MATHEMATICAL MODEL FOR MULTIPLE PRODUCTS ALLOCATION OF A DISTRIBUTION NETWORK

แบบจำลองคณิตศาสตร์สำหรับการจัดสรรสินค้าหลายชนิดของเครือข่ายกระจายสินค้า

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Abstract

This paper involves a mathematical model of a multiple product allocation problem for a distribution network in Thailand. The distribution network includes four members: one factory, one internal warehouse, three external warehouses, and many customers. The problem considers multiple products, differentiated by quality level, package, and product movement, in multiple periods, with two shipment methods, and deterministic demand. The objective is to find optimal product allocation to multiple warehouses in the distribution network so as to minimize the total cost of transportation and warehouse. A linear programming model was developed to solve the problem.

Keywords: Distribution network, Optimal product allocation, Linear programming

บทคัดย่อ

บทความวิจัยนี้นำเสนอแบบจำลองคณิตศาสตร์สำหรับการจัดสรรสินค้าที่มีหลายประเภทในเครือข่ายกระจายสินค้าเครือข่ายหนึ่งในประเทศไทย ซึ่งประกอบด้วยโรงงานผู้ผลิตสินค้า คลังสินค้าที่ตั้งอยู่ในเขตโรงงาน คลังสินค้าภายนอกที่ทางโรงงานเช่าเพื่อใช้จัดเก็บสินค้าส่วนเกิน 3 แห่ง และลูกค้าในจังหวัดต่างๆ ปัญหาการจัดสรรสินค้าเพื่อจัดเก็บในคลังสินค้าต่างๆ ของบทความวิจัยนี้มีลักษณะคือ พิจารณาสินค้าหลายชนิดที่มีความแตกต่างกันโดยระดับคุณภาพของสินค้า บรรจุภัณฑ์ และอัตราการเคลื่อนไหวของสินค้า ทำการแก้ปัญหาสำหรับหลายช่วงเวลา (ปี) รวมถึงการกระจายสินค้า 2 วิธี คือ ส่งสินค้าจากคลังสินค้าของโรงงานถึงลูกค้าโดยตรง และส่งสินค้าที่มีการจัดเก็บในคลังสินค้าเช่าภายนอก โดยใช้ค่าประมาณความต้องการสินค้าของลูกค้าต่อปีเป็นค่าคงที่ วัตถุประสงค์การแก้ปัญหาคือ เพื่อหาการจัดสรรสินค้าที่เหมาะสมที่สุดสำหรับการจัดเก็บสินค้าหลากหลายในคลังสินค้าทั้ง 4 แห่งในเครือข่าย

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การกระจายสินค้านี้ ที่จะทำให้ต้นทุนการกระจายสินค้าซึ่งประกอบด้วยค่าขนส่งและค่าจัดการคลังสินค้ามีค่าต่ำที่สุด ซึ่งแบบจำลองเชิงเส้นได้ถูกพัฒนาขึ้นเพื่อใช้ในการแก้ปัญหาดังกล่าว

คำสำคัญ: เครือข่ายกระจายสินค้า การจัดสรรสินค้าที่เหมาะสมที่สุด แบบจำลองเชิงเส้น

Introduction

Product distribution in a supply chain is an importation operation in today business' intense competition. One of the key decisions is product allocation in a distribution network, which affects its competiveness because proper allocation leads to efficiency in satisfying customer demand Chopra (2003). This study involves a case study of designing a distribution network of a company in Thailand. The network structure is shown in Figure 1.

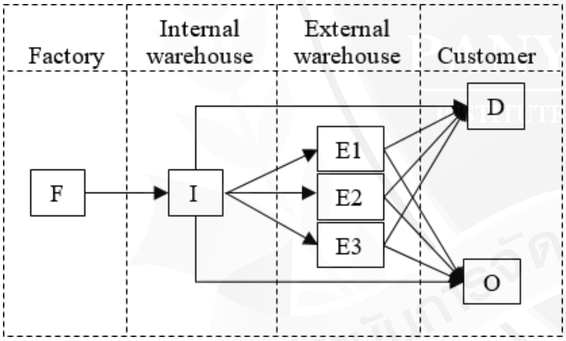

Figure 1 Distribution network

Figure 1 illustrates the network under study, which consists of one factory, one internal warehouse, three external warehouses and many customers, domestic and oversea. The factory has a production capacity of 250,000 mt per year, and has its dedicated internal warehouse with storage capacity of 20,000 mt. Due to the limited capacity of the internal warehouse, the company currently uses three externally rent warehouses, two small (located closer to the factory) and one large, all of which charge storage cost on a per unit per period basis. Customers can be divided into domestic customers in more than fourty provinces of Thailand and a group of oversea customers, whose delivery destination is the largest seaport of Thailand.

Products vary by level of quality and are packed in six different package sizes and types. There is a total of 91 products resulting from unique combinations of quality level and package type. Customer demands can be satisfied by direct shipment from the internal warehouse or by inventories stored at the external warehouses, which require product to be transferred from internal to external warehouses.

Future customer demand mixes between domestic and oversea are forecasted for a period of three years, from 2018 to 2020 (Figure 2). As seen from the figure, domestic demands are expected to slightly increase for the next two years (2018-2019), and grow in the third year (2020). In contrast, oversea demands are forecasted to decrease slightly for the next few years (2018-2019), and decrease relatively higher in the third year (2020).

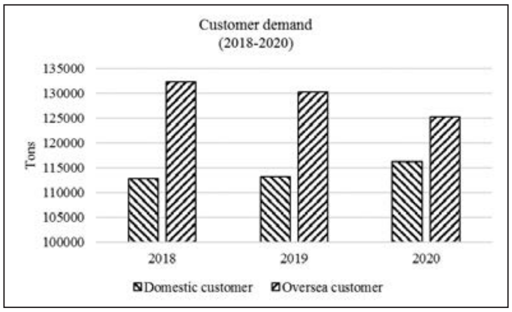

Figure 2 Customer demand

Product movement is simply divided into fast moving and slow moving. Table 1 shows the number of SKUs and average inventory days of the products.

Table 1 Average inventory days of fast and slow moving product

		Factory
Fast moving	No. of SKU	12
	Avg. Inv. Day	10.5
Slow moving	No. of SKU	79
	Avg. Inv. Day	53.8

The warehouse operations, both internal and external, include packaging, inbound loading and unloading with forklift or labor, putaway, storage, retrieval, and outbound loading and unloading. At internal warehouses, all products are delivered from factory for packaging first, Then, products are either stored at the internal warehouse, or transferred to one of the external warehouses. For transferred products, they will be packed, wrapped, and loaded before transferring. The products to be delivered to the customers, at both internal and external warehouses, are retrieved from storage, picked, wrapped, load and unload on to delivery trucks.

There are three types of storages that require different storage areas in the warehouses: normal package and large package are block stacked in conventional storage areas, and some special products are kept in tent. Products and storage areas are preassigned according to the product quality level, package type, and value. These storage types must be taken into account, when considering the warehouse capacity.

There are six modes of transportation: two types of 10-wheel trucks, two types (sizes) of 18-wheel trucks, bulk truck, and pipe. They are used to deliver products from factory to warehouses (pipe and 10-wheel truck), from warehouses to domestic customers (bulk truck and 10-wheel trucks), and from warehouses to oversea customers (18-wheel trucks).

To efficiently meet future customer demand, an important decision is to find optimal product allocation in this network: from factory to each warehouse and from each warehouse to the customers. The objective is to minimize the total cost, consisting of transportation and warehouse costs, over the period of planning horizon. A mixed integer linear programming (MILP) model is developed to find optimal solution of this problem.

Literature review

The network design problems have been studied in the past few decades because of its importance in satisfying customer demand. Table 2 summarizes the decisions and problem characteristics of these studies.

Table 2 Characteristics of the recent relevant studies

Study	No. of SC echelos	Product allocation	No. of product (s)	Direct shipment	Throung D.C	Demand	No. of period(s)
Wu, Zhang & Zhang (2006)	2	✓	1		✓	U	1
Tuzkaya & Onut (2009)	3	✓	>1		✓	U	>1
Sourirajan, Ozsen & Uzsoy (2009)	3	✓	1		✓	U	1
Conceição et al. (2012)	3	✓	>1		✓	D	1
Askin, Baffo & Xia (2014)	3	✓	>1	✓	✓	U	1
Hlayl et al. (2015)	3	✓	1		✓	D	1
Shankar et al. (2013)	4	✓	1		✓	D	1
This study	4	✓	91	✓	✓	D	3

Note: U denotes uncertain demand, D denotes deterministic demand

In the previous studies, the number of supply chain echelons ranges from two to four members and a decision of product allocation appeared in all of them. There are some different characteristics of the relevant studies. In all studies, products are distributed through distribution center (DC), except Conceição et al. (2012). Various distribution network problems can be grouped into (1) a single product, single period, and deterministic demand in Hlyal et al. (2015) and Shankar et al. (2013); (2) single product, single period uncertain demand in Wu, Zhang & Zhang (2006) and Sourirajan, Ozsen & Uzsoy (2009); (3) multiple product, single period, and deterministic demand in Conceição et al. (2012); (4) multiple products, single period, and uncertain demand in Askin, Baffo & Xia (2014); and (5) multiple products, multiple periods, and uncertain demand in Tuzkaya & Onut (2009).

Mathematical model

Some notations are used for the mathematical formulation of model.

Sets

p : product, which are defined uniquely by quality level and package type.

e : external warehouse.

o : oversea customer.

d : domestic customer.

t : time period.

m : transportation mode.

opi : operations in internal warehouse.

ope : operations in external warehouse.

opt : operations for transferring products from internal warehouse to external warehouses.

k : storage type.

M_{IO} = {5, 6}: Transportation mode set from internal warehouse to oversea customers.

M_{EO} = {5, 6}: Transportation mode set from external warehouses to oversea customers.

M_{ID} = {2, 3, 4}: Transportation modes from internal warehouse to domestic customers.

M_{ED} = {2, 3}: Transportation modes from external warehouses to domestic customers.

$M_{DD} = M_{ID} \cup M_{ED}$: Transportation modes from internal or external warehouses to domestic customers.

$M_{OD} = M_{IO} \cup M_{EO}$: Transportation modes from internal or external warehouses to oversea customers.

P = {1, 2, 3, .., 91}: All product set.

T = {1, 2, 3}: Time period set.

E = {1, 2, 3}: External warehouse set

D = {1, 2, 3, .., 44}: domestic customer set.

A = {1, 2, 3,.., 8}: all warehousing operation set at internal warehouse.

B = {3, 5, 6, 9, 10, 11}: all warehousing operation set at external warehouses.

C = {1, 4, 5, 6, 10}: all warehousing operation set of transferring from internal warehouses to external warehouses.

K = {1, 2, 3}: storage type set.

Parameters

CFI_t : Unit transportation cost from factory to internal warehouse in period t.

$CIE_{e,t}$: Unit transportation cost from internal warehouse to external warehouse e in period t.

$CIO_{m,t}$: Unit transportation cost from internal warehouse to oversea customer using mode m in period t.

$CEO_{e,m,t}$: Unit transportation cost from external warehouse e to oversea customer using mode m in period t.

$CID_{d,m,t}$: Unit transportation cost from internal warehouse to domestic customer d using mode m in period t.

$CED_{e,d,m,t}$: Unit transportation cost from external warehouse e to domestic customer d using mode m in period t.

C_{opi} : Unit cost of performing all warehousing operations for products stored at internal warehouse.

$C_{ope,e}$: Unit cost of performing all warehousing operations for products stored at external warehouse e.

C_{opt} : Unit cost of performing all warehousing operations of for products transferred from internal warehouse to external warehouse e.

$CAP_{e,k}$: Warehouse capacity at external warehouse.

$CAPI_k$: Warehouse capacity at internal warehouse.

I_p : Inventory day of product p.

$DD_{d,p,m,t}$: Domestic customer d demand of product p using mode m in period t.

$OD_{p,m,t}$: Oversea customer demand of product p using mode m in period t.

$FCap_{p,t}$: Amount of products p supplied from factory in period t.

Decision variable

$XFI_{p,t}$: Flow of product p from factory to internal warehouse in period t.

$XIE_{e,p,t}$: Flow of product p from internal warehouse to external warehouse e in period t.

$XIO_{m,p,t}$: Flow of product p from internal warehouse to oversea customers using mode m in period t.

$XEO_{e,m,p,t}$: Flow of product p from external warehouse e to oversea customers using mode m in period t.

$XID_{d,m,p,t}$: Flow of product p from internal warehouse to domestic customers d using mode m in period t.

$XED_{e,d,m,p,t}$: Flow of product p from external warehouse e to domestic customers d using mode m in period t.

$Y_{p,t}$: Amount of products p stored at internal warehouse in period t.

$Y_{e,p,t}$: Amount of products p stored at external warehouse e in period t.

$Z_{p,t}$: Amount of products p transferred from internal warehouse in period t.

$S_{k,t}$: Total storage space of storage type k at internal warehouse in period t.

$S_{e,k,t}$: Total storage space of storage type k at external warehouse e in period t.

Mathematical model

Minimize:

$$\sum_{t\in T}\sum_{p\in P} CFI_t XFI_{p,t} + \sum_{e\in E}\sum_{t\in T}\sum_{p\in P} CIE_{e,t} XIE_{e,p,t} + \sum_{m\in M_{IO}}\sum_{t\in T}\sum_{p\in P} CIO_{m,t} XIO_{m,p,t} + \sum_{e\in E}\sum_{m\in M_{EO}}\sum_{t\in T}\sum_{p\in P} CEO_{e,m,t} XEO_{e,m,p,t} + \sum_{d\in D}\sum_{m\in M_{ID}}\sum_{t\in T}\sum_{p\in P} CID_{d,m,t} XID_{d,m,p,t} + \sum_{e\in E}\sum_{d\in D}\sum_{m\in M_{ED}}\sum_{t\in T}\sum_{p\in P} CED_{e,d,m,t} XED_{e,d,m,p,t} + \sum_{opi\in A}\sum_{t\in T}\sum_{p\in P} C_{opi} Y_{p,t} + \sum_{ope\in B}\sum_{e\in E}\sum_{t\in T}\sum_{p\in P} C_{ope,e} Y_{e,p,t} + \sum_{opt\in C}\sum_{t\in T}\sum_{p\in P} C_{opt} Z_{p,t} \quad (1)$$

Subject to:

$$\sum_{p\in P} XFI_{p,t} = FCap_{p,t}, \forall t\in T \quad (2)$$

$$\sum_{p\in P} XFI_{p,t} = Y_{p,t} + Z_{p,t}, \forall t\in T \quad (3)$$

$$\sum_{d\in D}\sum_{m\in M_{ID}} XID_{d,m,p,t} + \sum_{m\in M_{IO}} XIO_{m,p,t} = Y_{p,t}, \forall p\in P, \forall t\in T \quad (4)$$

$$\sum_{e\in E}\sum_{p\in P} XIE_{e,p,t} = Z_{p,t}, \forall t\in T \quad (5)$$

$$\sum_{p\in P} XIE_{e,p,t} = Y_{e,p,t}, \forall e\in E, \forall t\in T \quad (6)$$

$$\sum_{d\in D}\sum_{m\in M_{ED}} XED_{e,d,m,p,t} + \sum_{m=M_{EO}} XEO_{e,m,p,t} = Y_{e,p,t}, \forall e\in E, \forall p\in P, \forall t\in T \quad (7)$$

$$\sum_{e\in E} XEO_{e,m,p,t} + XIO_{m,p,t} = OD_{p,m,t}, \forall p\in P, \forall m\in M_{OD}, \forall t\in T \quad (8)$$

$$\sum_{e\in E} XED_{e,d,m,p,t} + XID_{d,m,p,t} = DD_{d,p,m,t}, \forall d\in D, \forall p\in P, \forall m\in M_{DD}, \forall t\in T \quad (9)$$

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

$$S_{k,t} = \sum_{\forall p\in P_k}\left(\frac{I_p}{365} Y_{p,t}\right), \forall k\in K, \forall t\in T \quad (11)$$

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

$$S_{k,t} \le CAPI_k, \forall k\in K, \forall t\in T \quad (13)$$

$$S_{e,k,t} \le CAP_{e,k}, \forall e\in E, \forall k\in K, \forall t\in T \quad (14)$$

The objective function in Eq.(1) includes the total transportation costs from factory to internal warehouse, then to external warehouses, and from all warehouses to domestic and oversea customers; and the total warehousing costs of 11 activities, ranging from unloading, packaging, putting away to loading, and all types of storage costs. Constraints (2-9) describe the flow balances of the network as follows. Constraints (2) force that the amount of products from factory to internal warehouse must not exceed the factory production capacity. Constraints (3) present the flow balance at internal warehouse that the amount of products that flow in must either be stored at the internal warehouse or transferred to an external warehouse. Constraints (4) relate the flow balance of stored products on the outbound of an internal warehouse that the total amount must be shipped to either domestic or oversea customers. Constraints (5) are the flow balances of transferred products on the outbound at internal warehouse that the products must be shipped to external warehouses. Constraints (6) are the flow balances on the inbound at an external warehouse that the transferred amount must be stored at that external warehouse. Constraints (7) are the flow balances on the outbound of external warehouses that the stored product must either be shipped to domestic or oversea customers. Constraints (8-9) display the flow balances from internal and external warehouses to domestic and oversea customers that the total amount shipped must satisfy the demand of domestic and oversea customers, respectively.

Constraints (10-14) relate requirements of storage at warehouses. Constraints (10) force that the total amount of a product stored at both internal warehouse and external warehouses must be equal to the production capacity for that product. Constraints (11-12) compute the total required storage area at the internal warehouses and external warehouses, respectively, by storage type. Constraints (13-14) force that the total storage areas at internal warehouse and external warehouse must not exceed its capacity, respectively, by storage type.

The problem contains one factory, one internal warehouse, three external warehouses, 91 products, and three periods. The MILP model has 72,920 variables and 10,175 constraints. The model is solved to optimality using CPLEX 12.6.3.0 in GAMS 24.7.3.

Results and discussion

The results show that the total logistics cost in three years is 418.3 million THB, which includes the total transportation cost of 277.0 million THB, and total warehouse cost of 141.3 million THB. Table 3 provides detail of the cost components, and Table 4 contains the optimal product allocation.

Table 3 Cost of the network (mil.THB)

Total cost (2018-2020):	**418.3**
Total transportation cost:	277.0
- From factory to int. W/H	0
- From int. W/H to ext. W/H's	17.7
- From int.W/H to domestic customers	110.2
- From int.W/H to oversea customers	63.3
- From ext.W/H's to domestic customers	44.3
- From ext. W/H's to oversea customers	41.4
Total warehouse cost:	141.3
- Int. W/H	88.1
- Ext. W/H's	53.2

Table 4 Fast-slow moving products of facilities

Product	Internal warehouse	External warehouse		
		E1	E2	E3
Fast moving	50.0%	0.5%	-	1.7%
Slow moving	14.9%	9.6%	5.9%	17.4%

The internal warehouse capacity is primarily used to store most fast moving items (50% of all product volumes), with the remaining capacity for slow-moving item (14.9% of the total product volumes). For the external warehouses, their capacities are used for slow moving item storage, with small percentage of the remaining fast moving items kept at a small external warehouse (E1) and at the large external warehouse (E3). In addition, with this optimal allocation, the utilizations of the internal warehouse and two small external warehouses (Ext. W/H 1 and Ext. W/H 2) are at 100%. For the other external warehouse (Ext. W/H 3), the utilization of the warehouse cannot be estimated because it is a rented warehouses that are shared with other factories, not included in this network. This indicates that using smaller and closer external warehouses is more cost effective than using the large but farther external warehouse. This implies that the main reason for this product allocation is the transportation cost.

The amount of products stored at each facility are presented in Table 5. Note that these amounts only represent the amounts of products that the model recommends to be store at these facilities, i.e. only some products are stored at each facility.

Table 5 Total amount of products stored at each facility

Facility	Amount (ton)
Factory:	730,147
Int. W/H:	474,416
• Domestic customers	239,080
• Oversea customers	235,336
Ext. W/H's:	255,731
+Ext. W/H 1:	73,609
• Domestic customers	37,673
• Oversea customers	35,935
+Ext. W/H 2:	43,190
• Domestic customers	16,567
• Oversea customers	26,623
+Ext. W/H 3:	138,932
• Domestic customers	48,981
• Oversea customers	89,952

The factory produces 730,147 ton of products that are totally moved to the internal warehouse for packaging. At internal warehouses, only 474,416 tons are stored, and the remaining 255,731 tons are transferred to the external warehouses. For the external warehouses: E1 stores 73,609 ton, E2 43,190 ton, and E3 138,932 tons. The table also provides the amounts at each facility that are distributed to the domestic and oversea customers. At each external warehouse, products are also supplied to domestic and oversea customers.

Each unique product is a combination of quality level and type (or size) of package. Table 6 shows the number of package types for each product quality level, stored at internal and each external warehouse. For example, the first row of Table 6 indicates that there are two type (or sizes) of packages for product quality level 1. All of them are stored at the internal warehouse and then a part of them are shipped to external warehouse 3.

Table 6 Kind of product of facilities

Quality level	No. of package type			
	Internal warehouse	External warehouse		
		E1	E2	E3
Level 1	1			1
Level 2	1			1
Level 3	4	3	1	1
Level 4	2	1	1	
Level 5	3	2	1	1
Level 6	4			2
Level 7	8	2	1	8
Level 8	1			
Level 9	5	2	1	3
Level 10	3	2	2	1
Level 11	1			
Level 12	1			1
Level 13	3	1	1	1
Level 14	1			1
Level 15	2			2
Level 16	4			4
Level 17	3			2
Level 18	3	1		1
Level 19	1	1		
Level 20	4	1	1	4
Level 21	2			2
Level 22	8	3	3	3
Level 23	6			2
Level 24	3			3
Level 25	3	2	1	
Level 26	3	2	1	1
Level 27	2			2
Level 28	2			2
Level 29	1			1
Level 30	1			1
Level 31	1			1
Level 32	1			1
Level 33	1			1

Conclusion

In this paper, we considered the problem of determining the optimal product allocation in a real-world distribution network. The problem is formulated as an MILP model. Solving the model gives a minimal total logistic cost is 418.3 million THB. The optimal solution clearly provides the amount of products in terms of quality level and type of package stored at each warehouse. This model provides an optimal base case scenario for further analysis in the case that a new facility is to be added to the network in the future.

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