

A Bi-Objective Model for Determining an Optimal Warehouse Capacity, and Product Allocation in a Green Multi-Product, Multi-Period Distribution Network

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ABSTRACT

Nowadays, the growing trend of environmental concerns is significantly higher than in the past. At the same time, the business also focuses on the supply chain more to serve the customer demand using the lowest resources possible, leading to two major decisions: capacity and product allocation. Therefore, this research aims at designing a multi-product, multi-period, and multi-echelon supply chain network with factories, internal warehouses, external warehouses, and customers while also trying to lower the environmental effect of the supply chain through gas emissions. For this problem, many products and 20 periods of planning horizon of a real-world polymer industry are considered. The product deliveries use direct shipment from both internal and external warehouses. We develop bi-objective mixed-integer linear programming to find the most optimal product allocation and capacity while minimizing the total logistic costs, which include warehouse and transportation costs and total CO₂ emission through transportation. The problem is solved by the min-max approach through a mixed integer linear programming model using the CPLEX solver. After we get the result, we compare it with the single-objective model's result to determine the trade-off between the total logistic cost and emission gas. Our base case result shows a better overall satisfaction level among all the models.

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1. Introduction

In recent years, environmental concerns have grown significantly due to global warming and environmental regulation by governments worldwide. In Thailand, TISI 2315-2551 is established to regulate pollutants such as carbon dioxide (CO₂). These regulations and the climate changes make the companies adjust their supply chain to be greener. The total carbon dioxide emission in Thailand was estimated at 279.31 mega-tons in 2018, while in 2019, it is slightly reduced to 275.06 mega-tons.

As for the distribution network, this research aims to improve the performance of the supply chain by optimizing the capacity and product allocation in one of Thailand's polymer distribution networks. Their supply chain network is a 4-echelon supply chain consisting of factories, internal warehouses, external warehouses, and customers from both overseas and domestic, as shown in Figure 1. The factory produces multiple products, which will be shipped to the internal warehouse for packaging. Due to the limited capacity of the internal warehouses, some of the products will be sent to the external warehouse. Therefore, the customer can receive the products from internal and external warehouses. Since the objective is to minimize the total cost, which includes transportation and warehousing costs as well as the CO₂ emission, a bi-objective mixed-integer linear programming (MILP) model is formulated. The model is solved using a commercial solver and the min-max method (Sun et al., 2019).

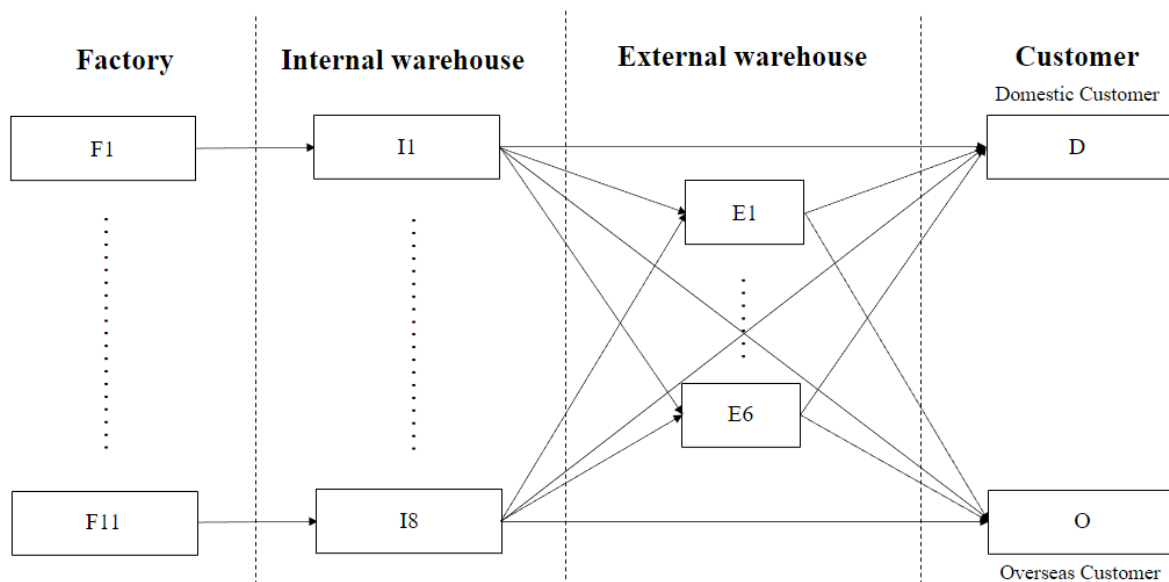


Figure 1: Model diagram

1.1 Literature Review

The supply chain network performance always involves capacity and product allocation. Therefore, relevant studies are reviewed to identify the research gap our study aims to cover. Table 1 summarizes the decision variable, characteristics, and method of approach.

Table 1.
Research gap

Study	Multiple Objective functions	Decision variable			Characteristic					Methods
		Location	Capacity	Product Allocation	Echelons	Multiple products	Environmental aspect	Multiple periods	Transportation mode	
Lee & Elsayed (2005)			✓		2					NLP, Heuristic
Zhu et al. (2021)				✓	2	✓				Heuristic
Askin et al. (2013)		✓	✓	✓	2	✓				MIP, GA, Heuristic
Santosa & Kresna (2015)		✓		✓	3	✓				MIP, SA
Chau et al. (2019)		✓	✓	✓	4	✓		✓	✓	MIP
Jamshidi et al. (2012)	✓	✓	✓	✓	4	✓	✓	✓		MIP, Memetic using Taguchi method
Paksoy et al. (2010)	✓		✓	✓	5	✓	✓	✓		MIP
Sadjady & Davoudpour (2012)		✓	✓	✓	5-Forward, 5-Reversed	✓		✓		MIP, Heuristic, Lagrangian relaxation
Shankar et al. (2013)	✓	✓	✓		2					MIP, Hybrid particle swarm optimization
Wang et al. (2011)	✓	✓	✓	✓	4	✓	✓			NLP, Normalized constraint method
Sun et al. (2019)	✓	✓	✓		3		✓			MIP, min-max approach
This study	✓		✓	✓	4	✓	✓	✓	✓	MIP, min-max approach

According to Table 1, the number of echelons is ranged from two (Lee & Elsayed, 2005; Zhu et al., 2020; Santosa & Kresna, 2015; Sadjady & Davoudpour, 2012) to three (Askin et al., 2013; Wang et al., 2011; Sun et al., 2019), four (Chau et al., 2019; Shankar et al., 2013), and five (Jamshidi et al., 2012; Paksoy et al., 2010). The two echelons supply chain (Lee & Elsayed, 2005; Zhu et al., 2021; Santosa & Kresna, 2015; Sadjady & Davoudpour, 2012) is the supply chain that involves direct shipment, while the three echelons (Askin et al., 2013; Wang et al. 2011; Sun et al., 2019) consider warehouse. For Chau et al. (2019), the study includes the external warehouse where customers can receive the product from both internal and external

warehouses. For Shankar et al. (2013), the supply chain includes suppliers, plants, distribution centers, and customers.

For the decision variable, the optimal location (Askin et al., 2013; Santosa & Kresna, 2015; Chau et al., 2019; Jamshidi et al., 2012; Sadjady & Davoudpour, 2012; Shankar et al., 2013; Wang et al., 2011; Sun et al., 2019) is considered by listing the possible location and using the binary variables to select the location to open the facility. The studies with facility's capacity (Lee & Elsayed, 2005; Askin et al., 2013; Chau et al., 2019; Jamshidi et al., 2012; Paksoy et al., 2010; Sadjady & Davoudpour, 2012; Shankar et al., 2013; Wang et al., 2011; Sun et al., 2019) also consider the number of products that can be kept in the facility. The studies that consider multiple products (Zhu et al., 2021; Askin et al., 2013; Santosa & Kresna, 2015; Chau et al., 2019; Jamshidi et al., 2012; Paksoy et al., 2010; Sadjady & Davoudpour, 2012; Wang et al., 2011) will have to allocate the product to match the time frame. Studies by Paksoy et al. (2010), Wang et al. (2011), Jamshidi et al. (2012), and Sun et al. (2019) consider the environmental aspect of the supply chain. Jamshidi et al. (2012) minimize the amount of nitrogen oxide, carbon monoxide, and volatile organic produced in the supply chain, while Paksoy et al. (2010) and Wang et al. (2011) minimize the amount of carbon dioxide emission. Lastly, Sun et al. (2019) minimize the impact of transport and facilities on the population's health.

Mixed-integer linear programming (MIP) is used to find the optimal solution (Askin et al., 2013; Santosa & Kresna, 2015; Chau et al., 2019; Jamshidi et al., 2012; Paksoy et al., 2010; Sadjady & Davoudpour, 2012; Shankar et al., 2013; Sun et al., 2019; Zhu et al., 2021). In addition to MIP, other heuristic approaches, including genetic (Askin et al., 2013), simulated annealing (Santosa & Kresna, 2015), Memetic (Jamshidi et al., 2012), Lagrangian relaxation (Sadjady & Davoudpour, 2012), hybrid particle swarm optimization (Shankar et al., 2013), clustering (Zhu et al., 2021) algorithms, are applied to find a near-optimal solution. The normalized constraint method is used in Wang et al. (2011), and the min-max approach is applied by Sun et al. (2019) to find a compromised solution. For the non-linear programming model (Lee & Elsayed, 2005; Wang et al., 2011), the heuristic method is used in Lee and Elsayed (2005), while the normalized constraint method is used in Wang et al. (2011).

In summary, our study is an extension of Chau et al. (2019). In addition to distribution planning with multiple modes of transportation, we explicitly consider the environmental impact of distribution planning activity in terms of greenhouse gas emissions. Another closely-related study is that from Jamshidi et al. (2012). The authors consider a network design problem with multiple modes of transportation and environmental aspect. The major difference between our study and Jamshidi et al. (2012) is that their mathematical model contains non-linear constraints while our model is linear.

1.2 Problem Statement

The major details of this case study, including the distribution network, transportation mode, product properties, warehouse operations, and gas emission, will be described in this section

1.2.1. Distribution network

In this case-study supply chain, there are eleven factories, eight internal warehouses, six external warehouses, one overseas customer, and domestic customers scattered in 44 provinces of Thailand. All products are produced at the factory and then sent to the internal warehouse for packaging and storage. Due to the limited capacity of the internal warehouses, some of the products will be transferred to the external warehouse, which means the products will be sent either from internal or external warehouses. For the transportation modes, there is a total of 12

modes, e.g., 10-wheel and 18-wheel trucks. In which different modes are used for transporting products from each node.

1.2.2. Products

Each factory produces one type of polymer product with over 100 different grades. Later they will be packed in different package sizes and types, e.g., 20-kg bag, 500-kg bag, slab, etc. Different modes of transportation are required for these packages. Therefore, the product combinations from factories, grades, and package types are around 711.

1.2.3. Gas Emissions

Carbon dioxide emissions data are obtained from the Life cycle assessment laboratory of The National Metal and Materials Technology Center. In the data, the amount of emission is measured by mode and per kilometer.

1.2.4. Assumptions

- Production capacity from the factories is enough to satisfy all the demand. This assumption makes sure that the model is feasible.
- The planning horizon is assumed to be 20 years due to the estimated useful life of the warehouse.

2. Methodology

2.1. Mathematical Model

The problem is formulated as mixed-integer linear programming (MIP) models, where each model minimizes the different objective functions. In addition, we formulated another model that seeks a compromise solution among two objective functions. Figure 2 illustrates typical parameter and decisions in the model.

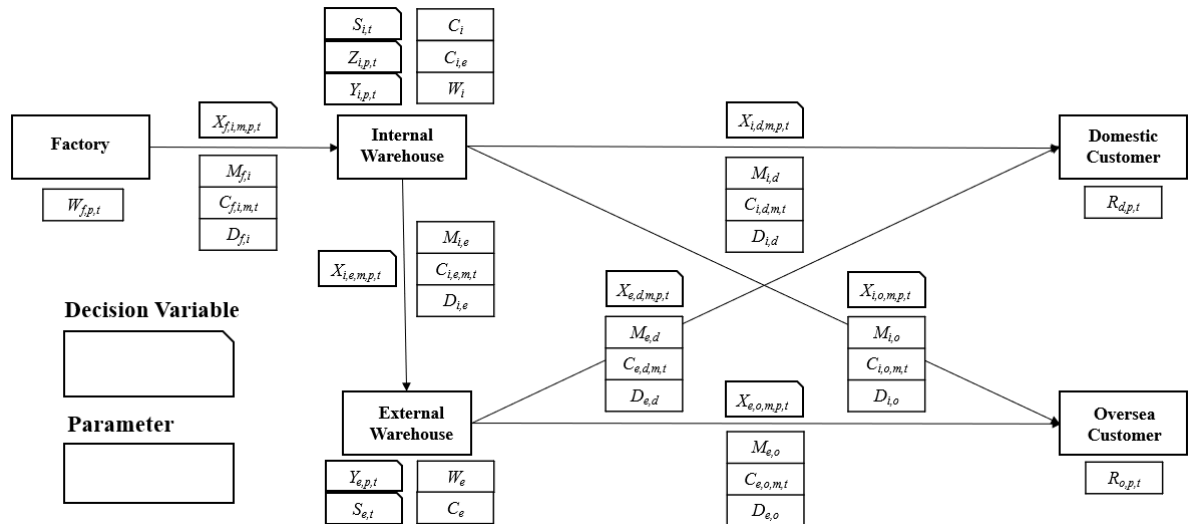


Figure 2: Model diagram

Set and index: products, $p \in P$; factory, $f \in F$; internal warehouses, $i \in I$; external warehouses, $e \in E$; domestic customers, $d \in D$; overseas customers $o \in O$; modes, $m \in M$; time period, $t \in T$; internal warehouse operation, $a \in A$; external warehouse operation, $b \in B$; transferred product

warehouse operation, $h \in H$; factory and internal warehouse, $(f, i) \in FI$; factory and product, $(f, p) \in FP$; internal warehouse and product, $(i, p) \in IP$.

Parameter: $C_{f,i,m,t}$ unit transportation cost from factory f to internal warehouse i using mode m in period t . $M_{f,i}$ transportation mode set from factory f to internal warehouses i , $D_{f,i}$ distance from factory f to internal warehouses i , G_m carbon dioxide emission using mode m ; C_i , C_e unit cost of performing all warehousing operations for products stored at internal warehouse i and external warehouse e , respectively. $C_{i,e}$ unit cost of performing all warehousing operations for products stored at internal warehouse i to external warehouse e ; W_i , W_e warehouse capacity at internal warehouse i and external warehouse e , respectively; $W_{f,p,t}$ amounts of products p supplied from factory f in period t ; $R_{d,p,t}$, $R_{o,p,t}$ domestic customer d and oversea customer o demand, respectively of product p in period t , I_p inventory days of product p

Decision variables: $X_{f,i,m,p,t}$ flow of product p from factory f to internal warehouse i using mode m in period t . $Y_{i,p,t}$, $Y_{e,p,t}$ amounts of products p stored at internal warehouse i and external warehouse e in period t , respectively. $Z_{i,p,t}$ amounts of products p transferred from internal warehouse i in period t . $S_{i,t}$, $S_{e,t}$ total storage space required at internal warehouse i and external warehouse e in period t , respectively.

2.1.1. MIP model for minimizing total cost

Minimize:

$$\begin{aligned}
 O_c = & \sum_{f \in F} \sum_{i \in I} \sum_{m \in M_{FI}} \sum_{t \in T} \sum_{p \in P} C_{f,i,m,t} X_{f,i,m,p,t} + \sum_{i \in I} \sum_{e \in E} \sum_{m \in M_{IE}} \sum_{t \in T} \sum_{p \in P} C_{i,e,m,t} X_{i,e,m,p,t} + \\
 & \sum_{i \in I} \sum_{o \in O} \sum_{m \in M_{IO}} \sum_{t \in T} \sum_{p \in P} C_{i,o,m,t} X_{i,o,m,p,t} + \sum_{e \in E} \sum_{o \in O} \sum_{m \in M_{EO}} \sum_{t \in T} \sum_{p \in P} C_{e,o,m,t} X_{e,o,m,p,t} + \\
 & \sum_{i \in I} \sum_{d \in D} \sum_{m \in M_{ID}} \sum_{t \in T} \sum_{p \in P} C_{i,d,m,t} X_{i,d,m,p,t} + \sum_{e \in E} \sum_{d \in D} \sum_{m \in M_{ED}} \sum_{t \in T} \sum_{p \in P} C_{e,d,m,t} X_{e,d,m,p,t} + \\
 & \sum_{a \in A} \sum_{i \in I} \sum_{t \in T} \sum_{p \in P} C_i Y_{i,p,t} + \sum_{b \in B} \sum_{e \in E} \sum_{t \in T} \sum_{p \in P} C_e Y_{e,p,t} + \sum_{h \in H} \sum_{i \in I} \sum_{t \in T} \sum_{p \in P} C_{i,e} Z_{i,p,t} \quad (1)
 \end{aligned}$$

Subject to:

$$\sum_{m \in M_{FI}} X_{f,i,m,p,t} = W_{f,p,t}, \forall (f, p) \in FP, \forall (f, i) \in FI, \forall t \in T \quad (2)$$

$$\sum_{m \in M_{FI}} X_{f,i,m,p,t} = Y_{i,p,t} + Z_{i,p,t}, \forall (i, p) \in IP, \forall t \in T \quad (3)$$

$$\sum_{d \in D} \sum_{m \in M_{ID}} X_{i,d,m,p,t} + \sum_{o \in O} \sum_{m \in M_{IO}} X_{i,o,m,p,t} = Y_{i,p,t}, \forall (i, p) \in IP, \forall t \in T \quad (4)$$

$$\sum_{e \in E} \sum_{m \in M_{IE}} X_{i,e,m,p,t} = Z_{i,p,t}, \forall (i, p) \in IP, \forall t \in T \quad (5)$$

$$\sum_{m \in M_{IE}} X_{i,e,m,p,t} = Y_{e,p,t}, \forall e \in E, \forall (i, p) \in IP, \forall t \in T \quad (6)$$

$$\sum_{d \in D} \sum_{m \in M_{ED}} X_{e,d,m,p,t} + \sum_{o \in O} \sum_{m \in M_{EO}} X_{e,o,m,p,t} = Y_{e,p,t}, \forall (i,p) \in IP, \forall t \in T \quad (7)$$

$$\sum_{e \in E} X_{e,o,m,p,t} + X_{i,o,m,p,t} = R_{o,p,t}, \forall o \in O, \forall (i,p) \in IP, \forall p \in P, \forall t \in T \quad (8)$$

$$\sum_{e \in E} X_{e,d,m,p,t} + X_{i,d,m,p,t} = R_{d,p,t}, \forall d \in D, \forall (i,p) \in IP, \forall p \in P, \forall t \in T \quad (9)$$

$$Y_{i,p,t} + \sum_{e \in E} Y_{e,p,t} = W_{f,p,t}, \forall (i,p) \in IP, \forall p \in P, \forall t \in T \quad (10)$$

$$S_{i,t} = \sum_{p \in P} \left(\frac{I_p}{365} \right) Y_{i,p,t}, \forall i \in I, \forall t \in T \quad (11)$$

$$S_{e,t} = \sum_{p \in P} \left(\frac{I_p}{365} \right) Y_{e,p,t}, \forall e \in E, \forall t \in T \quad (12)$$

$$S_{i,t} \leq W_i, \forall i \in I, \forall t \in T \quad (13)$$

$$S_{e,t} \leq W_e, \forall e \in E, \forall t \in T \quad (14)$$

$$\sum_{i \in I} \sum_{m \in M_{IE}} \left(\frac{I_p}{365} X_{i,e,m,p,t} \right) \leq W_e, \forall e \in E, \forall t \in T \quad (15)$$

The objective function (1) is to minimize the total transportation costs from each node and the total warehouse warehousing costs. Constraints (2) ensure that the factory production capacity must equal the amount of product supplied from the factory to the internal warehouse. Constraints (3) state that the number of products flowing into the internal warehouse must either be stored there or transferred to the external warehouse. Constraints (4) force the stored products in the internal warehouse to be sent to domestic or overseas customers. Constraints (5) force the transferred product from the internal warehouse must be shipped to the external warehouse. Constraints (6) state that the number of products flowing into the external warehouse must be stored there. Constraints (7) force the stored products in the external warehouse to be sent to domestic or overseas customers. Constraints (8, 9) ensure that domestic and overseas customers' demand must equal the number of products sent from the internal and external warehouse to domestic and overseas customers, respectively. Constraint (10) forces the stored product in internal and external warehouses to equal the production capacity. Constraints (11, 12) describe the storage area at the internal and external warehouse to be adjusted by the products' inventory day. Constraints (13, 14) ensure that the storage areas at the internal and external warehouses must not surpass their capacity. Constraint (15) enforces that the flow from the internal to external warehouses is already adjusted by the inventory day not to exceed the external warehouse's capacity.

2.1.2. MIP model for minimizing total carbon dioxide emission

Minimize:

$$O_{co} = \sum_{f \in F} \sum_{i \in I} \sum_{m \in M_{FI}} \sum_{p \in P} \sum_{t \in T} X_{f,i,m,p,t} D_{f,i} G_m + \sum_{i \in I} \sum_{e \in E} \sum_{m \in M_{IE}} \sum_{p \in P} \sum_{t \in T} X_{i,e,m,p,t} D_{i,e} G_m$$

$$\begin{aligned}
 & + \sum_{i \text{ in } I} \sum_{d \text{ in } D} \sum_{m \text{ in } M_{ID}} \sum_{p \text{ in } P} \sum_{t \text{ in } T} X_{i,d,m,p,t} D_{i,d} G_m + \sum_{e \text{ in } E} \sum_{o \text{ in } O} \sum_{m \text{ in } M_{EO}} \sum_{p \text{ in } P} \sum_{t \text{ in } T} X_{e,o,m,p,t} D_{e,o} G_m \\
 & + \sum_{i \text{ in } I} \sum_{o \text{ in } O} \sum_{m \text{ in } M_{IO}} \sum_{p \text{ in } P} \sum_{t \text{ in } T} X_{i,o,m,p,t} D_{i,o} G_m + \sum_{e \text{ in } E} \sum_{d \text{ in } D} \sum_{m \text{ in } M_{ED}} \sum_{p \text{ in } P} \sum_{t \text{ in } T} X_{e,d,m,p,t} D_{e,d} G_m
 \end{aligned} \tag{16}$$

The model that minimizes the total carbon dioxide emission from each node uses the objective function (16) and the same set of constraints as the previous model.

2.1.3. MIP model for determining compromise solutions

We formulated a compromise solution using the min-max approach to find the solution that minimizes the deviations from the ideal result.

Let O_c^* , O_{co}^* be the optimal solution obtained from models 2.11 and 2.12. Furthermore, let O_c^{worst} , O_{co}^{worst} be the worst result obtained from models 2.11 and 2.12. We can now find the deviation between the ideal and current results by normalizing the functions below.

$$\sigma_c = \frac{O_c - O_c^*}{O_c^{worst} - O_c^*} \tag{17}$$

$$\sigma_{co} = \frac{O_{co} - O_{co}^*}{O_{co}^{worst} - O_{co}^*} \tag{18}$$

We can now develop a min-max algorithm to include the deviations of our objectives in the model by adding a new decision variable Y as follows.

$$\text{Minimize:} \quad Y \tag{19}$$

$$\text{Subject to:} \quad \sigma_c \leq Y \tag{20}$$

$$\sigma_{co} \leq Y \tag{21}$$

$$(1) - (16) \tag{22}$$

The goal of the min-max algorithm is to minimize the largest deviation from the optimal result among the two objectives.

3. Results

3.1 Case study data

There are four products $P = \{1, 2, 3, 4\}$, two factories $F = \{1, 2\}$, two internal warehouses $I = \{1, 2\}$ which has two operations within the warehouse $A = \{1, 2\}$ and two operations to transfer products to external warehouses $H = \{1, 2\}$. There are two external warehouses $E = \{1, 2\}$ which has two operations $B = \{1, 2\}$, four domestic customers $D = \{1, 2, 3, 4\}$ and one overseas customer since all shipments go through the same seaport $O = \{1\}$ and five time periods $T = \{1, 2, 3, 4, 5\}$. There are three transportation modes $M = \{1, 2, 3\}$ where different modes are used depending on the origin and destination. The amount of generated Carbon dioxide is dependent on transportation mode and distance between the nodes.

3.2 Base case results

Table 2.

Result of single and multiple objective optimizations

		Single Objective		Multiple Objective
		Minimizing Total Cost	Minimizing CO2	Minimizing Total Cost and CO2
Total Cost	Total Transportation Cost	95,836,968	175,048,028	118,757,452
	Total Warehousing Cost	144,597,571	144,597,571	144,597,571
	Total Overall Cost	240,434,539	319,645,599	263,355,023
Total CO2 Emission	Satisfaction Level	100%	0%	71%
	Total CO2	1,880,372,221	1,867,521,491	1,871,239,974
	Satisfaction Level	0%	100%	71%
Average Satisfaction Level		50%	50%	71%

The summary of the total cost and gas emission is shown in Table 1. The results from the MIP model for minimizing total cost are shown in column "Minimizing Total Cost" the total overall cost is equal to 240,434,539 Baht, which is composed of transportation cost (95,836,968 Baht) and warehousing cost (144,597,571 Baht). The total gas emission is equal to 1,880,372,221 grams. The satisfaction level of total cost and gas emission is at 100% and 0%, respectively, indicating that this model gives the best optimal result for the total cost while giving the worst result for the gas emission. The results from the MIP model for minimizing total gas emission are shown in column "Minimizing Total Gas Emission" the optimal overall cost is equal to 319,645,599 Baht, which is composed of transportation cost (175,048,028 Baht) and warehousing cost (144,597,571 Baht). The total gas emission is equal to 1,867,521,491 grams. The satisfaction level of total cost and gas emission is at 0% and 100%, respectively, indicating that this model gives the best optimal result for the total gas emission while giving the worst result for the total cost.

For the compromise solutions, the results are shown in column "Minimizing Total Cost and Gas Emission" the total overall cost is equal to 263,355,023 Baht, which is composed of transportation cost (118,757,452 Baht) and warehousing cost (144,597,571 Baht). The total gas emission is equal to 1,871,239,974 grams. The total cost and gas emission satisfaction levels are both 71%. Based on the result, there is a clear trade-off between minimizing the total cost and emission. Therefore, our model allows the decision maker to find a compromised solution that balances the two conflicting objectives. In addition, the compromised solution offers a more environmentally friendly distribution policy regarding carbon emission than that obtained from a conventional model, in which the total distribution cost is minimized.

4. Conclusion and Future work

In this paper, we formulate a MIP model for determining the product allocation and capacity in a multi-product, multi-period distribution network to minimize total cost and gas emission. Later, we developed a model to find a compromised solution using a min-max approach to minimize the deviation from the ideal result. The limitation of this model is that it can only solve a small problem instance for now. The future work is to add more types of emission gas, develop a model that can solve a large-scale problem, and use the stochastic data type instead.

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