)</td>
<td>(204.6) 11:24:36 AM</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>(264.6) 12:24:36 PM</td>
<td>(86.3)</td>
<td>(120.0)</td>
<td>(0)</td>
<td>(470.9) 3:50:54 PM</td>
</tr>
<tr>
<td>V4</td>
<td>1</td>
<td>(0) 8:00:00 AM</td>
<td>(54.4)</td>
<td>(69.3)</td>
<td>(40.7)</td>
<td>(164.4) 10:44:24 AM</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>(224.4) 11:44:24 AM</td>
<td>(117.8)</td>
<td>(102.0)</td>
<td>(7.9)</td>
<td>(452.1) 3:32:06 PM</td>
</tr>
</tbody>
</table>

Moreover, Figure 4.1 shows the duration time of travelling time, unloading time, waiting time and re-loading time on the Gantt Chart to discover where the non-added value activity is occurred along the time sequence because the vehicles came before the opening time of each customer. It can describe the time windows affect the transportation problem.
Assumes that vehicle must travel to wait the opening time, which cannot stop the engine due to narrow lane, and the traffic rule in a city, so the waiting time has the fuel consumption expense, which can be computed by variable cost and speed to be the waiting cost. Hence, the V3 and V4 must include the waiting cost 26.78 baht and 91.85 baht, then the total operating cost will be changed from 6,139.1 baht to 6,257.73 baht. Although this problem is not quite significant (the operating cost difference is only 118.63 baht), the others may be shown the waiting time is higher than this instance led to increase the operating cost significantly.

4.1.2 Transportation problem under flexible departure time

As we mentioned that the more waiting time inside the time process, the lower vehicle performance will be occurred, so we try to reduce it by taking into account the vehicle’s waiting time into the objective model either.

After running the single optimization within 4,762.14 seconds and the sequential optimization within 118.50 seconds (68.75 and 49.75 seconds), which the optimal operating cost including the waiting time. The result shows that the utilized vehicle and routing are the same as Table 4.6 under optimum at 6,139.1 baht. From Table 4.7 shows the waiting time is not appeared throughout the routing obviously. However, all utilized vehicles work later than regular beginning time. MTVRPTW is allowed to be flexible departure time because of the starting time in trip 1: V3 is 8:12:24
a.m. (12.4 mins), V4 is 9:05:00 a.m. (65.0 mins), to get rid of the vehicle waiting, however, the travelling time and unloading time are still the same. Even though the time before beginning time does not use in this problem, it is useful to use another project instead of waiting period in this problem.

Table 4.7 Time schedule (mins.) under flexible departure time

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Trip</th>
<th>Starting time (mins)</th>
<th>Traveling time (mins)</th>
<th>Unloading time (mins)</th>
<th>Waiting time (mins)</th>
<th>Ending time (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V3</td>
<td>1</td>
<td>(12.4) 8:12:24 AM</td>
<td>(58.9)</td>
<td>(133.3)</td>
<td>(0)</td>
<td>(204.6) 11:24:36 AM</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>(264.6) 12:24:36 PM</td>
<td>(86.3)</td>
<td>(120.0)</td>
<td>(0)</td>
<td>(470.9) 3:50:54 PM</td>
</tr>
<tr>
<td>V4</td>
<td>1</td>
<td>(65.0) 9:05:00 AM</td>
<td>(54.4)</td>
<td>(69.3)</td>
<td>(0)</td>
<td>(188.7) 11:08:42 AM</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>(248.7) 12:08:42 PM</td>
<td>(117.8)</td>
<td>(102.0)</td>
<td>(0)</td>
<td>(468.5) 3:48:30 PM</td>
</tr>
</tbody>
</table>

So, we can conclude that transportation problem under flexible departure time (including waiting cost in objective) is better because it reduces the non-added value time 118.63 baht, which affects the operating cost from 6,139.1 baht to 6,257.73 baht. Even though the single optimization is run one time, but it has a computational time higher than sequential optimization around 40 times (4,762.14 and 118.5 seconds). So, the sequential optimization should be run instead of single optimization.

4.2 Worker assignment problem for the initial data.

In this section evaluates between pre-assignment and post-assignment comparison, pre-assignment can propose into 3 policies: (1) random pattern orders worker as mentioned
in Table 4.4, (2) low energy capacity workers to small vehicles orders as ascending pattern, and (3) low energy capacity workers to large vehicles arranges as descending pattern. The energy capacity of worker is combined to be the energy capacity of vehicle as shown in Table 4.8.

Table 4.8 The energy capacity in vehicle for pre-assignment (kcal/day)

<table>
<thead>
<tr>
<th>Policy</th>
<th>Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V1</td>
</tr>
<tr>
<td>(1) assign randomly</td>
<td>4,054</td>
</tr>
<tr>
<td>(2) assign low energy capacity workers to small vehicles</td>
<td>(W15, W19)</td>
</tr>
<tr>
<td></td>
<td>3,327</td>
</tr>
<tr>
<td></td>
<td>4,817</td>
</tr>
</tbody>
</table>

For the worker assignment, the workload will be acquired from the transportation solution, which is total operating cost 6,139.1 baht with no amount of waiting time. All of policies yield the same transportation because the energy expenditure of operated vehicle of all policies are not violated to energy capacity of operated vehicle as constraint (9). In our assumption, a vehicle must distribute energy expenditure (workload) to worker in the same team equally. Hence, The V3 totally has energy expenditure 4,560 kcal/day (2 mins a unit*6 kcal per min* 380 units of loads) to distribute into W5, W6 and W7 under random sequence, so each of them has 1,520 kcal/day. To evaluate the best policy, the percent residual in each worker will be formed as equation (32). For instance, W5 whose energy capacity is 2,234 kcal/day (From Table 4.4), who obtains the energy left 16.67% as shown in equation (33).
Percent residual energy in each worker (%PRE) = \( \frac{\text{Energy capacity} - \text{Energy expenditure}}{\text{Energy capacity}} \times 100 \) (32)

Percent residual energy in each worker (%PRE) = \( \frac{2,234 - 1,520}{2,234} \times 100 = 16.67\% \) (33)

Table 4.9 shows the performance of the random policy, W7 works harder than the others because the percent energy remaining is 30.08%. On the other hand, W10 works lighter than the others because the percent energy remaining is 53.63%. The different residual between the maximum and minimum among workers is 23.55%. The average of %PRE is 42.20%, and standard deviation of %PRE is 10.88%.

Table 4.9 Workload assignment in random policy

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Energy capacity (kcal/day)</th>
<th>Energy Expenditure (kcal/day)</th>
<th>Worker</th>
<th>Energy capacity (kcal/day)</th>
<th>Energy Expenditure (kcal/day)</th>
<th>%PRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>V3</td>
<td>6,753</td>
<td>4,560</td>
<td>W5</td>
<td>2,234</td>
<td>1,520</td>
<td>31.96%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W6</td>
<td>2,345</td>
<td>1,520</td>
<td>35.18%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W7</td>
<td>2,174</td>
<td>1,520</td>
<td>30.08%</td>
</tr>
<tr>
<td>V4</td>
<td>6,427</td>
<td>3,084</td>
<td>W8</td>
<td>2,109</td>
<td>1,028</td>
<td>51.26%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W9</td>
<td>2,101</td>
<td>1,028</td>
<td>51.07%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W10</td>
<td>2,217</td>
<td>1,028</td>
<td>53.63%</td>
</tr>
</tbody>
</table>

Table 4.10 shows the result of the second policy “assign low energy capacity workers to small vehicles”. W13 works harder than the others because the percent energy remaining is 20.96%. On the other hand, W3 works lighter than the others because the percent energy remaining is 52.43%. The difference between the maximum and minimum %PRE is 31.47%. The average %PRE is 38.37% with the standard deviation of 15.08%.
Table 4.10 Workload assignment in low energy capacity workers to small vehicles policy

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Energy capacity (kcal/day)</th>
<th>Energy Expenditure (kcal/day)</th>
<th>Worker</th>
<th>Energy capacity (kcal/day)</th>
<th>Energy Expenditure (kcal/day)</th>
<th>%PRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>V3</td>
<td>6,069</td>
<td>4,560</td>
<td>W13</td>
<td>1,923</td>
<td>1,520</td>
<td>20.96%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W20</td>
<td>2,045</td>
<td>1,520</td>
<td>25.67%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W9</td>
<td>2,101</td>
<td>1,520</td>
<td>27.65%</td>
</tr>
<tr>
<td>V4</td>
<td>6,424</td>
<td>3,084</td>
<td>W8</td>
<td>2,109</td>
<td>1,028</td>
<td>51.26%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W1</td>
<td>2,154</td>
<td>1,028</td>
<td>52.27%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W3</td>
<td>2,161</td>
<td>1,028</td>
<td>52.43%</td>
</tr>
</tbody>
</table>

Table 4.11 shows the result of the third policy “assign low energy capacity workers to large vehicles”. W5 works harder than the others because the percent energy remaining is 31.96%. On the other hand, W10 works lighter than the others because the percent energy remaining is 53.63%. The difference between the maximum and minimum %PRE is 21.67%. The average %PRE is 43.28% with the standard deviation of 10.79%.
Table 4.11 Workload assignment in low energy capacity workers to large vehicles policy

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Energy capacity (kcal/day)</th>
<th>Energy Expenditure (kcal/day)</th>
<th>Worker</th>
<th>Energy capacity (kcal/day)</th>
<th>Energy Expenditure (kcal/day)</th>
<th>%PRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>V3</td>
<td>6,858</td>
<td>4,560</td>
<td>W17</td>
<td>2,341</td>
<td>1,520</td>
<td>35.07%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W12</td>
<td>2,283</td>
<td>1,520</td>
<td>33.42%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W5</td>
<td>2,234</td>
<td>1,520</td>
<td>31.96%</td>
</tr>
<tr>
<td>V4</td>
<td>6,574</td>
<td>3,084</td>
<td>W10</td>
<td>2,217</td>
<td>1,028</td>
<td>53.63%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W4</td>
<td>2,183</td>
<td>1,028</td>
<td>52.91%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W7</td>
<td>2,174</td>
<td>1,028</td>
<td>52.71%</td>
</tr>
</tbody>
</table>

For post-assignment, even though this policy used average available worker and number of worker instead of the actual energy capacity of vehicle, the transportation solution is identical to pre-assignment. After that, it executed the worker assignment model to select the worker to vehicle within 0.03 secs. The solution will show in Table 4.12, which express the result of the fourth policy “post-assignment”. W2 works harder than the others because the percent energy remaining is 20.00%. On the other hand, W11 works lighter than the others because the percent energy remaining is 39.24%. The difference between the maximum and minimum %PRE is 19.24%. The average %PRE is 31.79% with the standard deviation of 8.00%.
### Table 4.12 Workload assignment in post-assignment policy

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Energy capacity (kcal/day)</th>
<th>Energy Expenditure (kcal/day)</th>
<th>Worker</th>
<th>Energy capacity (kcal/day)</th>
<th>Energy Expenditure (kcal/day)</th>
<th>%PRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>V3</td>
<td>6,099</td>
<td>4,560</td>
<td>W1</td>
<td>2,154</td>
<td>1,520</td>
<td>29.43%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W2</td>
<td>1,900</td>
<td>1,520</td>
<td>20.00%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W20</td>
<td>2,045</td>
<td>1,520</td>
<td>25.67%</td>
</tr>
<tr>
<td>V4</td>
<td>5,019</td>
<td>3,084</td>
<td>W11</td>
<td>1,692</td>
<td>1,028</td>
<td>39.24%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W15</td>
<td>1,648</td>
<td>1,028</td>
<td>37.62%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W19</td>
<td>1,679</td>
<td>1,028</td>
<td>38.77%</td>
</tr>
</tbody>
</table>

#### 4.3 Result and Discussion for the initial data

As we launched the initial data, the vehicle routing will affect to select which policy will be implemented because we have to determine the workload of operated vehicle firstly from transportation problem, then distribute to worker who will be chosen from the available delivery worker.

After we solve the transportation problem into sequential optimization because whose computational time is lower than single optimization under the same result. It can conclude that the vehicle routing does not affect among policies. The operating costs is the same at 6,139.1 baht under the utilized vehicles: V3 and V4, six employed workers, and workload of each vehicle is the same to serve products to twelve customers because all policies subject to whose energy capacity of vehicle is sufficient to energy expenditure within the minimum operating cost.

Table 4.13 shows the performance comparison among four policies. Initially, we can conclude that the second policy is the worst under this problem because the highest value of S.D. %PRE and the difference between the maximum and minimum %PRE are 15.08% and 31.47% respectively. Later, the first policy and the third policy are not quite different, which the worker who works the lightest is the same person (W10) with energy left 53.63%; the worker who works the hardest is different a bit with.
energy left 30.08% in the first policy and 31.96% in the third policy, but these policies are still worse because of higher S.D. and max-min difference: the first policy: 10.88% and 23.55%, the third policy: 10.79% and 21.67% respectively. So, the post-assignment policy is the best in workload fairness with S.D. and max-min difference 8.00% and 19.24%.

Table 4.13 Percent residual energy among policies comparison

<table>
<thead>
<tr>
<th>Policy</th>
<th>Maximum %PRE</th>
<th>Minimum %PRE</th>
<th>The difference between the maximum and minimum %PRE</th>
<th>Average %PRE</th>
<th>Standard deviation %PRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) random</td>
<td>53.63%</td>
<td>30.08%</td>
<td>23.55%</td>
<td>42.20%</td>
<td>10.88%</td>
</tr>
<tr>
<td>(2) low energy capacity workers to small vehicles</td>
<td>52.43%</td>
<td>20.96%</td>
<td>31.47%</td>
<td>38.37%</td>
<td>15.08%</td>
</tr>
<tr>
<td>(3) low energy capacity workers to large vehicles</td>
<td>53.63%</td>
<td>31.96%</td>
<td>21.67%</td>
<td>43.28%</td>
<td>10.79%</td>
</tr>
<tr>
<td>(4) post-assignment</td>
<td>39.24%</td>
<td>20.00%</td>
<td>19.24%</td>
<td>31.79%</td>
<td>8.00%</td>
</tr>
</tbody>
</table>
4.4  Worker assignment problem for the nine small data sets

The overall small data information is determined as mentioned earlier, which will be varied due to demand and load capacity only. However, Table 4.14-4.15 show the precise information that we provide. (D1 refers to demand set 1, L1 refer to load capacity set 1)

Table 4.14 Customer demand (units) data of three sets

<table>
<thead>
<tr>
<th>Set</th>
<th>D</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
<th>C7</th>
<th>C8</th>
<th>C9</th>
<th>C10</th>
<th>C11</th>
<th>C12</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1</td>
<td>0</td>
<td>65</td>
<td>52</td>
<td>76</td>
<td>80</td>
<td>28</td>
<td>64</td>
<td>72</td>
<td>36</td>
<td>44</td>
<td>56</td>
<td>40</td>
<td>24</td>
</tr>
<tr>
<td>D2</td>
<td>0</td>
<td>76</td>
<td>44</td>
<td>46</td>
<td>53</td>
<td>11</td>
<td>115</td>
<td>40</td>
<td>66</td>
<td>56</td>
<td>60</td>
<td>36</td>
<td>129</td>
</tr>
<tr>
<td>D3</td>
<td>0</td>
<td>91</td>
<td>35</td>
<td>186</td>
<td>44</td>
<td>50</td>
<td>18</td>
<td>115</td>
<td>3</td>
<td>3</td>
<td>67</td>
<td>175</td>
<td>105</td>
</tr>
</tbody>
</table>

Table 4.15 The load capacity (units) data of three sets

<table>
<thead>
<tr>
<th>Set</th>
<th>V1</th>
<th>V2</th>
<th>V3</th>
<th>V4</th>
<th>V5</th>
<th>V6</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>100</td>
<td>100</td>
<td>200</td>
<td>200</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>L2</td>
<td>150</td>
<td>150</td>
<td>300</td>
<td>300</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>L3</td>
<td>200</td>
<td>200</td>
<td>400</td>
<td>400</td>
<td>600</td>
<td>600</td>
</tr>
</tbody>
</table>

Reminds that the list is ordered as D1L1, D1L2, D1L3, D2L1, D2L2, D2L3, D3L1, D3L2, D3L3 respectively.

Finally, we run all the nine data. Although the transportation solution will be differed among data sets, the vehicle routing still does not affect among policies in the same data except the ninth data, which the second policy is changed.

For the ninth data, the operating cost in pre-assignment of random assignment and low energy to large vehicle assignment with post-assignment are 6,346.25 baht. However, low energy to small vehicle assignment is 6,360.85 (only V3 is the same routing among policies) as shown in Figure A.A.9. Moreover, the running time of single optimization and sequential optimization among data and policies are shown in Table 4.16 and Table 4.17 respectively of second unit. Noted that the post-assignment is
applied in two models, nevertheless, the worker assignment model is not significant to impact the computational time.

Table 4.16 The computational time of single optimization (sec.)

<table>
<thead>
<tr>
<th>Small Data</th>
<th>Single Obj.</th>
<th>Pre-assignment</th>
<th>Post-assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model1 Transportation</td>
<td>(1) assign randomly</td>
<td>4762.14</td>
<td>4762.14</td>
</tr>
<tr>
<td></td>
<td>(2) assign low energy capacity workers to small vehicles</td>
<td>4762.14</td>
<td>4762.14</td>
</tr>
<tr>
<td></td>
<td>(3) assign low energy capacity workers to large vehicles</td>
<td>4762.14</td>
<td>4762.14</td>
</tr>
<tr>
<td></td>
<td>(4) Post-assignment</td>
<td>4762.14</td>
<td>4762.14</td>
</tr>
<tr>
<td>Model1 Transportation</td>
<td></td>
<td>19086.86</td>
<td>19086.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td>19086.86</td>
<td>19086.86</td>
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<tr>
<td></td>
<td></td>
<td>7434.23</td>
<td>7434.23</td>
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<td>7434.23</td>
<td>7434.23</td>
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<td></td>
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<td>2769.41</td>
<td>2769.41</td>
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<td>2769.41</td>
<td>2769.41</td>
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<td></td>
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<td>3236.50</td>
<td>3236.50</td>
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<td>3236.50</td>
<td>3236.50</td>
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<td></td>
<td>2634.81</td>
<td>2634.81</td>
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<tr>
<td></td>
<td></td>
<td>693.53</td>
<td>693.53</td>
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<td></td>
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<td>693.53</td>
<td>693.53</td>
</tr>
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<td></td>
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<td>5134.59</td>
<td>5134.59</td>
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<td></td>
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<td>2889.55</td>
<td>2889.55</td>
</tr>
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<td></td>
<td></td>
<td>2889.55</td>
<td>2889.55</td>
</tr>
<tr>
<td>avg</td>
<td>4470.608</td>
<td>4788.38</td>
<td>4470.61</td>
</tr>
</tbody>
</table>
Table 4.17 The computational time of sequential optimization (sec.)

<table>
<thead>
<tr>
<th>Small Data</th>
<th>Sequential Obj.</th>
<th>Pre-assignment</th>
<th>Post-assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1) assign randomly</td>
<td>(2) assign low energy capacity workers to small vehicles</td>
<td>(3) assign low energy capacity workers to large vehicles</td>
</tr>
<tr>
<td>Seq1</td>
<td>Seq2</td>
<td>Seq1</td>
<td>Seq2</td>
</tr>
<tr>
<td>1</td>
<td>68.75</td>
<td>49.75</td>
<td>68.75</td>
</tr>
<tr>
<td>2</td>
<td>485.06</td>
<td>146.8</td>
<td>485.06</td>
</tr>
<tr>
<td>3</td>
<td>122.55</td>
<td>179.83</td>
<td>122.55</td>
</tr>
<tr>
<td>4*</td>
<td>180.08</td>
<td>135.45</td>
<td>180.08</td>
</tr>
<tr>
<td>5*</td>
<td>105.63</td>
<td>101.14</td>
<td>105.63</td>
</tr>
<tr>
<td>6*</td>
<td>262.98</td>
<td>42.39</td>
<td>262.98</td>
</tr>
<tr>
<td>7</td>
<td>78.91</td>
<td>6.44</td>
<td>78.91</td>
</tr>
<tr>
<td>8*</td>
<td>77.66</td>
<td>147.55</td>
<td>77.66</td>
</tr>
<tr>
<td>9*</td>
<td>71.59</td>
<td>237.89</td>
<td>71.59</td>
</tr>
<tr>
<td>avg</td>
<td>132.94</td>
<td>91.28</td>
<td>133.69</td>
</tr>
<tr>
<td>Total avg</td>
<td>224.22</td>
<td>217.40</td>
<td>224.22</td>
</tr>
</tbody>
</table>

Noted that the asterisk (*) after number of data. It means the solution is changed between sequential optimization.

The nine data are obtained the same result in both approach, so, we can select which technique should be implemented by the running time. The computation comparison can conclude that the sequential optimization should be launched because its running time is faster than single optimization around 20 times in average of all nine data.

In term of selecting the policy, we construct the performance comparison among policies and among data sets. Table 4.18-4.19 show the S.D. %PRE, and the maximum and minimum %PRE difference, which both imply the level of fairness (the higher is unfairness). Table 4.17 implies that post-assignment is the best policy because the 8 data sets out of 9 have the lowest value of S.D. clearly excepts the third data is chose the random assignment. Also, the average S.D. among data is only 5.00%.
Table 4.18 The S.D. %PRE among policies and data sets

<table>
<thead>
<tr>
<th>S.D. (%PRE)</th>
<th>Pre-assignment</th>
<th>Post-assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1) assign randomly</td>
<td>(2) assign low energy capacity workers to small vehicles</td>
</tr>
<tr>
<td>Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>10.9%</td>
<td>15.1%</td>
</tr>
<tr>
<td>2</td>
<td>7.0%</td>
<td>10.9%</td>
</tr>
<tr>
<td>3</td>
<td>3.7%</td>
<td>5.1%</td>
</tr>
<tr>
<td>4</td>
<td>16.0%</td>
<td>14.3%</td>
</tr>
<tr>
<td>5</td>
<td>10.8%</td>
<td>14.8%</td>
</tr>
<tr>
<td>6</td>
<td>6.7%</td>
<td>3.3%</td>
</tr>
<tr>
<td>7</td>
<td>6.9%</td>
<td>7.1%</td>
</tr>
<tr>
<td>8</td>
<td>11.5%</td>
<td>16.0%</td>
</tr>
<tr>
<td>9</td>
<td>12.3%</td>
<td>17.4%</td>
</tr>
<tr>
<td>avg</td>
<td>9.5%</td>
<td>11.6%</td>
</tr>
</tbody>
</table>

Table 4.19 also implies the post-assignment is the best because the eight data sets out of nine have the lowest maximum and minimum difference (to compare between the worker who works the lightest and the highest) with average among data is 12.7%

Table 4.19 The maximum and minimum %PRE difference among policies and data sets

<table>
<thead>
<tr>
<th>Max-Min (%PRE)</th>
<th>Pre-assignment</th>
<th>Post-assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1) assign randomly</td>
<td>(2) assign low energy capacity workers to small vehicles</td>
</tr>
<tr>
<td>Data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>23.5%</td>
<td>31.5%</td>
</tr>
<tr>
<td>2</td>
<td>16.3%</td>
<td>23.6%</td>
</tr>
<tr>
<td>3</td>
<td>8.9%</td>
<td>11.8%</td>
</tr>
<tr>
<td>4</td>
<td>37.0%</td>
<td>32.9%</td>
</tr>
<tr>
<td>5</td>
<td>26.2%</td>
<td>38.2%</td>
</tr>
<tr>
<td>6</td>
<td>15.6%</td>
<td>8.5%</td>
</tr>
<tr>
<td>7</td>
<td>20.7%</td>
<td>18.7%</td>
</tr>
</tbody>
</table>
For summary in term of the average %PRE in Table 4.20, its average all of data is collected that the third data is better than the others due to the highest of energy remaining at 41.8%. It implies that the overall employed worker work lower than other policies, however; we should consider the S.D. and maximum and minimum difference instead of average because the fairness among workers is important than overall picture; no one prefers working than the others. Also, the data can prove while returning the Table 4.17-4.18. Those tables state that the third policy and post-assignment policy difference at 3.5% in S.D., 6.2% in Max-Min difference.

Table 4.20 the average %PRE among policies and data sets

<table>
<thead>
<tr>
<th>Data</th>
<th>(1) assign randomly</th>
<th>(2) assign low energy capacity workers to small vehicles</th>
<th>(3) assign low energy capacity workers to large vehicles</th>
<th>(4) post-assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42.2%</td>
<td>38.4%</td>
<td>43.3%</td>
<td>31.8%</td>
</tr>
<tr>
<td>2</td>
<td>42.1%</td>
<td>38.5%</td>
<td>43.2%</td>
<td>31.4%</td>
</tr>
<tr>
<td>3</td>
<td>29.1%</td>
<td>18.2%</td>
<td>34.4%</td>
<td>13.4%</td>
</tr>
<tr>
<td>4</td>
<td>48.7%</td>
<td>44.6%</td>
<td>51.5%</td>
<td>44.0%</td>
</tr>
<tr>
<td>5</td>
<td>42.0%</td>
<td>31.9%</td>
<td>46.3%</td>
<td>33.6%</td>
</tr>
<tr>
<td>6</td>
<td>33.2%</td>
<td>29.7%</td>
<td>34.5%</td>
<td>19.2%</td>
</tr>
<tr>
<td>7</td>
<td>43.5%</td>
<td>40.8%</td>
<td>46.8%</td>
<td>38.6%</td>
</tr>
<tr>
<td>8</td>
<td>37.4%</td>
<td>31.1%</td>
<td>41.4%</td>
<td>29.7%</td>
</tr>
<tr>
<td>9</td>
<td>28.8%</td>
<td>16.2%</td>
<td>34.7%</td>
<td>19.7%</td>
</tr>
<tr>
<td>avg</td>
<td>38.5%</td>
<td>32.1%</td>
<td>41.8%</td>
<td>29.0%</td>
</tr>
</tbody>
</table>

Therefore, it can conclude that the post-assignment is the best within provided nine data sets. Even though the overall picture (the post-assignment’s average %PRE is obtained the lowest energy left) illustrates that they work hard than other policies, but it will not be fair when we realize the overall picture replaced to individual worker.
**Chapter 5**

**Computational Experiment**

This section extends the number of customer with fixed number of vehicle and worker to observe the limitation of IBM ILOG CPLEX Optimization program. It is run only the transportation problem because the computational time in the worker assignment is not significant at 0.03 seconds. So, Table 5.1 states the comparison of the solutions among single and sequential optimization for MTVRPTW-MMH, where the number of customer (NC) is gradually increased, number of available (NV) and utilized vehicles (NV use), cost, waiting time (WT), waiting cost (WC), starting time of each utilized vehicle (ST), and computational time. Reader must remind that the cost in sequential optimization 1 is considered only the fixed and variable cost. So, it must include the waiting cost to obtain the total operating cost, however, it should be run until sequential optimization 2 to yield as solution as single optimization.

Table 5.1 the comparison of the solutions among single and sequential optimization

<table>
<thead>
<tr>
<th>No.</th>
<th>Solution Approach</th>
<th>NC</th>
<th>NV (use)</th>
<th>Cost (baht)</th>
<th>WT (min) (WC (baht))</th>
<th>ST (min)</th>
<th>Computational Time (sec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Single Opt.</td>
<td>9</td>
<td>6(3:1,3,5)</td>
<td>8,686</td>
<td>0</td>
<td>(0,29.6,207)</td>
<td>14(Opt.)</td>
</tr>
<tr>
<td></td>
<td>Seq Opt1 Seq Opt2</td>
<td></td>
<td>6(3:1,3,5)</td>
<td>8,686</td>
<td>330.1(785.5)</td>
<td>(0,0,0)</td>
<td>3(Opt.) 0.89(Opt.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6(3:1,3,5)</td>
<td>8,686</td>
<td>0</td>
<td>(0,29.6,207)</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>Single Opt.</td>
<td>15</td>
<td>6(3:1,3,5)</td>
<td>*9,017.7</td>
<td>0</td>
<td>(120,28,26)</td>
<td>*18,000(56.14%)</td>
</tr>
<tr>
<td></td>
<td>Seq Opt1 Seq Opt2</td>
<td></td>
<td>6(3:1,3,4)</td>
<td>7,737.8</td>
<td>218.4(405.6)</td>
<td>(0,0,0)</td>
<td>29.368(Opt.) *23,054(--)%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P3</td>
<td>Single Opt.</td>
<td>15</td>
<td>6(3:1,3,5)</td>
<td>*8,769.0</td>
<td>0</td>
<td>(87.4,151.3,0.5)</td>
<td>*18,000(66.90%)</td>
</tr>
<tr>
<td></td>
<td>Seq Opt1 Seq Opt2</td>
<td></td>
<td>6(3:1,3,4)</td>
<td>*7,650.9</td>
<td>138.5(266.6)</td>
<td>(0,0,0)</td>
<td>*18,000(29.74%)</td>
</tr>
</tbody>
</table>
In the three test problems, the nine-customer data (P1) is obtain the optimal solution among two approaches within running quickly. Moreover, the fifteen-customer data (P2-P3) have the asterisk (*) imposed that Cplex program is interrupted after exceeding the five hours computational time limit, so, these instances are not obtained the optimum excepts the data P2 in sequential optimization phase 1, which got optimality within 8 hours, however, in phase 2 cannot find the solution. Noted that the number insides the parenthesis express the running percent left in program.

Hence, it should apply the heuristic or the metaheuristic algorithms, which are technique designed help to solve the unsolved problem. Although the solution will be not optimum, however, the solution will obtain the near optimality under reasonable time so that the realistic practice promptly decides what is the best solution to response the customer needs as fast as they can.
Chapter 6
Conclusions and Recommendations

6.1 Conclusions
This research studies the Multiple Trip Vehicle Routing Problem with Time Windows and Manual Material Handling (MTVRPTW-MMH). The company has different vehicle sizes to serve a single product from one depot to many customer locations. Moreover, it does not only consider the routing and the number of utilized vehicles but also concern on the ergonomic side of workers who has his own individual energy capacity. Specifically, we analyze the workload fairness under different worker assignment policies.

We express the single optimization and the sequential optimization in transportation problem, which two method approach require to minimize fixed, variable and waiting costs using a Mixed Integer Linear Programming (MILP). Also, the model is coded and run by IBM ILOG CPLEX Optimization program.

The three pre-assignment policies and a post-assignment policy are analyzed: (1) random assignment, (2) low energy capacity workers to small vehicles assignment, (3) low energy capacity workers to large vehicles assignment, and (4) post-assignment, which only one policy is run in the worker assignment model.

The result shows that two methods are obtained the same solution, so, the sequential optimization is the best technique to implement because its running time is faster than single optimization around 20 times in average of small instances.

The standard deviation of percent residual energy of worker (%PRE), the maximum and minimum %PRE (those indicate the level of fairness; the lowest is workload fairness) and the average %PRE (it illustrates the overall picture; the highest is the lowest working) are evaluated to select policy.

The results show that post-assignment and low energy capacity workers to large vehicles assignment (or it is called the third policy) are closer in S.D. %PRE with 5.0% and 8.5% and Max-Min %PRE with 12.7% and 18.9% respectively within nine data sets. Apart from that post-assignment is the lowest at 29.0% and the third policy is the
highest at 41.8% in average %PRE. However, the average %PRE cannot be a good indicator conclusion because it will not be fair if we concern the overall picture to be representative. So, we should use the S.D. %PRE and Max-Min %PRE to obtain the workload fairness among employed worker. Then, the post-assignment policy is the best to implement because it tends to assign workload fairly and evenly among worker because the energy remaining is less different among workers.

6.2 Recommendations

Besides, the transportation problem can be developed to cope the uncertain situation as the changed business model to be a practical such as contributing the soft time windows VRP, the pick and delivery VRP, the multiple depot, and so on.
Chapter 7
Significant of Study

The results obtained the multi-trip with time windows vehicle routing problem and manual materials handling (MTVRPTW-MMH) in which contributed both academic field and industry field.

1) Academic sector

Mathematical model is very likely to be enhanced new knowledge involved in Operation Research, Transportation Management, Logistics and Supply Chain and Safety Engineering.

2) Industrial sector

This study help decreases operation cost under customer’s time interval in transportation aspect. Aside from that, it helps decision maker plan a process of hiring workers who is suitable with workload of each utilized vehicle. Because of the unfair distribution, the complaint may arise simply from the worker’s opinion that the company assign them to work to the point of illness, exhaustion, chronic pain or mental health problem. Even though the concept of individual energy of worker does not pay serious attention to choose worker to vehicle, this research can be the beginning of two collaboration between cost reduction in logistics terms and ergonomic consideration.
References


Appendix
Appendix A

The workload assignment for nine data sets.

<table>
<thead>
<tr>
<th>Pre-random</th>
<th>Max-Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>ECK</td>
</tr>
<tr>
<td>V3</td>
<td>6,753</td>
</tr>
<tr>
<td>W6</td>
<td>2345</td>
</tr>
<tr>
<td>W7</td>
<td>2174</td>
</tr>
<tr>
<td>V4</td>
<td>6,427</td>
</tr>
<tr>
<td>W9</td>
<td>2101</td>
</tr>
<tr>
<td>W10</td>
<td>2,217</td>
</tr>
<tr>
<td>Avg(%PRE)</td>
<td>S.D.(%PRE)</td>
</tr>
<tr>
<td>23.55%</td>
<td>11%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pre-second</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>ECK</td>
</tr>
<tr>
<td>V3</td>
<td>6069</td>
</tr>
<tr>
<td>W20</td>
<td>2,045</td>
</tr>
<tr>
<td>W9</td>
<td>2,101</td>
</tr>
<tr>
<td>V4</td>
<td>6,424</td>
</tr>
<tr>
<td>W1</td>
<td>2,154</td>
</tr>
<tr>
<td>W3</td>
<td>2,161</td>
</tr>
<tr>
<td>Avg(%PRE)</td>
<td>31.47%</td>
</tr>
<tr>
<td>S.D.(%PRE)</td>
<td>15%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pre-third</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>ECK</td>
</tr>
<tr>
<td>V3</td>
<td>6,858</td>
</tr>
<tr>
<td>W12</td>
<td>2,283</td>
</tr>
<tr>
<td>V4</td>
<td>6,574</td>
</tr>
<tr>
<td>W10</td>
<td>2,217</td>
</tr>
<tr>
<td>W7</td>
<td>2,174</td>
</tr>
<tr>
<td>Avg(%PRE)</td>
<td>21.67%</td>
</tr>
<tr>
<td>S.D.(%PRE)</td>
<td>11%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Post</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>ECK</td>
</tr>
<tr>
<td>V3</td>
<td>4,560</td>
</tr>
<tr>
<td>W2</td>
<td>1,900</td>
</tr>
<tr>
<td>W20</td>
<td>2,045</td>
</tr>
<tr>
<td>V4</td>
<td>3,084</td>
</tr>
<tr>
<td>W15</td>
<td>1,648</td>
</tr>
<tr>
<td>W19</td>
<td>1,679</td>
</tr>
<tr>
<td>Avg(%PRE)</td>
<td>19.24%</td>
</tr>
<tr>
<td>S.D.(%PRE)</td>
<td>8%</td>
</tr>
</tbody>
</table>

Figure A.A.1 The workload assignment in data 1
<table>
<thead>
<tr>
<th>Vehicle</th>
<th>ECK</th>
<th>EEk</th>
<th>Worker</th>
<th>Ecl</th>
<th>EEl</th>
<th>%PRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-random</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16.26%</td>
</tr>
<tr>
<td>V3</td>
<td>6753.0</td>
<td>4320</td>
<td>W5</td>
<td>2234</td>
<td>1440</td>
<td>35.54%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W6</td>
<td>2345</td>
<td>1440</td>
<td>38.59%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W7</td>
<td>2174</td>
<td>1440</td>
<td>33.76%</td>
</tr>
<tr>
<td>V4</td>
<td>6427.0</td>
<td>3324</td>
<td>W8</td>
<td>2109</td>
<td>1108</td>
<td>47.46%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W9</td>
<td>2101</td>
<td>1108</td>
<td>47.26%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>W10</td>
<td>2217</td>
<td>1108</td>
<td>50.02%</td>
</tr>
</tbody>
</table>

| Pre-second |     |     |        |     |     | 23.61% |
| V3         | 6069.0 | 4320 | W13    | 1923 | 1440 | 25.12% |
|            |        |     | W20    | 2045 | 1440 | 29.58% |
|            |        |     | W9     | 2101 | 1440 | 31.46% |
| V4         | 6424.0 | 3324 | W8     | 2109 | 1108 | 47.46% |
|            |        |     | W1     | 2154 | 1108 | 48.56% |
|            |        |     | W3     | 2161 | 1108 | 48.73% |

| Pre-third |     |     |        |     |     | 14.48% |
| V3         | 6858.0 | 4320 | W17    | 2341 | 1440 | 38.49% |
|            |        |     | W12    | 2283 | 1440 | 36.93% |
|            |        |     | W5     | 2234 | 1440 | 35.54% |
| V4         | 6574.0 | 3324 | W10    | 2217 | 1108 | 50.02% |
|            |        |     | W4     | 2183 | 1108 | 49.24% |
|            |        |     | W7     | 2174 | 1108 | 49.03% |

| Post |     |     |        |     |     | 10.30% |
| V3   | 4320 |     | W1     | 2154 | 1440 | 33.15% |
|      |      |     | W2     | 1900 | 1440 | 24.21% |
|      |      |     | W20    | 2045 | 1440 | 29.58% |
| V4   | 3324 |     | W11    | 1692 | 1108 | 34.52% |
|      |      |     | W15    | 1648 | 1108 | 32.77% |
|      |      |     | W19    | 1679 | 1108 | 34.01% |

Figure A.A.2 The workload assignment in data 2
<table>
<thead>
<tr>
<th>Vehicle</th>
<th>EClk</th>
<th>EElk</th>
<th>Worker</th>
<th>Ecl</th>
<th>EEl</th>
<th>%PRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-random</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V1</td>
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Figure A.A.4 The workload assignment in data 4
Figure A.A.5 The workload assignment in data 5
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Figure A.A.6 The workload assignment in data 6
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40.81% 7%

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46.84% 7%

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Figure A.A.7 The workload assignment in data 7

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Figure A.A.8 The workload assignment in data 8

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<th>Worker</th>
<th>Ecl</th>
<th>EEI</th>
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<td>W16</td>
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<tr>
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<td>W12</td>
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%PRE: 14.4%

### Post

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<th>Worker</th>
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%PRE: 8.7%

Figure A.A.9 The workload assignment in data 9

53