DEVELOP A CAPACITATED VEHICLE ROUTING MODEL WITH TIME WINDOWS FOR COLD CHAIN LOGISTICS USING OPENSOLVER

BY

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ABSTRACT

Cold Chain Logistics (CCL) is a critical aspect of supply chain management for industries that handle temperature-sensitive products, especially aquatic products. However, challenges related to transportation cost, cluster infrastructure, and temperature control requirements must be addressed. This study developed a customized CVRPTW model to improve distribution network efficiency and minimize the cost by using OpenSolver. The model was evaluated using real-world data from a Thai cold chain logistics company. The results demonstrated that the model significantly reduced total costs, the number of trucks required, and routing for each truck. These findings highlight the potential of VRP models to optimize cold chain logistics.

Keywords: VRP, Cold Chain, Freight Transport, Optimization, Logistics, Quality

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LIST OF SYMBOLS/ABBREVIATIONS

Symbols/Abbreviations	Terms
CAGR	Compound Annual Growth Rate
CCL	Cold Chain Logistic
CCP	Cold Chain Product
DC	Distribution Center
OSRM	Open-Source Routing Machine
SCM	Supply Chain Management
VRP	Vehicle Routing Problem
CVRPTW	Capacitated Vehicle Routing Problem with Time Window

CHAPTER 1
INTRODUCTION

In today's dynamic industries, the incorporation of modern technologies and technological advances is critical to maximizing profits and improving work efficiency across multiple sectors. Supply Chain Management (SCM), which coordinates interconnected chains aimed at meeting customer demands smoothly, is at the forefront of this technological evolution (Fernando, n.d.). SCM encompasses purchasing, manufacturing, storage, distribution, and delivery, forming the foundation for efficient and responsive business operations.

Cold Chain Logistics (CCL) is an important part of supply chain management, especially in industries that handle expiring goods like food, pharmaceuticals, and certain chemicals. CCL focuses on keeping products at a suitable temperature to maintain their shelf life during the supply chain process. Despite the high costs associated with CCL, the industry has experienced significant growth, with the global cold chain logistics market projected to grow at a significant compound annual growth rate (CAGR) of 15.1% from 2021 to 2028, driven by changes in social structures, consumer habits, and increased global concerns about product safety and quality (Bio, 2023). Thailand's cold chain industry has grown significantly, emphasizing its economic importance. The country's freight and logistics market are expected to grow at a CAGR of 6.37% between 2023 and 2029 (Mordor Intelligence, n.d.). Rising consumer expectations, supply chain globalization, and stringent regulatory requirements have all contributed to an increase in demand for efficient cold chain solutions (Prapinit, Sabar, & Melan, 2019; Boonlua, 2019; Bandoophanit, Sangpukdee, Kaengaew, & Chotkawee, 2023).

The Vehicle Routing Problem (VRP), which focuses on routing optimization, is a key challenge in logistics, particularly for trucks seeking the most effective routes for product delivery. VRP is a widely used algorithm in the cold chain market, helping businesses manage the number of trucks on the road, and thereby avoiding higher fixed costs, maintenance costs, and other expenses (Pamuar, Petrovi, & irovi, 2018). Specifically, the Vehicle Routing Problem with Time Windows (VRPTW) is crucial in cold chain logistics as it ensures that transportation routes are strategically planned to minimize costs and energy consumption while meeting strict temperature requirements for perishable goods and customer satisfaction (Pureza, Morabito, & Reimann, 2012).

The main objective of this independent study is to create and implement a customized CVRPTW model to reduce total costs within the context of cold chain management. This study aims to improve the efficiency of the distribution network by considering factors such as procurement and storage. It focuses on providing a practical and efficient approach to cold chain logistics by leveraging Excel OpenSolver to optimize algorithms and sustainable transportation solutions. This tool ensures that the method is accessible and easy to use for a wide audience, addressing the unique challenges in the transportation of aquatic goods across Thailand's provinces. By tackling these issues, this study intends to contribute valuable knowledge and solutions that align with current trends and requirements in the cold chain industry, particularly within the context of retail businesses.

This independent study paper will be structured into approximately six sections. Section 2 will explore the economic importance and growth of the cold chain industry, and the application of VRP and VRPTW in CCL, including relevant previous research. Section 3 will detail the specific objectives, mathematical model, and OpenSolver. Section 4 will present a concise overview of the algorithm's results. Section 5 will provide the conclusion, and Section 6 will include a discussion and suggestions for future work.

CHAPTER 2
REVIEW OF LITERATURE

2.1 Cold Chain Logistic

Cold chain logistics involves the transportation and storage of temperature-sensitive products, such as perishable foods, pharmaceuticals, and other goods requiring controlled environmental conditions. The primary objective is to maintain product integrity and quality from origin to destination. Maintaining the required temperature throughout the supply chain is crucial for preventing spoilage and ensuring safety. Challenges include temperature fluctuations, equipment failures, and handling delays. The complexity increases when different products require varying temperature settings.

Advancements in technology, such as real-time temperature monitoring, insulated packaging, and refrigerated transportation units, have significantly improved cold chain logistics. For instance, Chen, Liu, and Langevin (2019) highlight the importance of multi-compartment vehicles that can carry goods at different temperatures, optimizing the distribution process for various perishable items. In a similar study, researchers examined how changes in surrounding temperature and storage temperature impact the quality of seafood (Yue et al., 2013). They identified three types of water temperature variation: constant, continuous fluctuations, and non-continuous fluctuations. They also found that the outside temperature affects how much energy is needed to keep the truck cool, which can increase the overall cost.

Researchers have also studied how often the truck doors are opened during transport. This is important because it can both damage the products and raise the temperature inside the truck. Zhang et al. (2018) did experiments with a refrigerated truck to see how opening doors in different places and the number of times affects how stable the temperature stays inside.

Optimizing cold chain logistics not only ensures product quality but also reduces economic losses due to spoilage and decreases environmental impact by improving energy efficiency. Li et al. (2020) emphasizes the use of green logistics practices, which aim to minimize the carbon footprint of transportation activities.

2.2 Vehicle Routing Problem in Cold Chain Logistic

The Vehicle Routing Problem (VRP) is a fundamental issue in logistics, aiming to determine the most efficient routes for a fleet of vehicles delivering goods to various locations. When applied to cold chain logistics, VRP must consider additional constraints such as temperature control and compartmentalization (Chen et al., 2019). Several models and algorithms have been developed to address VRP in the context of cold chain logistics. Chen, Liu, and Langevin (2019) developed a multi-compartment VRP model that optimizes routes based on different temperature requirements. Similarly, Leelertkij, Parthanadee, and Buddhakulsomsiri (2021) introduced a transshipment model to enhance efficiency by allowing goods transfer between vehicles at intermediate points.

Heuristic and metaheuristic approaches, such as those proposed by Guo, Huang, and Huang (2021), provide practical solutions to complex VRP instances by approximating optimal solutions within reasonable computational times. These methods are particularly useful for handling constraints like incompatible loading and split deliveries. Yildirim and Kuvvetli (2021) and Li et al. (2020) explored hybrid and genetic algorithms to solve capacitated and heterogeneous fleet VRPs. These algorithms combine various optimization techniques to improve solution quality and computational efficiency, addressing the complexities of cold chain logistics.

Several studies, such as those by Syahputra et al. (2018) and Singhtaun and Piyapornthana (2022), provide practical applications and case studies demonstrating the effectiveness of these models and algorithms in real-world scenarios. These applications highlight the improvements in route efficiency, cost reduction, and overall performance of cold chain logistics operations.

The optimization of cold chain logistics, particularly with vehicle routing problem (VRP) methodologies, is a critical area of research. Various models and algorithms have been developed to address the unique challenges presented by cold chain logistics, such as maintaining specific temperature ranges and managing heterogeneous fleets. Below is a summary of key studies in the field.

Table 2.1 Related works

Authors	Model	Objective function			Methodology		Tool
		Min distance	Min cost	Min Carbon	Small Problem	Cold Chain Logistic	
Chen, L. (2019)	MC-VRPWT	✓				✓	CPLEX
Guo, F. et al. (2021)	VRPILC-SDO		✓			✓	CPLEX
Yildirim, U. (2021)	OVRP		✓		✓		Taguchi
Leelertkij et al. (2021)	VRP		✓				MILP
Li et al. (2020)	GVRP			✓		✓	CPLEX
(Mostafa & Eltawil, 2017)	VRP	✓			✓		CPLEX
Pamuar et al. (2018)	VRPTF		✓		✓		OpenSolver & VBA
Prapinit et al. (2019)	HFOVRP		✓		✓		OpenSolver & VBA
This study	CVRPTW		✓		✓	✓	OpenSolver

CHAPTER 3
METHODOLOGY

This section outlines each methodological step. This study aims to provide a thorough framework for minimizing transportation costs in the delivery of aquatic goods. The methodology encompasses critical stages, including data collection, organization, model formulation, mathematical representation, tool selection, and scenario analysis.

3.1 Methodological Steps

The methodological approach, as depicted in Figure 3.1, begins with Data Collection, where pertinent information such as locations, demand volumes, time windows and vehicle details are gathered. Subsequently, the collected data undergoes meticulous organization and preparation for analysis. The next phase involves Project OSRM, utilizing the Open-Source Routing Machine (OSRM) to calculate accurate travel times and distances between locations. With these inputs, the optimization model is formulated and solved using OpenSolver, an Excel add-in for optimization. Finally, the optimized routes and associated cost savings are presented as the Result of the optimization process.

This streamlined approach guides the systematic exploration and resolution of the cold chain logistics optimization problem, ensuring a structured and rigorous approach to achieving the study objectives.

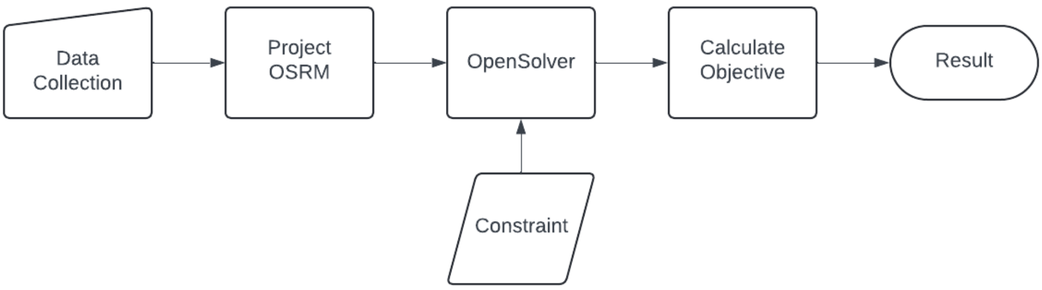


Figure 3.1 Methodological steps

3.2 Collecting Data

The study's data represents real-world cold chain logistics in Thailand, with 15 customers across locations, each with unique demands and time constraints. Samut Sakhon acts as the distribution hub, shipping goods to urban centers like Bangkok and Nonthaburi.

This dataset includes information on customer demand volumes and time window constraints as shown in Table 3.2 and Table 3.3. Demand data is represented in terms of pallets of boxes of aquatic goods, where each pallet stores 24 boxes. Time window constraints are measured in hours, with the zero hour marking the start time at 08:00 AM. By analyzing demand patterns and adhering to predefined time windows, distributors can optimize delivery schedules, minimize waiting times, and enhance overall service quality.

Additionally, the study utilizes Project OSRM (Open-Source Routing Machine) to calculate accurate travel times and distances between locations. This tool plays a crucial role in route optimization by providing essential data for efficient distribution planning to study area.

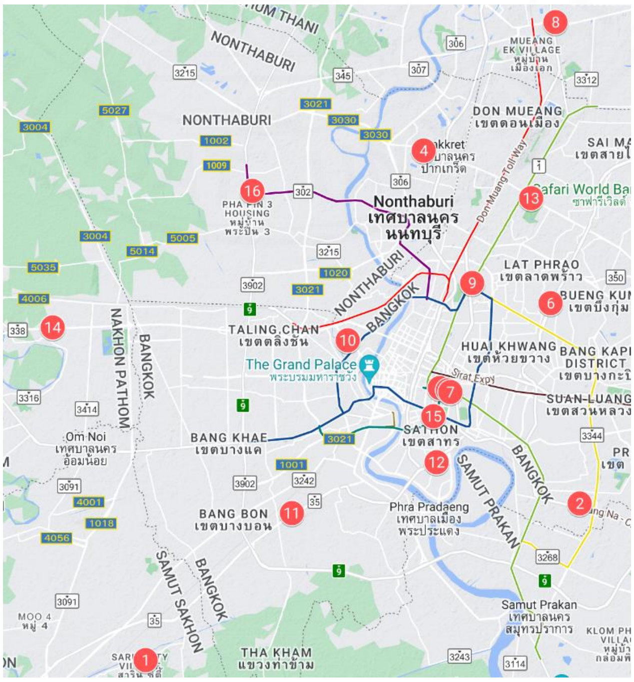


Figure 3.2 Location of nodes

Table 3.1 Node and location of Figure 3.2

Node	Location	Node	Location
0	DC Samut Sakhon	8	Central Ladprao
1	Central Bangna	9	Central Pinklao
2	Central World	10	Central Rama 2
3	Chaeng Wattana	11	Central Rama 3
4	Central Chidlom	12	Central Ramindra
5	Central EastVille	13	Central Salaya
6	Embassy	14	Silom Complex
7	Future Park	15	Central WestGate

Table 3.2 Demand for each node individual day

Node	Demand (Pallets)					
	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
1	1	2	1	1	1	4
2	5	5	4	1	5	5
3	2	3	3	3	5	1
4	3	1	5	4	4	5
5	2	1	5	1	3	4
6	3	1	2	5	2	5
7	1	5	5	3	4	5
8	3	5	5	4	4	2
9	4	2	3	1	5	5
10	3	5	1	3	5	2
11	3	4	3	3	1	1
12	5	2	5	4	5	1
13	2	3	5	1	2	5
14	4	5	1	2	4	2
15	5	2	4	1	2	2
Total Demand	46	46	52	37	52	49

Table 3.3 Time window for each node individual day

Node	Time window (hr)											
	Monday		Tuesday		Wednesday		Thursday		Friday		Saturday	
	Earliest time	Latest time	Earliest time	Latest time	Earliest time	Latest time	Earliest time	Latest time	Earliest time	Latest time	Earliest time	Latest time
1	3.25	5.38	0.92	3.22	6.07	8.03	1.98	4.11	1.79	3.84	2.30	4.60
2	0.67	2.60	0.57	2.50	0.37	2.14	3.38	4.98	1.98	3.50	1.98	4.00
3	1.98	4.35	1.53	3.98	1.98	4.18	2.82	5.02	3.18	5.21	3.97	6.42
4	0.11	2.26	0.54	2.37	4.99	7.06	3.35	4.76	5.32	6.89	0.75	2.82
5	0.45	2.40	3.01	5.04	6.57	8.68	1.15	2.93	2.29	4.15	3.18	5.12
6	0.16	1.49	1.08	2.91	0.34	2.08	6.21	7.95	3.69	5.43	3.52	5.59
7	4.26	7.19	0.48	3.15	1.39	3.73	5.58	8.00	1.66	4.34	1.38	4.14
8	4.71	6.55	4.37	5.79	1.84	4.02	0.20	2.12	0.28	2.29	0.58	2.42
9	0.86	3.29	4.66	6.93	0.69	2.70	0.49	2.51	0.96	3.48	0.48	3.00
10	1.42	3.53	0.68	3.30	2.91	4.70	1.91	4.03	2.42	4.21	0.85	3.47
11	1.68	3.31	0.94	2.65	2.60	3.98	2.17	3.97	0.17	2.39	2.33	3.88
12	0.19	2.36	4.10	6.44	5.45	7.29	2.75	4.84	0.47	2.56	1.69	3.69
13	2.56	4.87	1.98	5.20	3.84	6.23	4.15	6.79	4.68	7.73	3.22	5.60
14	3.27	4.87	0.44	2.62	0.44	2.28	4.86	6.37	2.71	4.64	2.22	4.48
15	2.36	4.52	3.58	5.74	4.36	6.59	3.30	5.37	0.91	3.56	2.61	4.85

3.3 Model Assumption

The Vehicle Routing Problem with Time Window model for cold chain logistics in Thailand is built upon several key assumptions:

- All trucks finishing delivery tasks must return to DC.
- All trucks are refrigerated trucks.
- Traffic congestion is not considered.
- The truck is traveling at a constant speed.
- Only delivery services are provided. There is no pickup pallet.
- All deliveries must arrive at the earliest time and leave before the latest time.
- Each customer site is only delivered by truck, with no exceed demand.
- The sum of capacity loaded is not greater than the limit.

The transportation fleet consists entirely of refrigerated trucks with the following specifications: Width 2.25 m, Length 6.09 m, Height 2.23 m, and a capacity weight of 5 tons. These trucks are equipped with temperature control capabilities, maintaining temperatures ranging from 25°C to -18°C. The cold air is circulated from the top of the truck to ensure uniform cooling throughout the cargo space. Each box containing aquatic goods measures Width 25 cm, Length 34 cm, and Height 47 cm, with a capacity of 20 kg of ice. These boxes are arranged on pallets, with each pallet capable of holding 24 boxes. Furthermore, each truck can accommodate up to 10 pallets, facilitating efficient loading and transportation of aquatic goods.

3.4 Mathematical Model (CVRPTW Model)

The CVRPTW model formulated for optimizing cold chain logistics in Thailand encompasses the following sets, parameters, decision variables, objective function, and constraints.

Sets

$\boldsymbol{C}$	Set of customers	$\boldsymbol{C} = \{\mathbf{1}, \mathbf{2}, \mathbf{3}, \dots, \boldsymbol{n}\}$
$\boldsymbol{N}$	Set of all nodes	$N = \{0,1,2, \dots, n\}$

Parameters

n	Number of customers
D_i	Demand of customer i (pallets)
m	Number of (homogeneous) trucks
Q	Capacity of truck (pallets)
d_{ij}	Distance from node i to node j (km)
s_i	Service time of node i (hr)
$[e_i, l_i]$	Time window requested by node i (hr)
t_{ij}	Travel time from node i to node j (hr)
M	Massive positive number
q_j	Number of pallets that customer j needed
Q_i	Number of pallets that left on truck from node i

Constant Parameters

		Unit	Value
F_1	Unit cost of using trucks	Baht/truck	1000
F_2	Unit cost of cold chain product (CCP)	Baht/pallet	2500
F_3	Unit cost of refrigeration during transit	Baht/hr	50
F_4	Unit cost of refrigeration during unloading	Baht/hr	100
F_5	Unit price of fuel	Baht/L	45
K_1	Constant value of CCP during transit	-	1
K_2	Constant value of CCP during unloading	-	0.99
α_1	Refrigeration equipment consumption of fuel during transit	L/hr	2
α_2	Refrigeration equipment consumption of fuel during unloading	L/hr	2.5
U_0	Fuel consumption when truck empty	L/km	0.08
U_1	Fuel consumption when truck full load	L/km	0.102
θ	Sensitivity factor of CCP	-	0.002
xh	Discharge efficiency	pallet/hr	6

Decision Variables

x_{ij}	Binary variable indicating if a vehicle travels from node i to node j
y_{ij}	Load carried by a truck when traveling from node i to node j
a_i	Arrival time to node i to node j
p_i	Departure time from node i = $a_i + s_i$ (hr)

3.4.1 Objective Function

The objective function aims to minimize the total cost, which includes the following costs: Vehicle operating cost (C_1), Quality loss cost (C_2), Product freshness cost (C_3) and Energy cost (C_4) as in Equation 3.1 (Li et al., 2019).

$$Min\ (C_1 + C_2 + C_3 + C_4) \tag{3.1}$$

3.4.1.1 Vehicle Operating Cost

This cost includes the expenses related to vehicle maintenance and the salary of the personnel. It depends on the number of trucks used rather than the travel time or distance covered. The vehicle operating cost is crucial for managing the overall expenses related to fleet operations:

$$C_1 = \sum_{j\in N} F_1 \cdot x_{0j} \tag{3.2}$$

3.4.1.2 Quality Loss Cost

In cold chain logistics, quality loss costs during distribution primarily arise from two factors: the degradation of product freshness and the decline in product quality due to internal convection caused by opening the door, which allows outside air to enter:

1) The quality loss cost incurred during the transit process is:

$$C_{21} = \sum_{i\epsilon N, i\neq 0} D_i \cdot F_2(1 - K_1 e^{-\theta\cdot a_i}) \tag{3.3}$$

2) The quality loss cost incurred during the unloading process is:

$$C_{22} = \sum_{i\epsilon N, i\neq 0} Q_i \cdot F_2(1 - K_2 e^{-\theta\cdot\frac{q_j}{xh}}) \tag{3.4}$$

Then, the total quality loss cost is:

$$C_2 = C_{21} + C_{22} = \sum_{i\epsilon N, i\neq 0} F_2\left(D_i(1 - K_1 e^{-\theta\cdot a_i}) + Q_i\left(1 - K_2 e^{-\theta\cdot q_j/xh}\right)\right) \tag{3.5}$$

3.4.1.3 Product Freshness Cost

Maintaining the freshness of the products is essential during transportation. This cost comprises two parts:

1) The cost of maintaining the temperature inside the trucks during transit to ensure the products remain fresh:

$$C_{31} = \sum_{i \epsilon N} \sum_{j \in N} x_{ij} \cdot t_{ij} \cdot F_3 \quad (3.6)$$

2) The cost incurred during the unloading process to maintain the required temperature levels:

$$C_{32} = \sum_{i \epsilon N} \sum_{j \in N, j \neq 0} x_{ij} \cdot \frac{q_j}{xh} \cdot F_4 \quad (3.7)$$

Then, the total product freshness cost is:

$$C_3 = C_{31} + C_{32} = \sum_{i \epsilon N} \sum_{j \in N} x_{ij} \cdot t_{ij} \cdot F_3 + \sum_{i \epsilon N} \sum_{j \in N, j \neq 0} x_{ij} \cdot \frac{q_j}{xh} \cdot F_4 \quad (3.8)$$

3.4.1.4 Energy Cost

Energy cost covers the fuel consumption during transportation and the energy required by the refrigeration equipment. It consists of:

1) The cost of fuel consumed by the truck during transit:

$$U(Q) = U_0 + \frac{(U_1 - U_0)}{Q} \cdot Q_i \quad (3.9)$$

$$C_{41} = \sum_{i \in N} \sum_{j \in N} x_{ij} \cdot F_5[y_{ij} \times U(Q)] \quad (3.10)$$

2) The cost of the fuel used by the refrigeration equipment during transportation:

$$C_{42} = \sum_{i \in N} \sum_{j \in N} x_{ij} \cdot F_5[\alpha_1 \cdot t_{ij} + \alpha_2 \cdot D_i] \quad (3.11)$$

Then, the total energy cost is:

$$C_4 = C_{41} + C_{42} = \sum_{i \in N} \sum_{j \in N} x_{ij} \cdot F_5([y_{ij} \times U(Q)] + [\propto_1 \cdot t_{ij} + \propto_2 \cdot D_i]) \quad (3.12)$$

3.4.2 Constraints

Each customer must be visited at most once by truck:

$$\sum_{j\in N, j\neq i} x_{ij} = 1;\ \forall i \in C \tag{3.13}$$

If a vehicle truck arrives, it must leave:

$$\sum_{j\in N, j\neq i} x_{ij} - \sum_{j\in N, j\neq i} x_{ji} = 0;\ \forall i \in N \tag{3.14}$$

Demand elimination constraint:

$$\sum_{j\in N, j\neq i} y_{ij} - \sum_{j\in N, j\neq i} y_{ji} = D_i;\ \forall i \in C \tag{3.15}$$

Vehicle capacity constraint:

$$y_{ij} \leq Q \times x_{ij};\ \forall i \in N, \forall j \in N \tag{3.16}$$

Only available trucks can be dispatched from the depot.

$$\sum_{j\in C} x_{0j} \leq m \tag{3.17}$$

Arrival time at each customer must be greater than or equal and less than or equal to the departure time plus travel time:

$$a_j \geq (p_i + t_{ij}) - (1 - x_{ij}) \times M; \forall i \in N, \forall j \in C \tag{3.18}$$

$$a_j \leq (p_i + t_{ij}) + (1 - x_{ij}) \times M; \forall i \in N, \forall j \in C \tag{3.19}$$

Arrival time, departure time, and service time are compatible with the time window constraint:

$$a_i = p_i - s_i;\ \forall i \in C \tag{3.20}$$

$$e_i \leq p_i \leq l_i;\ \forall i \in C \tag{3.21}$$

Departure time from the depot is 0:

$$p_0 = 0 \tag{3.22}$$

Binary and non-negativity conditions:

$$x_{ij} \in 0,1; \forall i \in N, \forall j \in N \tag{3.23}$$

$$y_{ij} \geq 0;\ \forall i \in N, \forall j \in N \quad (3.24)$$

3.5 Tools

The optimization process in this study leverages OpenSolver, an advanced Excel add-in designed to handle large-scale linear and integer programming problems efficiently. OpenSolver extends Excel's built-in Solver capabilities, offering a robust and accessible platform for solving the CVRPTW model.

OpenSolver is particularly suited for this research due to its ability to handle complex constraints and large datasets, which are common in cold chain logistics. It utilizes sophisticated algorithms, including branch-and-bound and cutting planes, to explore the solution space and identify optimal or near-optimal solutions for the CVRPTW model.

The integration of OpenSolver with Excel provides a user-friendly interface for defining decision variables, constraints, and objective functions. This makes the tool highly practical for real-world applications, enabling logistics managers to easily input data, run optimization models, and interpret results without requiring extensive programming knowledge.

Additionally, the study utilizes Project OSRM (Open-Source Routing Machine) to calculate accurate travel times and distances between locations. This tool plays a crucial role in route optimization by providing essential data for efficient distribution planning to study area.

CHAPTER 4
RESULT

The Results section presents the outcomes of the optimization process for cold chain logistics in Thailand, specifically focusing on the delivery of aquatic goods. The findings include a comparison between minimizing total cost and minimizing total distance over six days (Monday to Saturday). Additionally, detailed examples of optimized routes, cost analysis, and the impact of varying demand are provided. This analysis aims to demonstrate the effectiveness of the optimization model and its impact on logistics efficiency and cost reduction.

4.1 Comparison Minimize Cost and Minimize Distance

The optimization process was conducted with two primary objectives: minimizing total cost and minimizing total distance. The goal is to demonstrate that minimizing cost is more optimal compared to minimizing distance. **Table 4.1** provides a comparison of the total cost and total distance achieved under each optimization criterion across six days (Monday to Saturday). This comparison highlights the differences in performance metrics between the two optimization objectives and underscores the superior outcomes achieved by focusing on cost minimization.

Table 4.1 Minimize Cost vs Minimize Distance

Day	Minimize Cost (Main Objective)		Minimize Distance	
	Total Cost	Total Distance	Total Cost	Total Distance
Monday	11003.500	547.006	11145.53	534.313
Tuesday	11284.108	567.510	11430.595	560.408
Wednesday	13184.650	663.518	13502.627	620.327
Thursday	9522.134	487.266	9726.117	486.756
Friday	12958.283	653.083	13266.314	646.959
Saturday	11561.400	602.971	11869.807	566.450

This table clearly illustrates that while both strategies aim to optimize logistics, the cost minimization strategy consistently results in lower overall costs compared to the distance minimization strategy. The trade-offs between cost and distance are evident, highlighting the importance of selecting the appropriate optimization objective based on operational priorities.

4.2 Optimized Routes

To provide a detailed understanding of the optimization results, we present the optimized routes and cost analysis for Monday. This includes a breakdown of the routes for minimizing cost and distance.

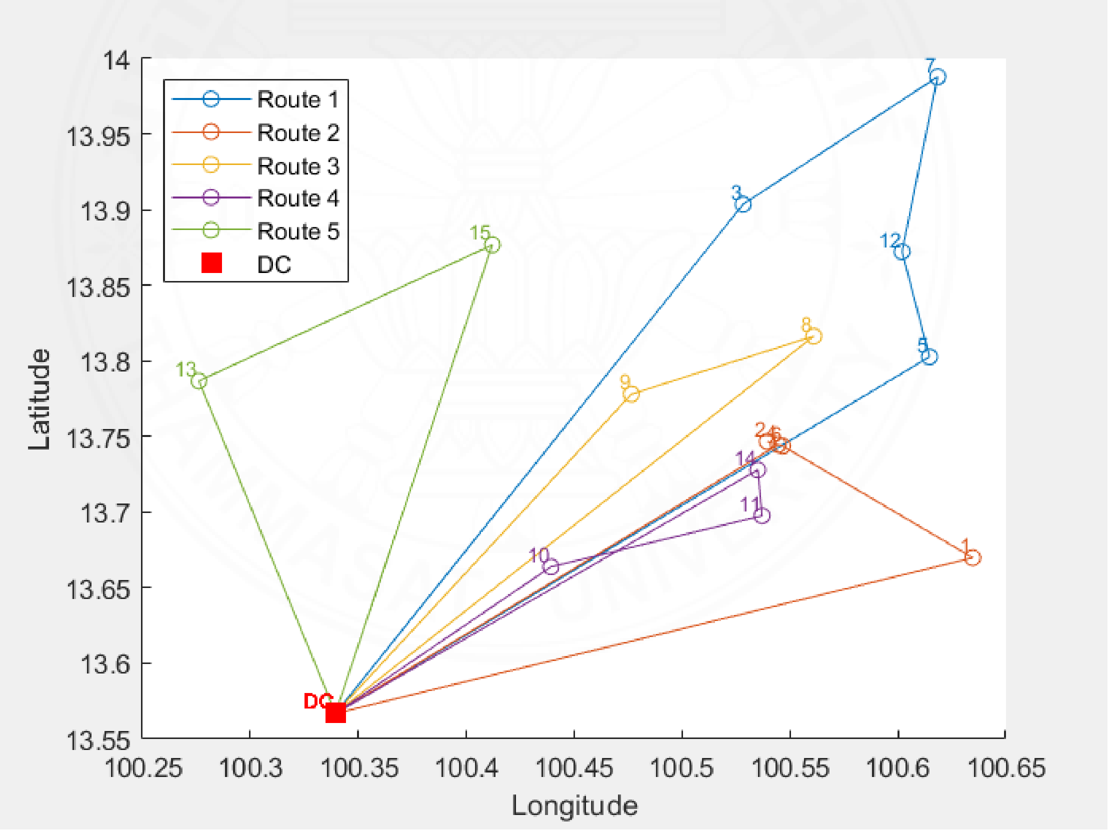


Figure 4.1 The route of the minimize cost on Monday

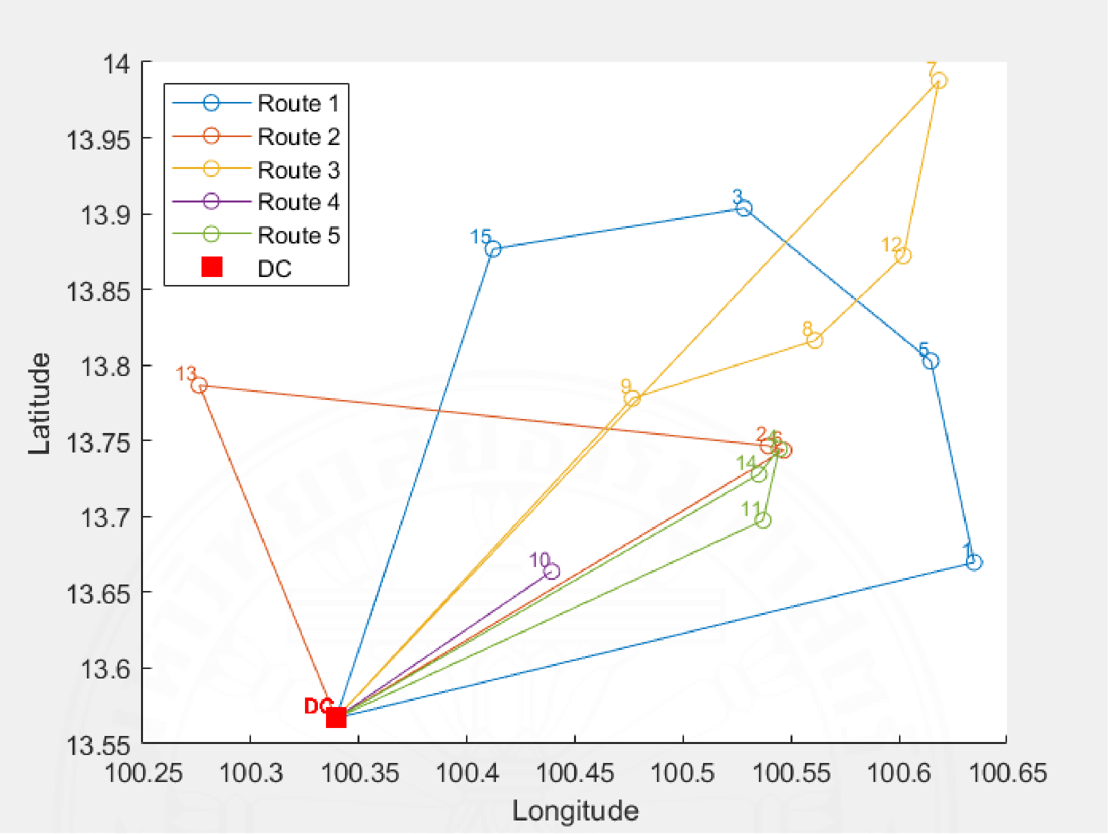


Figure 4.2 The route of the minimize distance on Monday

Figure 4.1 shows the specific routes taken by vehicles when the objective is to minimize costs, planning the routes to optimize overall transportation expenses considering factors such as vehicle operating costs, quality loss cost, product freshness cost, and energy cost. In contrast, **Figure 4.2** highlights the routes when the objective is to minimize the total distance traveled. This approach focuses on covering the shortest possible distances, which may not always align with cost minimization but can provide insights into different operational efficiencies.

4.3 Cost Analysis

The cost analysis section highlights the savings achieved through the optimization process.

Figure 4.3 Comparison of costs between Min cost and Min Distance on Monday

Figure 4.3 shows a bar chart comparing different cost components for Monday under both optimization strategies. The vehicle operating cost remains constant in both strategies since the same number of vehicles are used. However, the quality loss cost is lower when minimizing cost due to better route planning that ensures quicker deliveries and reduces spoilage. The product freshness cost is slightly lower when minimizing cost, indicating that the optimized routes better preserve the freshness of the aquatic goods. Additionally, the energy cost is lower when minimizing cost, reflecting more efficient fuel usage and refrigeration. This comparison highlights that while the vehicle operating cost remains the same, other cost components significantly benefit from a cost minimization strategy. This demonstrates that minimizing total cost not only reduces expenses directly related to logistics but also indirectly improves product quality and reduces energy consumption.

4.4 Impact of Demand Variability

The optimization based on minimize cost, process was evaluated under varying demand conditions each day to assess its adaptability and efficiency in real-world scenarios. **Table 4.2** presents the results for the cost minimization strategy, detailing the cost components and total distance for each day.

Table 4.2 Result under different demand each day

Day	Trucks	C_1	C_2	C_3	C_4	Total Cost	Total Distance
Monday	5	5000	1532.71	720.16	3750.63	11003.50	547.00
Tuesday	5	5000	1427.30	872.45	3984.36	11284.11	567.51
Wednesday	6	6000	1366.75	1034.15	4783.75	13184.65	663.52
Thursday	4	4000	1336.55	828.59	3357.00	9522.13	487.27
Friday	6	6000	1532.55	857.21	4568.52	12958.28	653.08
Saturday	5	5000	1566.40	792.03	4202.97	11561.40	602.97

In analyzing the results, it's evident that the number of trucks deployed each day directly influences vehicle operating costs. Quality loss costs, representing the deterioration of aquatic goods during transit, fluctuated across days. The lowest quality loss cost of 1336.55 baht was observed on Thursday, indicating efficient route planning with fewer trucks. In contrast, the highest quality loss cost of 1566.40 baht occurred on Saturday, suggesting a greater risk of spoilage, possibly due to longer or less efficient routes. Product freshness costs, reflecting expenses to maintain the freshness of aquatic goods, also varied. Wednesday saw the highest freshness cost at 1034.15 baht, potentially due to longer delivery routes or higher ambient temperatures affecting preservation efforts. In contrast, Monday recorded the lowest freshness cost of 720.16 baht, indicating more efficient routing and faster deliveries. Energy costs, including refrigeration and fuel expenses, were influenced by route efficiency and distance traveled. The highest energy cost of 4783.75 baht was observed on Wednesday, corresponding with the highest total distance of 663.52 km, indicating increased energy consumption for refrigeration and fuel. Conversely, Thursday recorded the lowest energy cost of 3357.00 baht, aligning with the lowest total distance of 487.27 km.

In summary, the cost minimization strategy effectively adapted to varying demand conditions, maintaining cost-efficiency across different days. Total costs ranged from 9522.13 baht on Thursday to 13184.65 baht on Wednesday, showcasing flexibility in handling different demand levels. Similarly, total distance traveled ranged from 487.27 km on Thursday to 663.52 km on Wednesday, highlighting the optimization model's adaptability in route planning. This adaptability to demand variability is crucial for the dynamic nature of cold chain logistics, where daily demand fluctuations can significantly impact operational efficiency.

4.5 Details of Optimization Execution

The optimization model was executed using OpenSolver version 2.9.3 on a computer equipped with Processor: AMD Ryzen 7 3750H with Radeon Vega Mobile Gfx 2.30 GHz. The model execution time averaged around 5 minutes per run.

CHAPTER 5
CONCLUSION

One of the critical findings of this study is the superiority of minimizing overall costs over merely minimizing travel distances in cold chain logistics. While traditional logistics optimization often focuses on minimizing the total distance traveled, this study has shown that such an approach may not be optimal for cold chain operations. By shifting the objective from minimizing distance to minimizing a comprehensive cost function, the study encapsulated various cost components, including vehicle operating costs, quality loss costs, product freshness costs, and energy costs. This cost-minimization approach resulted in substantial savings across these components. Specifically, the optimization model reduced fuel consumption and maintenance costs by selecting routes that balance distance with fewer stops and smoother traffic conditions. Additionally, by optimizing delivery routes to ensure timely deliveries within the specified time windows, the model minimized the degradation of aquatic goods, reducing costs associated with spoiled products and ensuring that products remained fresh upon delivery. This not only improved customer satisfaction by reducing the likelihood of returns but also lowered energy consumption and costs related to maintaining the required cold temperatures within the refrigerated vehicles.

CHAPTER 6
DISCUSSION

The findings of this study underscore the effectiveness of a customized CVRPTW model in optimizing cold chain logistics by minimizing total transportation costs. This approach significantly enhances the efficiency of the distribution network by considering a comprehensive set of factors, such as fuel consumption, vehicle maintenance, and energy costs, rather than merely focusing on minimizing travel distances. By prioritizing cost reduction across the transportation process, the model ensures a more economically sustainable approach to delivering aquatic goods across Thailand's provinces.

In real-world scenarios, drivers may need to adapt to changing circumstances, such as customer urgency or traffic disruptions, which may require deviations from the optimized routes provided by the model. Despite this flexibility, the model serves as a valuable tool for guiding decision-making and providing insights into the most cost-effective routing options. However, it's essential to acknowledge that the time required to run the model may sometimes pose challenges in dynamic situations where immediate action is necessary. In such cases, drivers may rely on their experience and judgment to make timely adjustments to the routing sequence, prioritizing customer satisfaction and operational efficiency.

Moving forward, future research could enhance the mathematical model by incorporating additional factors such as greenhouse gas emissions and penalty costs for deviations from optimal routes. Furthermore, exploring the integration of advanced tools and technologies could further improve the model's accuracy and applicability in dynamic logistics environments. By continually refining and expanding upon these models, the cold chain logistics industry can continue to evolve towards more sustainable, efficient, and customer-centric practices.

REFERENCES

Awad, M., Ndiaye, M., & Osman, A. (2021). Vehicle routing in cold food supply chain logistics: a literature review. *The International Journal of Logistics Management, 32*(2), 592-617.

Bandoophanit, T., Sangpukdee, W., Kaengaew, W., & Chotkawee, S. (2023). *The future of Thailand's international logistics: A literature review. Kasetsart Journal of Social Sciences*, *44*(2), 355-364.

Bio, A. (2023). Retrieved from https://www.upperinc.com/guides/cold-chain-logistics/

Boonlua, S. (2019). Learning and growth for sustainable development of logistics companies in Thailand. *Polish Journal of Management Studies*, *20*(1), 92-102.

Chen, L., Liu, Y., & Langevin, A. (2019). A multi-compartment vehicle routing problem in cold-chain distribution. *Computers & Operations Research, 111*, 58-66.

Feng, T., Ji, J., & Zhang, X. (2023). Research progress of phase change cold energy storage materials used in cold chain logistics of aquatic products. *Journal of Energy Storage, 60*, 106568.

Fernando, J. (n.d.). Supply Chain Management (SCM): How it works & why it's important. Retrieved from https://www.investopedia.com/terms/s/scm.asp

Guo, F., Huang, Z., & Huang, W. (2021). Heuristic approaches for a vehicle routing problem with an incompatible loading constraint and splitting deliveries by order. *Computers & Operations Research, 134*, 105379.

Leelertkij, T., Parthanadee, P., & Buddhakulsomsiri, J. (2021). Vehicle routing problem with transshipment: mathematical model and algorithm. *Journal of Advanced Transportation, 2021*, 1-15.

Li, D., Cao, Q., Zuo, M., & Xu, F. (2020). Optimization of green fresh food logistics with heterogeneous fleet vehicle route problem by improved genetic algorithm. *Sustainability, 12*(5), 1946.

Li, Y., Lim, M. K., & Tseng, M. L. (2019). A green vehicle routing model based on modified particle swarm optimization for cold chain logistics. *Industrial Management & Data Systems, 119*(3), 473-494.

Mordor Intelligence. (n.d.). Thailand freight and logistics market size & share analysis - industry research report - growth trends. Retrieved from https://www.mordorintelligence.com/industry-reports/thailand-freight-and-logistics-market

Mostafa, N., & Eltawil, A. (2017, April). Solving the heterogeneous capacitated vehicle routing problem using K-means clustering and valid inequalities. *In Proceedings of the international conference on industrial engineering and operations management* (pp. 2239-2249).

Pamuar, D., Petrovi, I., & irovi, G. (2018). Modification of the Best-Worst and MABAC methods. *Expert Systems with Applications, 91*, 89–106. https://doi.org/10.1016/j.eswa.2017.08.042

Prapinit, P., Sabar, R., & Melan, M. (2019). Demand for logistics management studies in North Eastern Thailand. *International Journal of Supply Chain Management, 8*(5), 481.

Pureza, V., Morabito, R., & Reimann, M. (2012). Vehicle routing with multiple deliverymen: Modeling and heuristic approaches for the VRPTW. *European Journal of Operational Research, 218(*3), 636-647.

Qin, G., Tao, F., & Li, L. (2019). A vehicle routing optimization problem for cold chain logistics considering customer satisfaction and carbon emissions. *International Journal of Environmental Research and Public Health, 16*(4), 576.

Singhtaun, C., & Piyapornthana, H. (2022). A mathematical model and solution approach for a heterogeneous fleet open vehicle routing problem. *GEOMATE Journal, 22*(90), 17-23.

Syahputra, R. H., Komarudin, K., & Destyanto, A. R. (2018, July). Optimization of distribution route with vehicle routing problem with transshipment facilities (VRPTF). *In 2018 3rd International Conference on Computational Intelligence and Applications (ICCIA)* (pp. 11-15). IEEE.

Yildirim, U., & Kuvvetli, Y. (2021). Solution of capacitated vehicle routing problem with invasive weed and hybrid algorithms. *International Journal of Industrial Engineering Computations, 12*(4).

APPENDIX

APPENDIX A
MANUAL

Step 1: Input Latitude and Longitude

Begin by plugging in the latitude and longitude of the Distribution Center (DC) and all customer locations. This data is essential for generating the distance and time matrices required for the optimization process.

Step 2: Generate Distance and Time Matrices

Next, input the location data into the OSRM_dist_mat_and_time colab. This script will generate the distance matrix and time matrix needed for further calculations. (Insert picture of the code, distance matrix, and time matrix here)

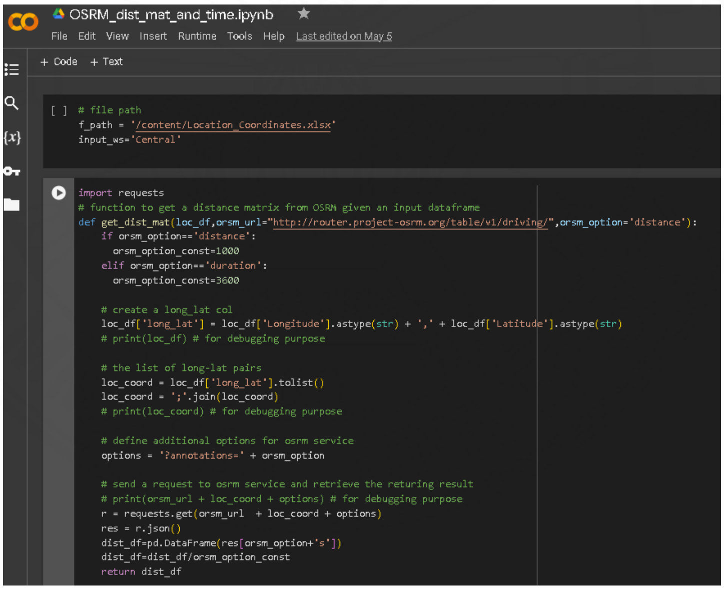
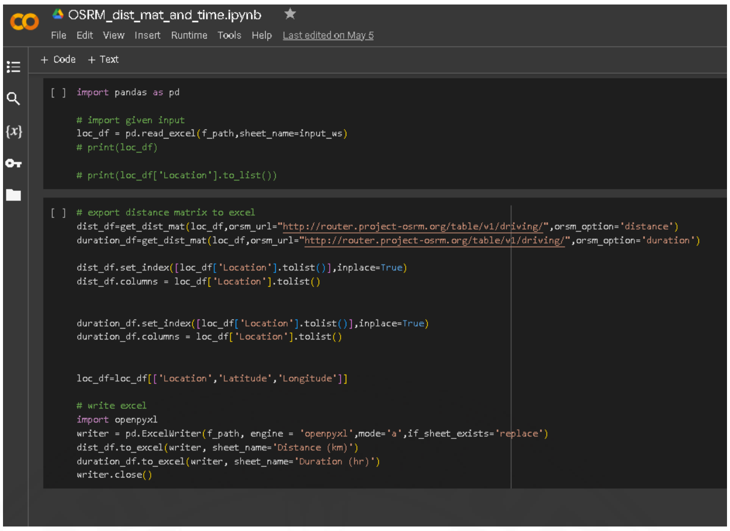


Figure A.1 OSRM_dist_mat_and_time colab code in first part



```
[ ] import pandas as pd

    # import given input
    loc_df = pd.read_excel(f_path,sheet_name=input_ws)
    # print(loc_df)

    # print(loc_df['Location'].to_list())

[ ] # export distance matrix to excel
    dist_df=get_dist_mat(loc_df,orsm_url="http://router.project-osrm.org/table/v1/driving/",orsm_option='distance')
    duration_df=get_dist_mat(loc_df,orsm_url="http://router.project-osrm.org/table/v1/driving/",orsm_option='duration')

    dist_df.set_index([loc_df['Location'].tolist()],inplace=True)
    dist_df.columns = loc_df['Location'].tolist()


    duration_df.set_index([loc_df['Location'].tolist()],inplace=True)
    duration_df.columns = loc_df['Location'].tolist()


    loc_df=loc_df[['Location','Latitude','Longitude']]

    # write excel
    import openpyxl
    writer = pd.ExcelWriter(f_path, engine = 'openpyxl',mode='a',if_sheet_exists='replace')
    dist_df.to_excel(writer, sheet_name='Distance (km)')
    duration_df.to_excel(writer, sheet_name='Duration (hr)')
    writer.close()
```


Figure A.2 OSRM_dist_mat_and_time colab code in second part

Step 3: Insert Matrices into Excel

Once you have the distance and time matrices, place them into the corresponding sheets labeled "Distance" and "Time" within your Excel workbook.

DC Samut Sakhon	Central Bangna	Central World	Chaengwattana	Chidlom	EastVille	Embassy	Future Park	Ladprao	Pinklao	Rama 2	Rama 3	Ramindra	Salaya	Silom Complex	WestGate
0	45.7741	39.5438	56.2091	38.9535	48.5054	37.8606	68.136	46.1385	35.8985	18.3354	31.178	54.39	46.6938	37.0643	41.5367
46.1318	0	19.3968	40.1895	18.8065	20.1643	15.4531	47.989	26.3084	26.91	31.1994	17.9461	31.301	50.7277	16.9439	47.6017
38.5984	17.3693	0	22.1363	2.0385	13.969	1.1517	31.434	9.8137	8.9068	21.7619	10.0656	18.0652	32.7245	2.544	30.4434
59.3456	39.3627	24.7715	0	24.9656	22.9826	25.2304	22.9211	20.3095	22.9036	42.5091	30.6734	11.6674	41.2699	26.4858	19.2146
39.5417	16.7557	1.3474	21.5957	0	13.0889	0.4538	31.8711	9.9271	9.5445	22.7052	9.4519	18.1786	33.3622	2.6172	29.9028
52.8278	22.611	16.3773	20.2125	15.7871	0	15.7438	30.1722	11.5186	23.8906	35.9913	22.7379	12.5224	46.3595	18.2785	29.7306
39.0878	16.3018	1.4838	23.6178	1.1747	12.6351	0	31.4173	9.7367	9.681	22.2514	8.998	17.9882	33.4987	2.7537	31.03
67.097	44.311	29.9143	21.9346	30.9241	25.676	30.1786	0	21.08	33.391	50.2605	37.0072	14.3608	56.1524	34.1788	31.3664
46.7682	23.9822	9.5855	15.8458	10.6806	9.1291	9.8498	24.2804	0	15.1108	29.9317	16.6784	8.8133	37.9668	13.85	23.1723
39.2668	27.636	12.5078	22.7191	13.2119	24.9119	12.9846	35.5016	16.2518	0	22.0229	18.2893	23.4966	24.4277	13.7482	20.5342
23.5107	27.654	21.4237	38.089	20.8335	30.3853	19.7405	50.0159	28.0184	17.7784	0	13.0579	36.2699	33.3419	18.9443	29.0116
32.5489	14.9136	8.6833	29.476	8.0931	17.6449	7.3782	37.2755	15.5949	16.1965	15.7124	0	23.8464	38.4957	4.8542	36.8882
56.9603	30.8266	20.8243	11.4723	20.5335	11.5593	20.042	21.432	12.4379	23.0003	40.1238	26.8705	0	45.7617	22.0547	30.3884
46.1205	46.3238	31.1956	42.2867	31.8997	43.6177	31.6724	54.2074	34.9576	23.853	34.6616	36.9771	42.2024	0	32.436	25.6657
35.6371	15.0039	4.135	24.9605	4.9394	16.1151	3.701	35.7978	12.4235	11.4145	18.8006	5.9078	20.675	35.2322	0	33.2676
42.0746	44.0539	29.4628	20.1104	29.6569	28.2113	29.9216	35.5744	21.1157	20.2408	30.6157	35.3646	24.3634	27.363	31.177	0

Figure A.3 Distance Matrices

Central World	Chaengwattana	Chidlom	EastVille	Embassy	Future Park	Ladprao	Pinklao	Rama 2	Rama 3	Ramindra	Salaya	Silom Complex	WestGate
0.661	0.834	0.630	0.788	0.628	0.970	0.731	0.628	0.385	0.542	0.823	0.833	0.615	0.784
0.341	0.544	0.311	0.356	0.299	0.650	0.412	0.436	0.498	0.300	0.493	0.828	0.291	0.750
0.000	0.305	0.058	0.245	0.031	0.426	0.167	0.161	0.364	0.167	0.259	0.553	0.068	0.510
0.388	0.000	0.369	0.341	0.354	0.339	0.282	0.364	0.601	0.414	0.170	0.716	0.371	0.305
0.056	0.304	0.000	0.235	0.014	0.411	0.164	0.166	0.355	0.156	0.256	0.558	0.064	0.509
0.332	0.352	0.302	0.000	0.300	0.505	0.253	0.427	0.592	0.393	0.260	0.797	0.349	0.568
0.052	0.290	0.045	0.221	0.000	0.397	0.158	0.162	0.340	0.142	0.250	0.554	0.060	0.496
0.444	0.305	0.437	0.384	0.395	0.000	0.309	0.488	0.682	0.484	0.213	0.863	0.452	0.553
0.195	0.214	0.180	0.169	0.146	0.343	0.000	0.254	0.434	0.235	0.128	0.617	0.203	0.423
0.285	0.401	0.285	0.446	0.264	0.568	0.333	0.000	0.445	0.355	0.398	0.443	0.291	0.422
0.316	0.489	0.286	0.443	0.283	0.625	0.386	0.283	0.000	0.197	0.478	0.652	0.270	0.572
0.183	0.386	0.152	0.309	0.147	0.492	0.254	0.277	0.291	0.000	0.346	0.666	0.124	0.591
0.309	0.158	0.291	0.192	0.275	0.311	0.177	0.342	0.562	0.363	0.000	0.717	0.318	0.429
0.477	0.590	0.477	0.637	0.456	0.760	0.524	0.326	0.488	0.548	0.590	0.000	0.483	0.414
0.131	0.340	0.127	0.300	0.086	0.474	0.228	0.218	0.336	0.133	0.321	0.610	0.000	0.545
0.490	0.331	0.472	0.477	0.456	0.540	0.385	0.362	0.468	0.516	0.389	0.503	0.473	0.000

Figure A.4 Time Matrices

Step 4: Input Interval Time and Demand Data

Now, input the interval time for each customer in hours and their respective demands for each day from Monday to Saturday. This data should be entered into the designated section of the Excel sheet.

	Node	Latitude	Longitude	Time window												LTL Demand (Remaining Pallets)					
				Monday		Tuesday		Wednesday		Thursday		Friday		Saturday		Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
				Earliest time	Latest time	Earliest time	Latest time	Earliest time	Latest time	Earliest time	Latest time	Earliest time	Latest time	Earliest time	Latest time						
1	Central Bangna	13.669778	100.634714	3.25	5.38	0.92	3.22	6.07	8.03	1.98	4.11	1.79	3.84	2.30	4.60	1	2	1	1	1	4
2	Central World	13.746686	100.539354	0.67	2.60	0.57	2.50	0.37	2.14	3.38	4.98	1.98	3.50	1.98	4.00	3	5	4	1	5	5
3	Chaengwattana	13.903515	100.528268	1.98	4.35	1.53	3.98	1.98	4.18	2.82	5.02	3.18	5.21	3.97	6.42	2	3	7	3	5	1
4	Chidlom	13.744542	100.544490	0.11	2.26	0.54	2.37	4.99	7.06	3.35	4.76	5.32	6.89	0.75	2.82	3	1	5	4	4	5
5	EastVille	13.802698	100.614656	0.45	2.40	3.01	5.04	6.57	8.68	1.15	2.93	2.29	4.15	3.18	5.12	2	1	5	1	3	4
6	Embassy	13.743757	100.546602	0.16	1.49	1.08	2.91	0.34	2.08	6.21	7.95	3.69	5.43	3.52	5.59	3	1	2	5	2	5
7	Future Park	13.987869	100.618455	4.26	7.19	0.48	3.15	1.39	3.73	5.58	8.00	1.66	4.34	1.38	4.14	1	5	5	3	4	5
8	Ladprao	13.816315	100.561016	4.71	6.55	4.37	5.79	1.84	4.02	0.20	2.12	0.28	2.29	0.58	2.42	3	6	5	4	4	2
9	Pinklao	13.777992	100.476543	0.86	3.29	4.66	6.93	0.69	2.70	0.49	2.51	0.96	3.48	0.48	3.00	1	2	3	1	5	5
10	Rama 2	13.663791	100.439211	1.42	3.53	0.68	3.30	2.91	4.70	1.91	4.03	2.42	4.21	0.85	3.47	3	5	1	3	5	2
11	Rama 3	13.697539	100.537054	1.68	3.31	0.94	2.65	2.60	3.98	2.17	3.97	0.17	2.39	2.33	3.88	3	4	7	3	1	1
12	Ramindra	13.872171	100.601954	0.19	2.36	4.10	6.44	5.45	7.29	2.75	4.84	0.47	2.56	1.69	3.69	5	2	5	4	5	1
13	Salaya	13.786709	100.276096	2.56	4.87	1.98	5.20	3.84	6.23	4.15	6.79	4.68	7.73	3.22	5.60	2	3	5	1	2	5
14	Silom Complex	13.727879	100.535081	3.27	4.87	0.44	2.62	0.44	2.28	4.86	6.37	2.71	4.64	2.22	4.48	4	5	1	2	4	2
15	WestGate	13.876693	100.412101	2.36	4.52	3.58	5.74	4.36	6.59	3.30	5.37	0.91	3.56	2.61	4.85	5	2	4	1	4	2
DC	DC Samut Sakhon	13.566830	100.339418																		

Figure A.5 Time window and demand (pallets)

Step 5: Select the Day for Calculation

In the calculation section, choose the day you wish to solve for. This selection will set up the specific parameters and data for that day's optimization.

Step 6: Set Parameters According to the Mathematical Model

Enter the necessary parameters based on the mathematical equations of this independent study. These parameters will guide the OpenSolver in finding the optimal solution.

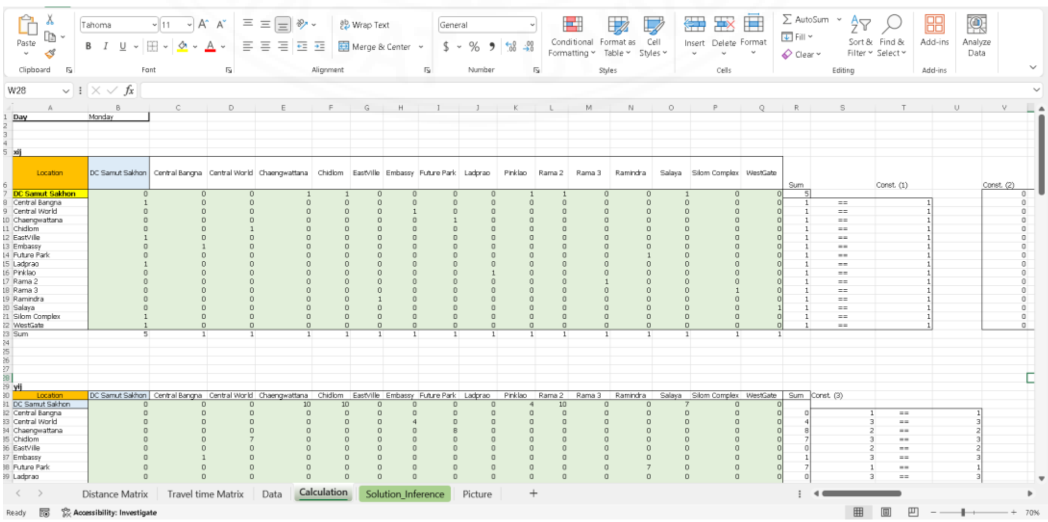


Figure A.6 Excel calculation section 1

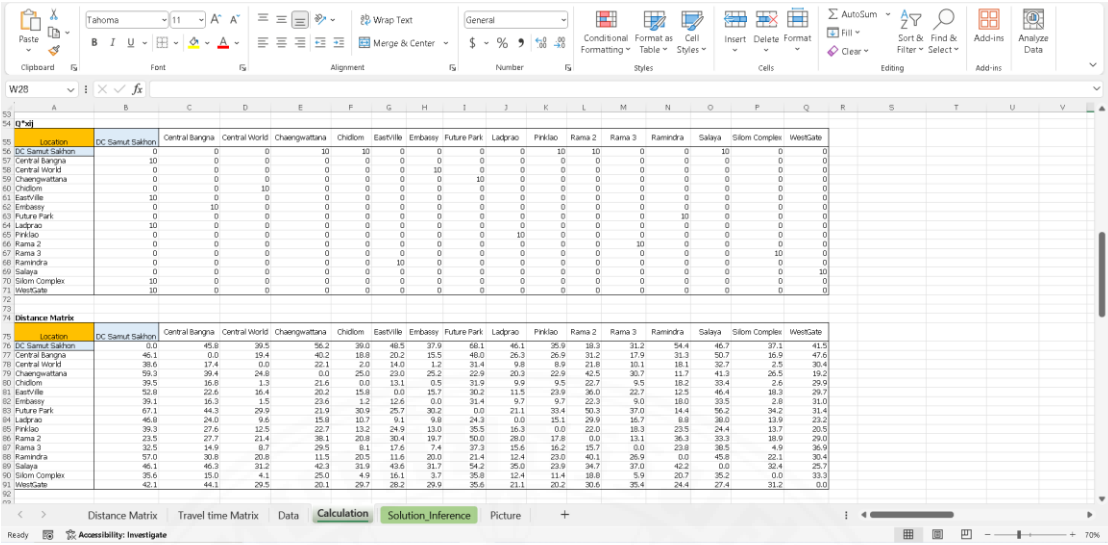


Figure A.7 Excel calculation section 2

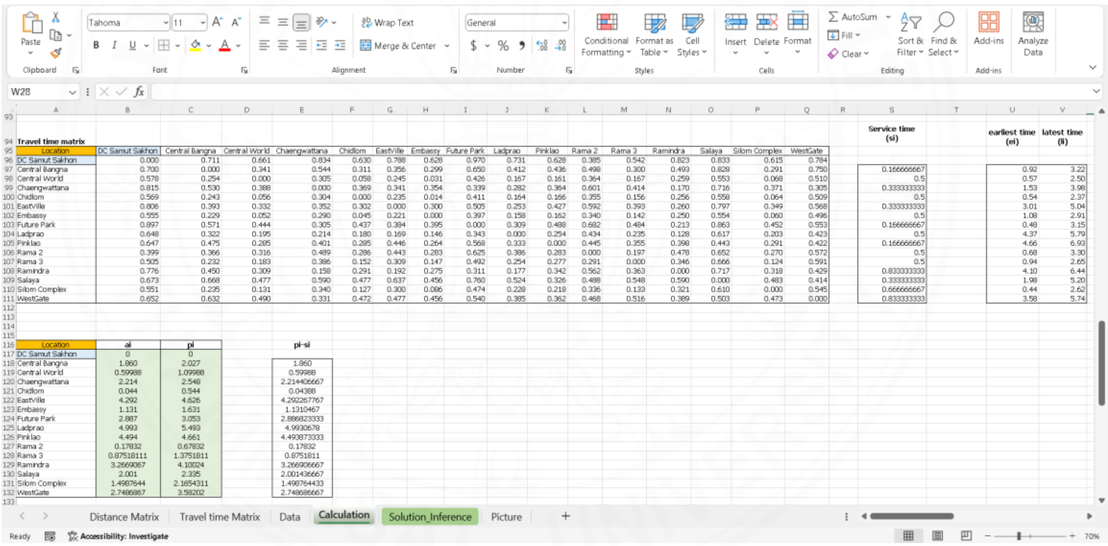


Figure A.8 Excel calculation section 3

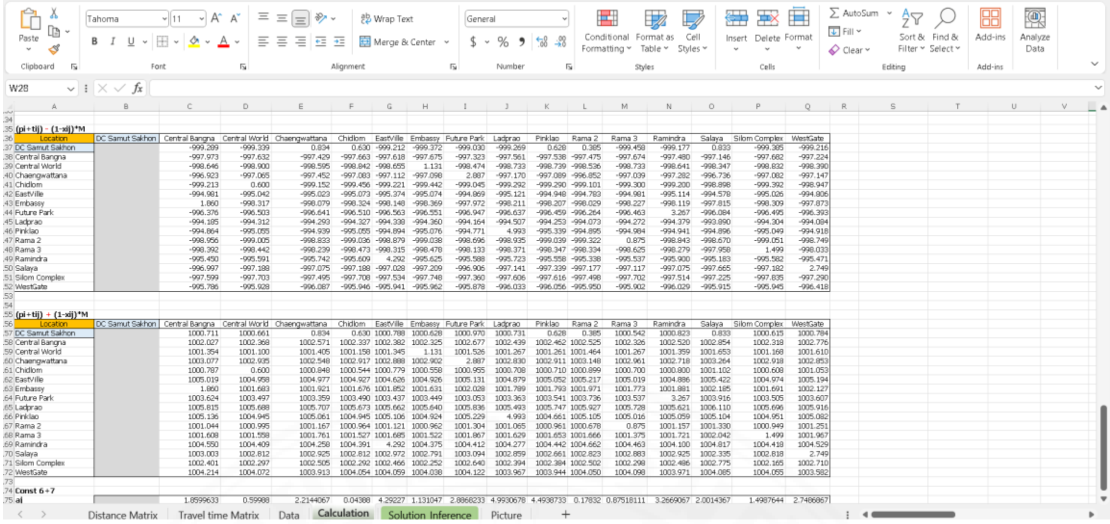


Figure A.9 Excel calculation section 4

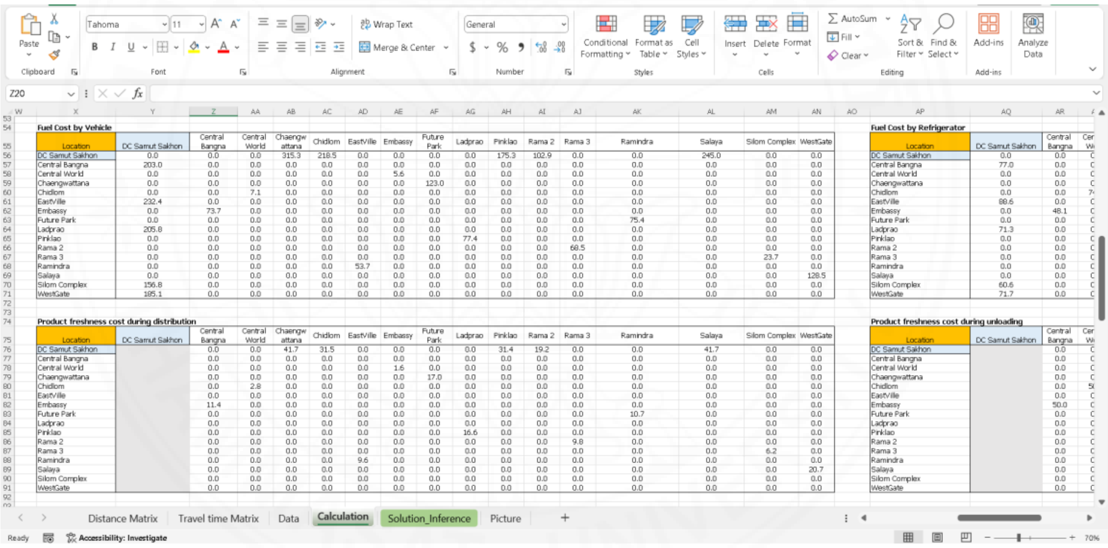


Figure A.10 Excel calculation section 5

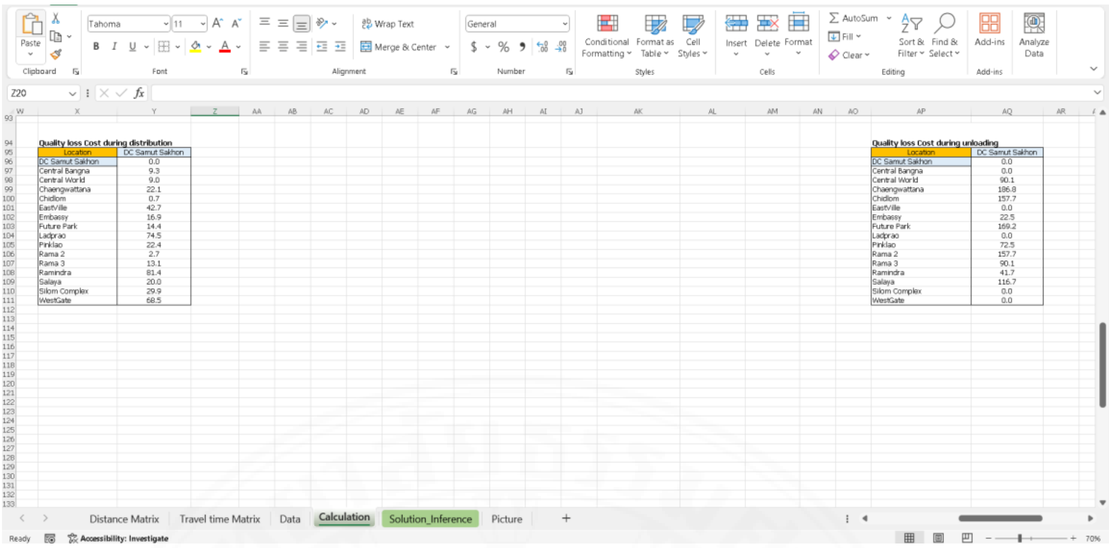


Figure A.11 Excel calculation section 6

Step 7: Configure OpenSolver

Set up OpenSolver by selecting the cell to minimize (objective cell), the variable cells (decision variables), and the constraint cells as defined by the mathematical model of this study. (Insert picture of OpenSolver configuration here)

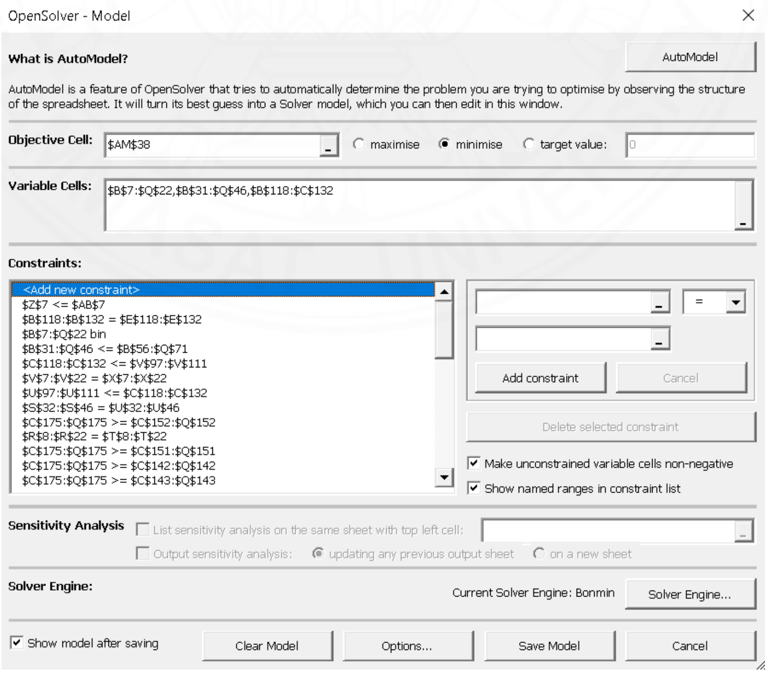


Figure A.12 OpenSolver window

F1	1000	Baht/truck	cost of vehicle operating
F2	2500	Baht/pallet	unit price of cold chain product
F3	50	Baht/hr	unit cost of refrigeration during transportation
F4	100	Baht/hr	unit cost of refrigeration during unloading
F5	55	Baht/L	unit price of fuel
U0	0.08	L/km	fuel consumption when vehicle empty
U1	0.102	L/km	fuel consumption when vehicle full load
α_1	2	L/hr	refrigeration equipment consumption of fuel in unit time during transportation
α_2	2.5	L/hr	refrigeration equipment consumption of fuel in unit time during unloading
K1	1	-	constant value of cold chain product during transportation
K2	0.99	-	constant value of cold chain product during the unloading
θ	0.002	-	sensitivity factor of cold chain products
xh	6	pallet/hr	discharge efficiency

Fuel Cost by Vehicle	2676.7
Fuel Cost by Refrigerator	1906.9
Quality loss Cost during transportation	427.6
Quality loss Cost during unloading	1105.1
Product freshness cost during transportation	271.9
Product freshness cost during unloading	433.3
Vehicle Operating Cost	5000
Total Cost	min 11821.6
Total Distance	547.0015
Total Travel Time	8.7940556

Figure A.13 Parameters and Calculation result

Step 8: Run the Solver

Run the OpenSolver to initiate the optimization process.

Step 9: Copy the Solution Matrix

After the solver has finished, copy all values from the matrix x_{ij} and paste them into the "Solution Interface" sheet. (Insert picture of copying and pasting the matrix here)

Step 10: Identify the Routes

In the "Solution Interference" sheet, identify the first visit for each route. Repeat this process to trace each vehicle's route until it returns to the DC. Finally, interpret the routing solution by following the identified routes from the previous step. This process will give you the detailed routes for each vehicle, showcasing the optimization achieved by the model.

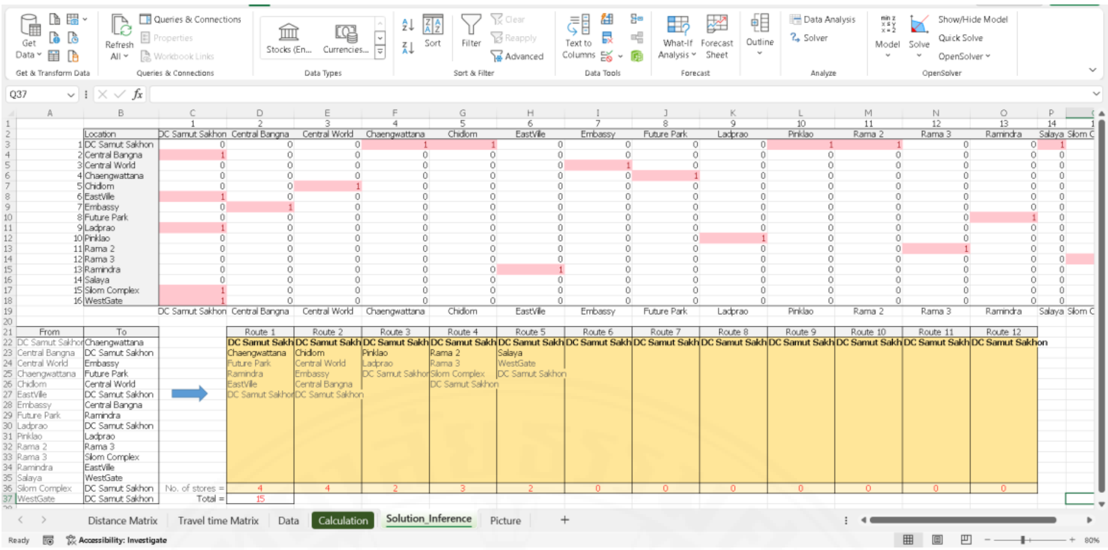


Figure A.14 Solution inference

By following these steps, you will be able to efficiently use the Excel tool developed in this independent study to run OpenSolver and obtain optimized routing solutions for cold chain logistics.