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Vendor Managed Inventory for Multi-Vendor Single-Manufacturer Supply Chain: A Case Study of Instant Noodle Industry

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Abstract. This paper develops a vendor-managed inventory (VMI) model for a multiple-vendor, single-manufacturer supply chain, in which the first stage members can be traders and/or producers and the second stage member is a manufacturer. The model utilizes a realistic transportation cost which is dependent on the sizes (small- or medium-sized) of trucks. It can determine suitable sizes and numbers of trucks that minimize the transportation cost. A genetic algorithm (GA) technique, implemented in MATLAB software, is used to determine the best solution to the problem. A case study in the instant noodle industry is conducted to demonstrate the usefulness of the proposed model. Based on the experimental results, the VMI model has reasonable behaviors using sensitivity analysis. To reduce the inventory level of raw materials, the penalty cost may be set at a relatively high level or the upper inventory limits may be set at relatively low levels, without significantly affecting the average total cost per period of the entire supply chain. When the vendors are allowed to make decision independently, the solution is still the same as the solution from the proposed VMI model, which means that the manufacture does not take advantage of the vendors.

Keywords: Supply Chain Management (SCM), multi-vendor, single manufacturer, Vendor Managed Inventory (VMI), instant noodle supply chain, multiple truck sizes.

1. Introduction

With the development of global markets, supply chain management (SCM) plays an important role in incorporating different parts of a supply chain (SC) for better performances. SCM comprises planning and controlling related activities in transportation, inventory, procurement, and conversion from the upstream to the downstream members of the supply chain. SCM includes coordination and collaboration between members that can be suppliers, intermediaries, manufacturers, warehouses, third-party service providers, and final customers [1]. Walmart is an enterprise that has applied SCM successfully [2]. In SCs, inventory management has a key role in planning for production and maintaining a high service level for improving supply chain performances [1]. Solving inventory issues is a key factor that various authors want to find out polices to minimize the inventory cost and total system costs [3–7]. Vendor-managed inventory (VMI) is known as an effective inventory control strategy.

The VMI technique uses cooperating business models, in which the buyer (retailer) of a product provides specific information to a supplier (vendor) of that product. The supplier is responsible for maintaining the inventory level according to a VMI contract [8–11]. Based on a win-win relationship, the VMI contract sets frameworks, constraints about sources, work for each partner involved, and guarantees that they receive benefits. Typically, this relationship is shown in the VMI contract that vendors and retailers negotiate for the agreement of policies and benefits for each member. This improves the performances of supply chain members [10]. In previous research, the VMI model showed good performances [8] even in a seasonal demand situation [12].

This paper is motivated by three issues. First, the VMI model proposed in this paper is specially developed to be suitable for an instant noodle supply chain in Thailand, which has some characteristics that the available VMI models in the literature cannot easily model. The characteristics of this instant noodle supply chain are as follows. The first stage is multiple suppliers, which may be traders or producers while the second stage is a manufacturer of instant noodles. Moreover, transportation from the first stage to the second stage can be performed using small- and/or medium-sized trucks. The medium-sized truck has a lower unit cost for transportation than the small-sized truck. These characteristics cannot be handled by the existing VMI models. Second, the manufacturer of the instant noodles, which is the second stage of the supply chain, sets a maximum limit for each raw material to be stored at the manufacturer. When the inventory level of the raw material exceeds the preset maximum limit, the supplier of that raw material must pay a penalty cost to the manufacturer. This policy is set to control the inventory holding cost at the manufacturer. However, the maximum limit and the penalty cost are not easy to be

reasonably set. The supply chain is concerned that when the maximum limit and the penalty cost are not suitably set, this may adversely affect the total cost of the entire supply chain. Therefore, the VMI model is specially developed to be suitable for the characteristics of the supply chain. In addition, the maximum limit and the penalty cost are varied. The effects on the average total cost per period of the entire supply chain are then determined. The result of this sensitivity analysis is useful for setting suitable values of the maximum limit of inventory at the manufacturer and the related penalty cost. Third, the instant noodle supply chain is dominated by the second stage which is the instant noodle manufacturer. The proposed VMI model is developed to minimize the total cost per period of the entire supply chain. It is suspected by the vendors whether they will have higher cost to follow the solution from the model when compared with making decision independently by minimizing the vendor's total cost.

This paper has specific objectives as follows.
1. To develop a VMI model that can be applied with the characteristics of the instant noodle supply chain in Thailand, which is a case study.
2. To verify that the VMI model has reasonable behaviors, using sensitivity analysis.
3. To analyze how the penalty cost and maximum limit of inventory affect the average total cost per period.
4. To analyze whether the vendors should follow the recommendation form the model or should make decision independently.

The structure of this paper is organized as follows. Section 2 reviews previous research works and explains how this paper is different from other works. Section 3 presents the concepts of the VMI model, notations of parameters and variables, and the mathematical formulas. Section 4 presents details of the GA method, which is used to solve for the best solutions to the problem. The case study data are presented in Section 5. The results are presented and discussed in Section 6. Finally, the conclusions and recommendations for further studies are presented in Section 7.

2. Literature Review

The VMI technique is renowned as a tactic for inventory management, cooperation between the vendor and retailer, and balancing profits of supply chain members by sharing information [13]. Key decisions of the VMI technique are to determine when and how much to replenish the inventory. The main objective is to reduce relevant costs including transportation and inventory costs [14]. Table 1 presents the characteristics of the VMI supply chain in this paper and previous research works. From Table 1, the VMI supply chain partnership can be categorized into the single-vendor single-retailer model [10, 11, 15–17]. Some authors consider the single-vendor multi-retailer model [18–25].

Fewer studies consider a multi-vendor multi-retailer model [14, 26]. This paper is different from most of the previous works in that it considers a multi-vendor, single-manufacturer supply chain, which is the structure of the instant noodle supply chain of interest.

Some previous research works consider the VMI model for the single-vendor single-retailer supply chain, in which the upstream member is a trader [8, 15, 27, 28] or the upstream member is a manufacturer [10, 11, 29]. Sadeghi, et al. [14] studied the multiple-vendor multiple-retailer supply chain where the upstream members are all traders. Most research works consider that the downstream member is a trader or traders, not a manufacturer. They include [10, 11, 15, 30] for a single downstream member that is a trader. For multiple downstream members that are traders, the research works include [12, 18-20, 31]. This paper extends the VMI technique to the multiple-vendor single-manufacturer supply chain where the upstream members may be traders and/or manufacturers, and the downstream member is a manufacturer.

There are some important issues of VMI models, including the replenishment cycle time, single inventory item or multiple inventory items, maximum inventory limit and penalty cost, and how to calculate a realistic transportation cost. The first issue to be discussed is the replenishment cycle time. Most research works assume that the replenishment cycle times of all members in the same echelon must be the same [18, 21, 25]. A few research works allow the replenishment cycle times of all members to be different [19, 20, 27]. This paper allows the upstream members to have different replenishment cycle times, making the model to be more flexible and resulting in lower average total costs per period.

Most previous research works consider only one product or inventory item to be controlled by the VMI model [10, 20, 31]. They are suitable for the supply chain of a trading business, not a manufacturing system. This paper develops the VMI model for a manufacturing supply chain, where the downstream member is an instant noodle factory that receives various raw materials from a number of vendors (both traders and manufacturers). Therefore, the supply chain involves many inventory items, which is more complicated than a single inventory item.

In the VMI model, the vendors manage when and how much to supply to the retailers. The vendors may send a large amount of product to the retailers to reduce the vendor holding cost. There is a technique to set the upper inventory limit at the retailer. If a vendor supplies beyond the upper limit, the vendor needs to pay a penalty cost (called an overstock penalty in Table 1) to the retailer. This technique restricts the quantity that the vendor delivers to the retailer, and balances the profit of the vendor and retailer in the supply chain [18, 19, 21]. This technique is different from setting the maximum storage limit at the retailers (see [14], [22]) since this is more rigid in that it does not allow the inventory level to be higher than the maximum storage limit. This paper analyzes how to set a suitable level of the upper inventory limit and the overstock penalty cost, which is rarely found in previous research works.

In the supply chain, the transportation cost is an expensive element that needs to be minimized. Most previous research works simply estimate the transportation cost per trip as a constant, which is not dependent on the transportation quantity. This paper considers a new method of computing the transportation cost that is more realistic. The transportation from the upstream to the downstream members is performed using small- and/or medium-sized trucks. The medium-sized truck has a lower unit cost for transportation than the small-sized truck. For a given transportation quantity, the vendor can consider which size of truck and how many trucks should be used to minimize the transportation cost.

3. Mathematical Model

The model is developed based on the following concepts.

1. The time bucket is daily.
2. The first stage of the supply chain is multiple vendors. Some vendors are producers and others are traders. The second stage of the supply chain is a manufacturer. Each vendor supplies different raw materials to the manufacturer.
3. There are two main decision variables, namely, the production cycle time of the manufacturer (T) and the replenishment frequency of vendor i (n_i). T is the number of days (integer) that the manufacturer continuously produces a batch of the product. During T days, vendor i (the producer) continuously produces a batch of raw material with a production quantity of Q_i. This vendor adjusts the production rate to be the same as the consumption rate of the raw material at the manufacturer, to minimize the inventory level according to the lean concept. Similarly, vendor i (the trader) orders a batch of raw material with an order quantity of Q_i from its supplier during T days.
4. During T days, vendor i delivers the raw material to the manufacturer for n_i times, where n_i is an integer. Therefore, the replenishment cycle time of vendor i (t_i) is $\frac{T}{n_i}$. Note that t_i may be an integer or a real number. The transportation quantity from vendor i to the manufacturer per each delivery (q_i) is $D_i t_i$, where D_i is the demand rate of the raw material supplied by vendor i.
5. When the maximum inventory level of material from vendor i at the manufacturer is higher than the upper limit (U_i), vendor i must pay a penalty cost [7].

Table 1. Comparison of previous research works and this research.

Paper	Type of model*				1st stage	2nd stage	Decision variables	constraints	Solution Algorithm
	A	B	C	D					
[10]	X				A manufacturer	A trader	Manufacturer's production quantity, Purchase price offered to manufacturer	Demand, Return leftover product to manufacturer	Analytical method based on expected profit
[15]	X				A trader	A trader	Replenishment quantity	none	Analytical method based on total cost
[20]		X			A manufacturer	Traders	Replenishment cycle time	none	Analytical method based on total cost
[19]		X			A trader	Traders	Order quantity, Delivery quantity, Replenishment cycle time	Overstock penalty	Iterative heuristic
[18]		X			A trader	Traders	Order quantity, Delivery quantity	Overstock penalty	An algorithm based on KKT points
[21]		X			A trader	Traders	Replenishment cycle time, Delivery quantity	Overstock penalty	Mathematical programming based on expected total cost
[22]		X			A trader	Traders	Replenishment cycle time, Order quantity	Maximum storage limit	GA
[25]		X			A manufacturer	Traders	Replenishment cycle time, Delivery quantity, Purchase price, Promotion level	Overstock penalty	PSO
[12]				X	Traders	A trader	Inventory quantity	none	Analytical method based on expected profit
[14]				X	Traders	Traders	Replenishment cycle time, Order quantity	Maximum storage limit, Maximum number of orders per period	GA, PSO
This paper			X		Traders or manufacturers	A manufacturer	Replenishment cycle time, Delivery quantity, Production cycle time	Overstock penalty, Different sizes of trucks	GA

A: **Single to single, B: Single to multiple, C: Multiple to single, D: Multiple to multiple***

6. There are two truck sizes for transporting raw materials from the vendors to the manufacturer: small and medium. The capacity of a medium truck is more than three times (but less than four times) the capacity of a small truck. Two trips of the small truck are cheaper than a trip of a medium truck but three trips of a small truck i are more expensive than a trip of a medium truck. To transport (q_i) kg of the raw material from vendor i to the manufacturer, a suitable number and size of trucks must be calculated to minimize the transportation cost.

7. The total costs under consideration include the set-up cost of the manufacturer, inventory holding cost of raw materials of the manufacturer, inventory holding cost of vendors, set-up cost of a vendor when it is a producer, ordering cost of a vendor when it is a trader,

penalty cost of a vendor when the inventory of raw material at the manufacturer exceeds the upper limit, and transportation cost of raw materials from vendors to the manufacturer.

8. The best values of T and n_i are determined using a Genetic Algorithm (GA) in MATLAB software, to minimize the average total costs per day TC_p.

Figure 1 shows inventory patterns of raw materials supplied by vendors to the manufacturer. The inventory patterns when the vendors are producer and trader are shown on the left and right, respectively. Various formulas for total costs and individual cost components are derived, based on the inventory patterns shown in Fig. 1. Before the formulas are developed, the index, parameters, decision variables, and intermediate variables are defined.
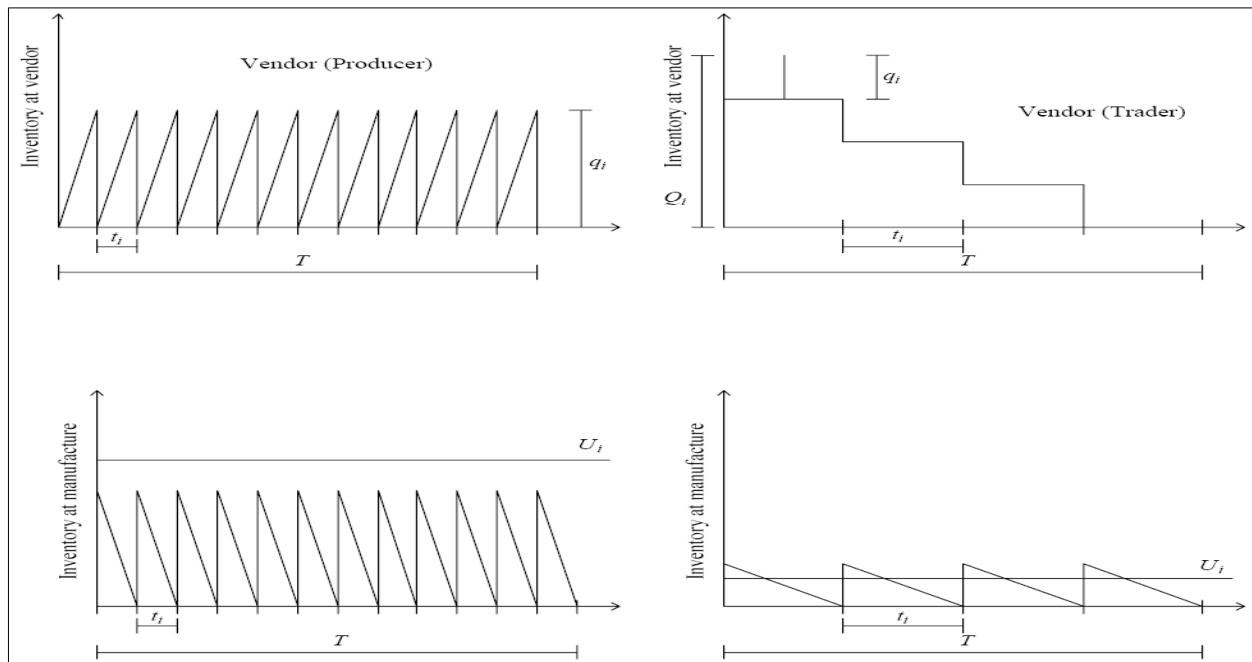

Fig. 1. Inventory pattern over time of vendors and the manufacturer.

3.1. Index

i Index of vendor, $i = (1, 2, 3,…, m)$

3.2. Parameters

m Total number of vendors
D_i Demand rate of the material supplied by vendor i (kg per day)
Cp_m Capacity of medium truck (kg)
Cp_s Capacity of small truck (kg)
Cm Transportation cost from vendor to manufacturer of medium truck (THB per trip)
Cs Transportation cost from vendor to manufacturer of small truck (THB per trip)
a_i Set-up cost of vendor i when it is a producer (THB per set-up)
A Set-up cost of manufacturer (THB per set-up)
hv_i Holding cost of vendor i (THB per kg-day)
H Holding cost of manufacturer for raw material supplied by vendor i (THB per kg-day)
π_i Penalty cost when material supplied by vendor i exceeds the upper limit at the manufacturer (THB per kg-day)
O_i Ordering cost of vendor i when it is a trader (THB per order)

U_i Upper limit of inventory level of material supplied by vendor i at the manufacturer (kg)
x_i 1 if vendor i is a trader, 0 if vendor i is a producer

3.3. Decision Variables

n_i Replenishment frequency of vendor i (number of times per T days)
T Production cycle time of manufacturer (days)

3.4. Intermediate Variables

Q_i Order quantity of vendor i (kg)
t_i Replenishment cycle time of vendor i (days)
tc_i Transportation cost from vendor i to manufacturer per replenishment (THB)
q_i Transportation quantity from vendor i to the manufacturer (kg)
I_i Average level of inventory at vendor i (kg)
TC Total cost per T periods (THB)
TC_p Total cost per period (THB per day)
$TSC1$ Set-up cost of the manufacturer for T periods (THB)
$THC1$ Holding cost of the manufacturer for T periods

(THB)

TRC   Transportation cost, from all vendors to the manufacturer for T periods (THB)

THC2   Total holding cost of all vendors for T periods (THB)

TOC   Total ordering cost of all vendors for T periods when they are traders (THB)

TPC_i Penalty cost of vendor i for T periods (THB)

TPC2   Total penalty cost of all vendors for T periods (THB)

TSC2   Total set-up cost of all vendors for T periods when they are producers (THB)

3.5. Cost Formula

The total cost per T periods (TC) has a number of components, as shown in Eq. (1).

$$TC = TSC1 + THC1 + TRC + THC2 + TOC + TPC2 + TSC2 \qquad (1)$$

Intermediate variables t_i, Q_i, and q_i are defined as functions of known parameters and decision variables, as shown in Eqs. (2–5).

$$t_i = \frac{T}{n_i} \qquad (2)$$

$$Q_i = D_i T \qquad (3)$$

$$Q_i = n_i q_i \qquad (4)$$

$$q_i = D_i t_i \qquad (5)$$

When the vendor is a trader, the vendor inventory is decreased by q_i for each replenishment time t. Therefore, the average inventory level at trader i (I_i) is derived as follows.

$$I_i = \frac{(Q_i - q_i) + (Q_i - 2q_i) + (Q_i - 3q_i) + \ldots + (Q_i - (n_i - 1)q_i)}{n_i}$$

Based on Eq. (4), the average inventory is represented by Eq. (6). Similar expression can be found in [24].

$$I_i = \frac{q_i(n_i - 1)}{2} \qquad (6)$$

The total holding cost of vendor i for T periods (THC_i) is presented by Eq. (7). Note that the first and the second terms represent the holding cost when the vendor is a producer and a trader, respectively.

$$THC2 = \sum_{i=1}^{m} \frac{hv_i q_i T}{2} (1 - x_i) + \sum_{i=1}^{m} hv_i I_i T x_i \qquad (7)$$

The set-up cost of vendor i for T periods when the vendor is a producer is presented by Eq. (8).

$$TSC1 = \sum_{i=1}^{m} a_i * (1 - x_i) \qquad (8)$$

The ordering cost of vendor i for T periods when the vendor is a trader is presented by Eq. (9).

$$TOC = \sum_{i=1}^{m} O_i x_i \qquad (9)$$

The penalty cost of vendor i for T periods is presented by Eq. (10 or 11).

$$TPC_i = 0 \text{ if } q_i \leq U_i, \text{ or} \qquad (10)$$

$$TPC_i = n_i * \frac{(q_i - U_i)^2}{2*D_i} * \pi_i, \text{ if } q_i > U_i \qquad (11)$$

The total penalty cost of all vendors for T periods is presented by Eq. (12).

$$TPC2 = \sum_{i=1}^{m} TPC_i \qquad (12)$$

The total set-up cost of the manufacturer for T periods is presented by Eq. (13).

$$TSC1 = A \qquad (13)$$

The total holding cost of the manufacturer for T periods is presented by Eq. (14).

$$THC1 = \sum_{i=1}^{m} \frac{H_i q_i T}{2} \qquad (14)$$

The total transportation cost from all vendors to the manufacturer for T periods is presented by Eqs. (15-16).

$$TRC = \sum_{i=1}^{m} n_i tc_i \qquad (15)$$

where

$$tc_i = \begin{cases} \left\lfloor \frac{q_i}{Cp_m} \right\rfloor * Cm + Cm, \\ \quad \text{when } MOD(q_i, Cp_m) > 2*Cp_s \\ \left\lfloor \frac{q_i}{Cp_m} \right\rfloor * Cm + 2*Cs, \\ \quad \text{when } 2*Cp_s \geq MOD(q_i, Cp_m) > Cp_s \\ \left\lfloor \frac{q_i}{Cp_m} \right\rfloor * Cm + Cs, \\ \quad \text{when } MOD(q_i, Cp_m) \leq Cp_s \end{cases} \qquad (16)$$

Equation (15–16) are developed based on the conditions that two trips of a small truck are cheaper than a trip of a medium truck but three trips of a small truck are more expensive than a trip of a medium truck. The capacity of a medium truck is more than three times (but less than four times) the capacity of a small truck. An example of the transportation cost calculation is as follows. The capacity of a small truck, Cp_s, is 2,000 kg with a transportation cost, Cs, of 2,500 THB, and the capacity of a medium truck, Cp_m, is 8,000 kg with a transportation cost, Cm, of 6,000 THB. Table 2 provides a numerical example, to calculate TC_i when q_i is equal to 3000, 7000, 9500, 11000, and 13000 kg.

The average total cost per period (TC_p) is presented by Eq. (17).

$$TC_p = \frac{TC}{T} \qquad (17)$$

4. Solution Method

The cost formula of TC_p is nonlinear because its components are nonlinear. For example, $I_i = \frac{q_i(n_i - 1)}{2}$ is nonlinear since q_i and n_i are decision variables. Based on Eq. (16), the transportation cost, tc_i, is not a continuous function since it has a modulo (MOD) function. A non-continuous function is not differentiable. The decision

variables (T and n_i) are integer not real numbers. Therefore, the mathematical model in Section 3 is integer nonlinear programming model which cannot be solved optimally by mathematical programming software. Moreover, the model has a non-differentiable function, which cannot be solved analytically. The model can be solved by numerical methods or metaheuristics. From Table 1, some research works [9, 17, 20] apply metaheuristics (GA and PSO) to successfully solve similar problems. Because of these reasons, this paper applies a metaheuristics instead of an analytic approach or mathematical programing approach to solve the proposed vendor-managed inventory problem.

A Genetic Algorithm (GA) is a stochastic search process based on natural selection [32]. A GA is an optimization search that starts with an initial random population. Every chromosome represents an individual in the population. In each generation, the chromosome progresses through sequential iterations called generations. The individuals are evaluated by fitness values. Offsprings are new chromosomes that are created by some operators, such as crossover and mutation. Throughout some generations, the algorithm finds the best individual [33].

The GA method, implemented in MATLAB 8.5 (R2015a), is used to solve the proposed vendor-managed inventory problem. There are some parameters to be set. Population size N_p is the number of individuals in a generation. In this model, the crossover operator C_f is a scattered crossover (see [34]) with the probability of crossover C_r of 0.8, and the mutation operator M_f is an adaptive mutation (see [35]). Note that the scatter crossover and adaptive mutation are recommended by MATLAB software when decision variables are integers. There are examples in MATLAB library that successfully apply scatter crossover and adaptive mutation to real cases. The above-mentioned parameters are summarized in Table 3.

A flowchart of the genetic algorithm (GA) is presented in Fig. 2, and the steps of the GA process are as follows.

1. Create the initial population.
2. Calculate the fitness value of all chromosomes.
3. If the termination condition is reached, stop; otherwise go to step 4.
4. Choose the top 5% of chromosomes with the highest fitness values, called the elite children. These children are chosen to survive to the next generation.
5. Based on the crossover rates, select the chromosomes from the current population using a "stochastic uniform" selection method on a mating pool. Apply the crossover operator (called "scattered crossover") to generate the offsprings.
6. Select the chromosomes from the current population for mutation using the default mutation rate in MATLAB software. Apply the mutation operator (called "adaptive mutation") to the selected chromosomes.
7. Offsprings from crossover and mutation, and elite children form a new generation.
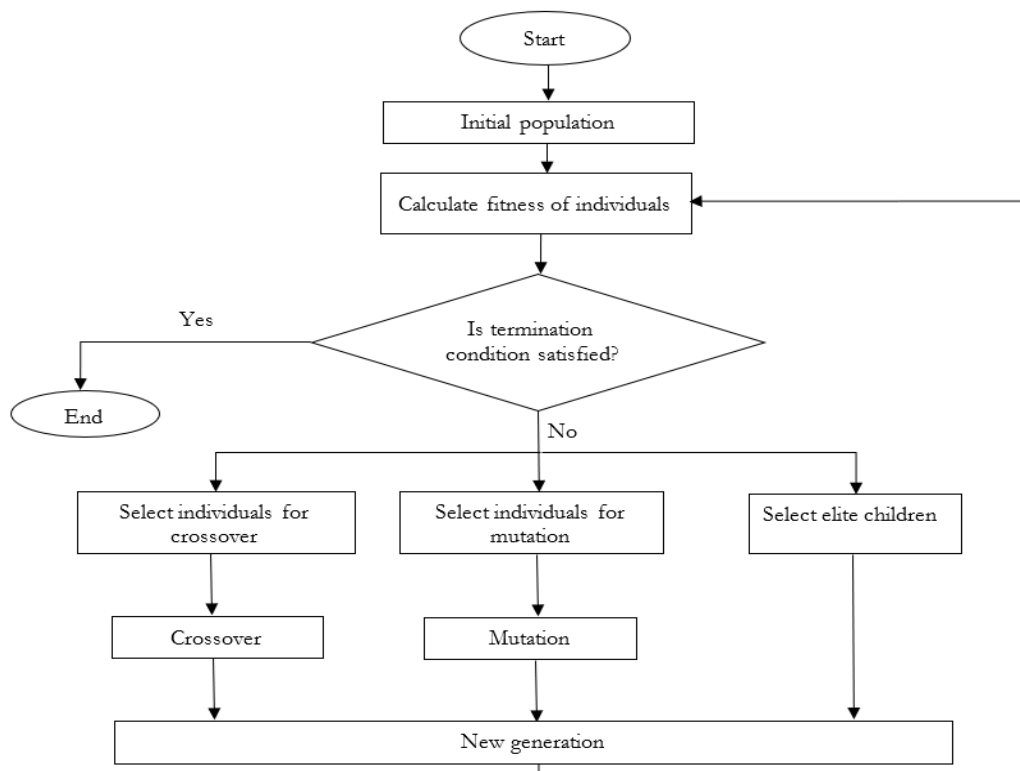8. Go to step 2.

Fig. 2. Flow chart of GA method.

Table 2. Numerical example to calculate tc_i

q_i (kg)	$\left\lfloor \dfrac{q_i}{Cp_m} \right\rfloor$	$MOD\left(q_i, Cp_m\right)$ (kg)	Number of trucks	tc_i (THB)
13,000	1	5,000	2 medium trucks	12,000
11,000	1	3,000	1 medium truck and 2 small trucks	11,000
9,500	1	1,500	1 medium truck and 1 small truck	8,500
7,000	0	7,000	1 medium truck	6,000
3,000	0	3,000	2 small trucks	5,000

Experiments are conducted to determine the suitable parameters (population size and number of generations) of the GA method since these parameters affect quality of solutions and computational times. Based on a guideline of MATLAB software, the population size should be set at 50 when the number of decision variables is 4, and the number of generations should be set at 200. Three experimental cases are set with the population size, N_p, of 25, 50, and 100. The number of generations, G_n, is fixed at 200. Each experimental case is run for 10 iterations since GA may not give the same best solution for each iteration. There are four performance indicators to be observed during the experiments, including the best solution, number of iterations that obtain the best solution (out of 10 iterations), the last generation that the solution is improved, and the computational times. Table 4 presents the performance indicators of all experimental cases.

All cases result in the same best solution (T, n_1, n_2, n_3) = (13, 13, 2, 2). Case 1 with the population size (N_p) of 25 obtains the best solution for only 8 iterations (out of 10 iterations). Moreover, the last generation that the solution is improved is more than 180 for some iterations. This indicates that the number of generations (G_n) of 200 is not enough when the population size is 25. However, the computational time of this case is the lowest. Cases 2 and 3 obtain the best solution for all iterations and the last generation that the solution is improved is less than 20. This means that Cases 2 and 3 offer reliable solution. However, Case 2 has lower computational time. Thus, the population size of 50 and number of generations of 200 is used for further analyses.

Table 3. Parameters of GA

Parameters	Value
Population size, N_p	50
Crossover type, C_f	Scattered crossover
Crossover rate, C_r	0.8
Mutation type, M_f	Adaptive mutation
Mutation rate, M_r	Default value of MATLAB software
Number of generations, G_n	200

Table 4. Effects of GA parameters on performances

Performance indicators	Case 1 $N_p = 25$	Case 2 $N_p = 50$	Case 3 $N_p = 100$
Number of iterations that obtain the best solution	8/10	10/10	10/10
Last generation that the solution is improved	>180	< 20	< 20
Computational time, average (seconds)	7.71	13.70	23.90
Standard deviation (seconds)	0.36	0.45	0.64

5. Case Study Data

A real case study of an instant noodle company was conducted. However, the case study is simplified to make it easy to understand and all data are scaled to protect the confidential information of the company. The simplified case involves a supply chain with three vendors (Vendor 1 is a producer and Vendors 2 and 3 are traders) and a manufacturer. Related data are summarized in Table 5.

6. Results and Discussion

This section presents results and discusses managerial insights that are concluded from the results. It is divided into 4 sub-sections as follows. First, it shows the best values of decision variables, the sensitivity analysis of the T variable (production cycle time of the manufacturer), how this variable affects other decision variables, the average total cost per period, and all cost components. Second, a sensitivity analysis is performed to show that the solutions from the model are reasonable. The sensitivity analysis includes the changing of vendor and manufacturer holding costs, and demand. Third, the effects of the maximum limit of the inventory level at the manufacturer, the penalty cost on the best solutions, and the average total cost per period are analyzed. It is useful to set suitable levels. Finally, the proposed VMI model that minimize the total cost of the entire supply chain is compared with the model that allow each vendor to minimize own total cost. It aims to prove whether the

manufacturer of instant noodle take advantage of the vendors.

6.1. The Best Solutions and Effects of T

The GA method, implemented in MATLAB 8.5 (R2015a), is used to solve the proposed vendor-managed inventory problem. Note that there are 4 decision variables, namely, replenishment frequency of vendors (n_1, n_2, n_3) and production cycle time of manufacturer (T). When the GA is run until 200 generations, which is the termination condition, the best solution is reported. Based on 10 independent runs, the GA reports the best solution of $T = 13$, $n_1 = 13$, $n_2 = 2$, and $n_3 = 2$ for all runs. This indicates that the GA parameters being used are suitable since the GA consistently generates the same solution for all runs.

There are some practical implications on the best value of T. When T is relatively high, the manufacturer produces an instant noodle product for a large production batch before switching to produce other products. This also creates a larger inventory of products, which violates the lean concept. When T is relatively low, the inventory levels of the noodle products are low. However, the manufacturer switches from one product to another more frequently. If the changeover time from one product to another is relatively long, the manufacturer may not be able to produce enough outputs to satisfy demands. Therefore, there are some situations that the best value of T obtained from the model may not be used but another value is used instead. The next paragraph provides an analysis when T deviates from the best value.

This part shows the sensitivity analysis of the T variable, how this variable affects other decision variables, the average total cost per period, and all cost components. The T value is varied from 10 to 20, and the problem is solved to determine the best values of n_i and all cost components. The results are shown in Table 6. It reveals that $(T, n_1, n_2, n_3) = (13, 13, 2, 2)$ results in the lowest average total cost per period (TC_P). However, if $T = 13$ cannot be used because of some practical reasons, a lower value of T is recommended since the average total cost per period increases less than when T is higher (see Fig. 3 and Table 6). When a lower value of T is selected, the supply chain operates closer to the lean concept.
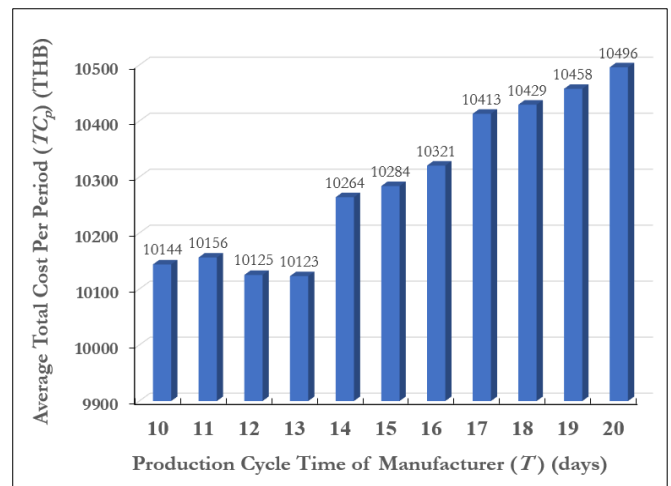

Fig. 3. Total cost per period when changing production cycle time of manufacturing (T)

Table 5. Data of the supply chain with three vendors and a manufacturer (base case).

	D_i (kg/day)	hv_i (THB/kg-day)	π_i (THB/kg-day)	a_i (THB)	H_i (THB/kg-day)	O_i (THB)	U_i (kg)
Vendor 1	8,000	0.12	0.24	1250	0.144	-	24,000
Vendor 2	1,000	0.12	0.24	-	0.144	1,000	3,000
Vendor 3	300	0.1	0.2	-	0.12	1,500	900
	A (THB)	Cp_s (kg)	Cp_m (kg)	Cs (THB)	Cm (THB)		
	1,500	2,000	8,000	2,500	6,000		

Table 6. Effects of T on other decision variables and components of the total cost per period. *

T	n_1	n_2	n_3	q_1	q_2	q_3	$THC1/T$	$THC2/T$	TOC/T	$TPC2/T$	TRC/T	$TSC1/T$	$TSC2/T$	TC_p
10	10	5	2	8,000	2,000	1,500	1,035	810	250	24	7,750	150	125	10,144
11	11	2	2	8,000	5,500	1,650	893	1,071	227	171	7,546	136	114	10,156
12	12	2	2	8,000	6,000	1,800	930	1,116	208	225	7,417	125	104	10,125
13	13	2	2	8,000	6,500	1,950	968	1,161	192	283	7,308	115	96	10,123
14	14	2	3	8,000	7,000	1,400	1,040	1,164	179	292	7,393	107	89	10,264
15	15	2	3	8,000	7,500	1,500	1,080	1,206	167	348	7,300	100	83	10,284
16	16	2	3	8,000	8,000	1,600	1,120	1,248	156	406	7,219	94	78	10,321
17	17	3	3	8,000	5,667	1,700	1,330	1,086	147	188	7,500	88	74	10,413
18	18	3	3	8,000	6,000	1,800	1,380	1,116	139	225	7,417	83	69	10,429
19	19	3	3	8,000	6,333	1,900	1,430	1,146	132	263	7,342	79	66	10,458
20	20	3	3	8,000	6,667	2,000	1,480	1,176	125	303	7,275	75	63	10,496

* Note that the units of T, n_i, q_i are in days, unitless, and kg, respectively. Other columns have the unit of THB.
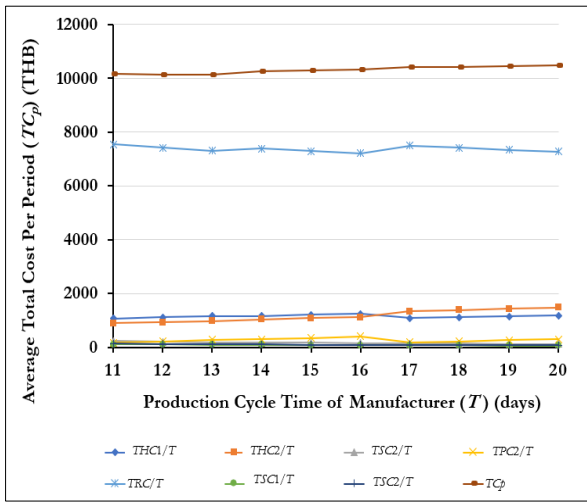
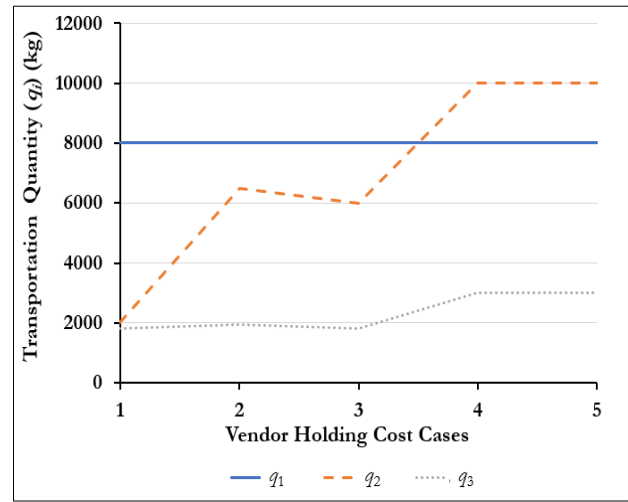Fig. 4. Components of the total cost per period when changing T.

6.2. Sensitivity Analysis to Show That the Solutions are Reasonable

6.2.1. Vendor holding cost

The vendor holding cost is varied as shown in Table 7 (note that Case 2 is the base case). The results in Table 7 show that when the vendor holding costs are higher, the best total cost per day of the supply chain is increased. The entire supply chain is adjusted to have lower inventory levels by setting a shorter production cycle time of the manufacturer (lower T value). The replenishment frequency of some vendors (n_i) is also adjusted to ensure economical transportation by two truck sizes (see Fig. 5). From Fig. 5, the transportation quantity per trip from vendor 1 to the manufacturer (q_1) is constant at 8,000 units since it is equal to the medium truck capacity. The transportation quantity from vendor 2 (q_2) varies for different cases at three levels, namely 2000, about 6,000, and 10,000 kg since 2,000 kg is the full capacity of a small truck, 6,000 kg is 75% of a medium truck, and 10,000 kg is the full capacity of small and medium trucks. The transportation quantity from vendor 3 (q_3) for Cases 4 and 5 is about 3,000 kg, which is suitable for two small trucks. This indicates that the transportation quantities are suitable for the two truck sizes and the quantities are economical.

Table 7. Effects of vendor holding cost on the best solutions and average total cost per period.*

Case	hv_1	hv_2	hv_3	T	n_1	n_2	n_3	TC_p
1	0.06	0.06	0.05	12	12	6	2	9,562
2	0.12	0.12	0.1	13	13	2	2	10,123
3	0.18	0.18	0.15	12	12	2	2	10,590
4	0.24	0.24	0.2	10	10	1	2	11,046
5	0.3	0.3	0.25	10	10	1	2	11,260

* Note that the units of hv_i, T, n_i, and TC_p are THB/kg-day, days, unitless, and THB, respectively.

Fig. 5. Effects of vendor holding cost on transportation quantity.

Figure 6 shows how the components of the total cost per period are affected by the unit holding cost at the vendors. It reveals that the holding cost at the vendors, holding cost at the manufacturer, transportation cost, and penalty cost are affected. The reasons for this change are explained as follows. When the transportation quantities from some vendors (to the manufacturer) are changed, this directly affects the transportation cost and indirectly affects the penalty cost. A higher transportation quantity from the vendor to the manufacturer tends to create more inventory of raw material at the manufacturer, and when it exceeds the maximum limit, the penalty cost is charged to the vendor.
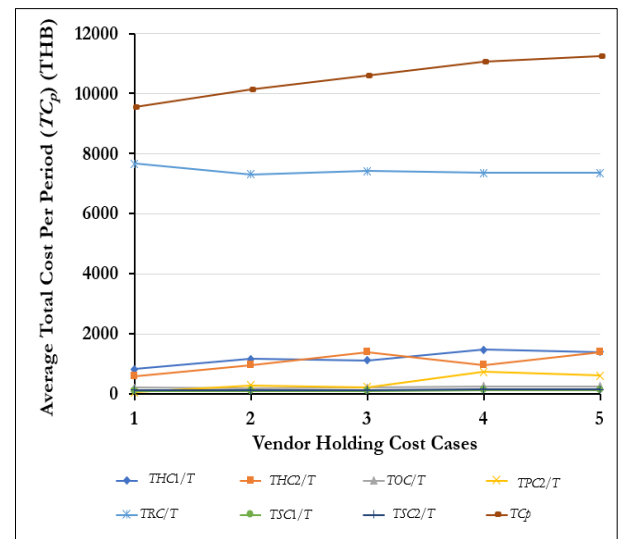

Fig. 6. Average total cost per period when changing the vendor holding cost

6.2.2. Manufacturer holding cost

To determine the effects of the manufacturer holding cost, the manufacturer holding cost is varied as shown in Table 8. Note that Case 2 is the base case. Table 8 shows that the average total cost per period is

significantly higher when the unit holding cost at the manufacturer is higher. This result is similar to the case of changing the vendor holding cost. To compensate for the higher unit holding cost at the manufacturer, the manufacturer production cycle time (T) is lower to reduce the inventory level of raw materials at the manufacturer.

Table 8. Effects of manufacturer holding cost on the best solutions and average total cost per period*

Case	H_1	H_2	H_3	T	n_1	n_2	n_3	TC_p
1	0.072	0.072	0.06	13	13	2	2	9,542
2	0.144	0.144	0.12	13	13	2	2	10,123
3	0.216	0.216	0.18	12	12	6	2	10,561
4	0.288	0.288	0.24	12	12	6	2	10,975
5	0.36	0.36	0.3	10	10	5	2	11,235

* Note that the units of H_i, T, n_i, and TC_p are THB/kg-day, days, unitless, and THB, respectively.
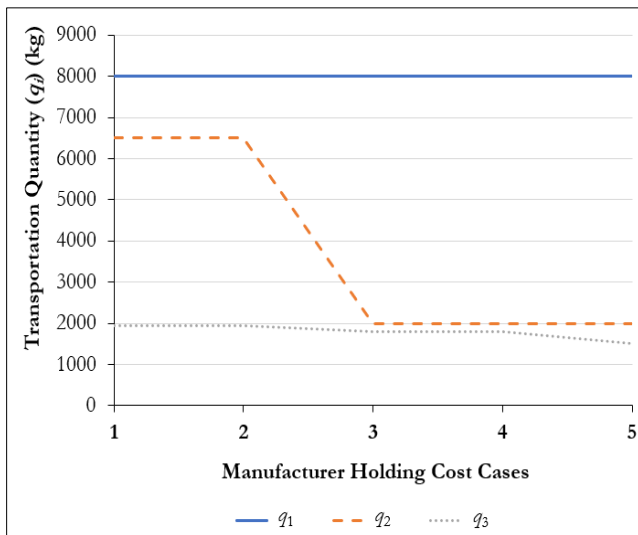

Fig. 7. Effects of manufacturer holding cost on transportation quantities.

Figure 7 shows that the transportation quantity from vendor 2 to the manufacturer is reduced from more than 6,000 kg (Cases 1 and 2) to only 2,000 kg (Cases 3, 4, and 5), to reduce the inventory of raw material from vendor 2 at the manufacturer. However, the transportation cost is increased since 6,000 kg is transported by a medium truck and 2,000 kg is transported by a small truck, which has a higher unit cost. Figure 8 shows that the average total cost per period is increased since the holding cost at the manufacturer and the transportation cost are higher.
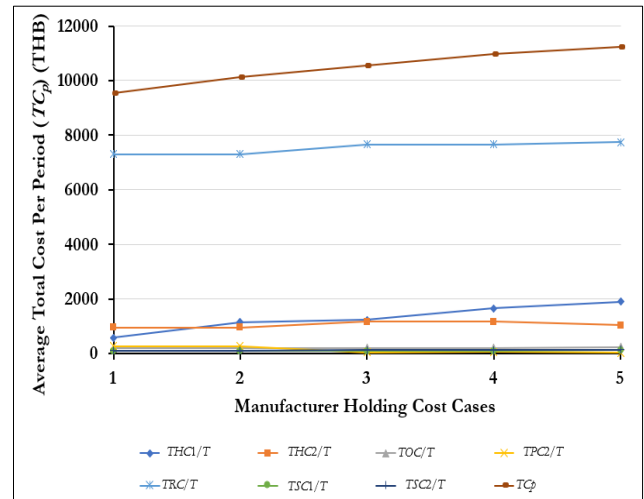

Fig. 8. Average total cost per period when changing the manufacture holding cost.

6.2.3. Demand

The effects of demand on the best solutions and the average total cost per period are presented in Table 9. Note that Case 3 is the base case. When the demand increases due to business growth, the proposed model suggests a reduction in the manufacturer production cycle time (T) and an adjustment to the replenishment frequencies of vendors, to minimize the average total cost per period. Figure 9 shows the best transportation quantities from all vendors to the manufacturer, and Fig. 10 shows the components of the average total cost per period. From Fig. 10, the average total cost per period is mainly affected by the increasing transportation cost when demand increases. Figure 9 shows that when the demand increases, the transportation quantities from some vendors to the manufacturer tend to increase. For example, the transportation quantity from vendor 2 increases from 2,000 kg (using a small truck) to 6,000 kg (using a medium truck), and transportation quantity from vendor 3 increases from 1,000 kg to 2,000 kg (both cases use a small truck). Note that the transportation quantity from vendor 1 does not increase since 8,000 kg is the capacity of a medium truck. Increasing the transportation quantity slightly beyond 8,000 kg results in a significantly higher cost.

Table 9. Effects of demand on the best solution and total cost per period*

Case	D_1	D_2	D_3	T	n_1	n_2	n_3	TC_p
1	6,000	800	200	12	9	5	2	8,190
2	7,000	900	250	12	11	2	2	9,392
3	8,000	1000	300	13	13	2	2	10,123
4	9,000	1100	350	11	13	2	2	11,368
5	10,000	1,200	400	10	13	2	2	12,293

* Note that the units of D_i, T, n_i, and TC_p are kg/day, days, unitless, and THB, respectively.
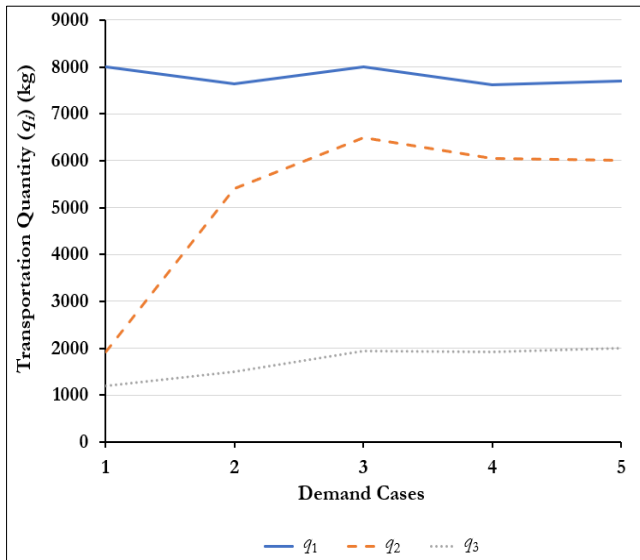
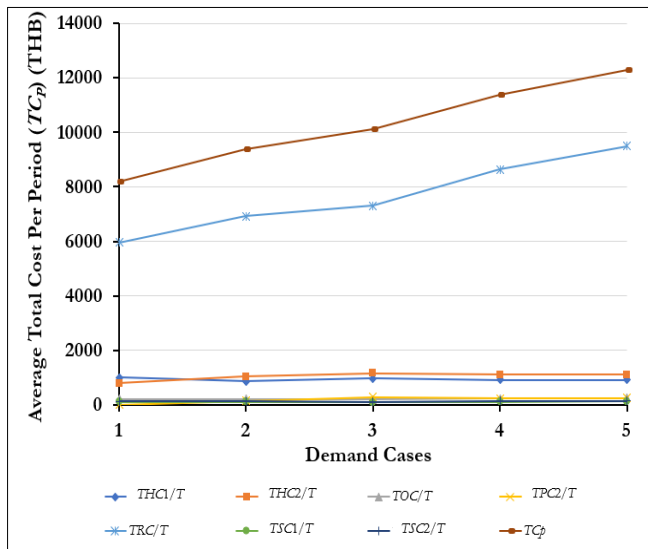Fig. 9. Effects of demand on transportation quantity.

Fig. 10. Total cost per period when changing demand.

6.3. Analysis of Upper Limit of Inventory Level at the Manufacturer and the Penalty Cost

The section is provided to analyze the effects of the maximum limit of the inventory level at the manufacturer and the penalty cost on the best solutions and the average total cost per period. It is useful to set suitable levels.

6.3.1. Penalty cost

To evaluate the effects of unit penalty cost, it is varied as shown in Table 10. Case 2 is the base case. Table 10 shows that when the penalty cost is increased, the model suggests a reduction in the production cycle time at the manufacturer (T) and an adjustment of the frequency of replenishment of vendors, to reduce transportation quantities from some vendors to the manufacturer as shown in Figs. 11-13. When the

transportation quantities are reduced, the inventory level of raw materials at the manufacturer is also reduced. This results in a lower amount of inventory that exceeds the maximum limit. This limits the incurred total penalty cost to a reasonable level although the unit penalty cost is higher. Figure 11 shows that vendor 1 has no penalty cost. Figure 12 shows that the transportation quantity from vendor 2 is reduced until it does not exceed the maximum limit. Figure 13 shows that the transportation quantity from vendor 3 is reduced, to control the amount that exceeds the maximum limit.

Table 10 and Figure 14 show that the average total cost per period of the supply chain system is only slightly increased when the unit penalty cost is higher. The degree that the average total cost per period increases is not as high as when the holding cost at the manufacturer or vendor increases (see Figs. 6 and 8).

Table 10. Effects of penalty cost on the best solutions and average total cost per period.*

Case	π_1	π_2	π_3	T	n_1	n_2	n_3	TC_p
1	0.12	0.12	0.1	13	13	2	2	9,981
2	0.24	0.24	0.2	13	13	2	2	10,123
3	0.36	0.36	0.3	10	10	5	2	10,156
4	0.48	0.48	0.4	10	10	5	2	10,168
5	0.6	0.6	0.5	10	10	5	2	10,180

* Note that the units of π_i, T, n_i, and TC_p are THB/kg-day, days, unitless, and THB, respectively.
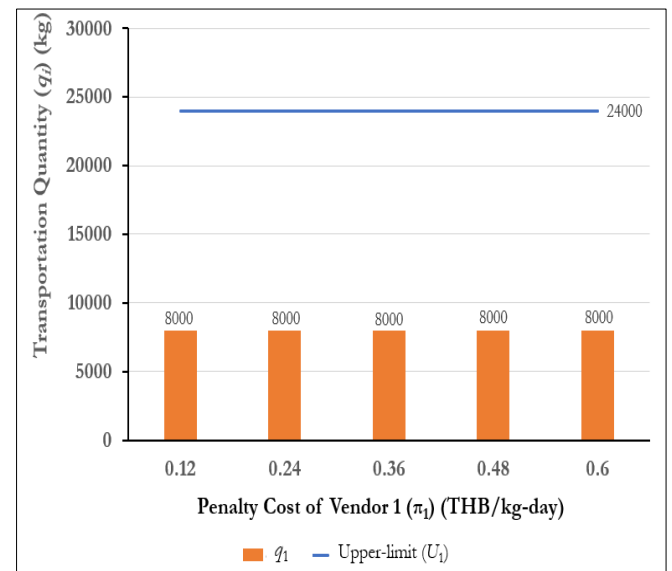

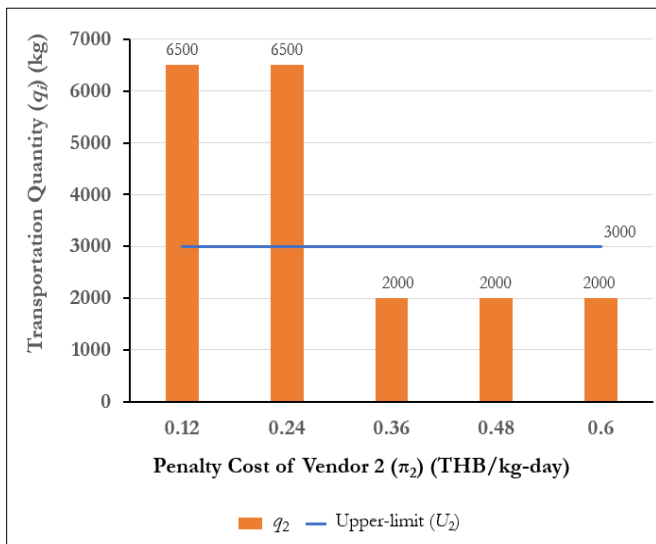Fig. 11. Effects of penalty cost on transportation quantity of vendor 1.

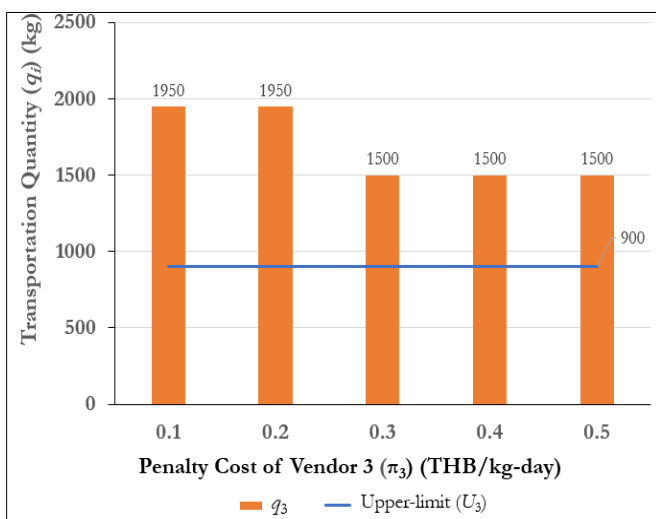Fig. 12. Effects of penalty cost on transportation quantity of vendor 2.

Fig. 13. Effects of penalty cost on transportation quantity of vendor 3.

Fig. 14. Average total cost per period when changing penalty cost.

6.3.2. Upper limit of inventory at the manufacturer

When the manufacturer wants to reduce the inventory level of raw materials, it sets the upper limit of inventory to be lower. This experiment is conducted to see whether it is possible to manage the VMI system so that the average total cost per period is not significantly increased when the upper limit of inventory is reduced. Table 11 shows five cases where the upper limit of the inventory level is reduced from the base case (Case 1). It reveals that the proposed model can suggest suitable values for the production cycle time of the manufacturer (T) and the replenishment frequency of vendors (n_i), to stabilize the average total cost per period (TC_p) as shown in Fig. 16. Figure 15 shows that the transportation quantity from vendor 2 is significantly reduced from more than 6,000 kg to 2,000 kg, reducing the penalty cost and also reducing the holding cost of the raw material at the manufacturer (see Fig. 16). However, the transportation cost (see Fig. 16) is higher since a small truck is used instead of a medium truck. Similarly, the transportation quantity from vendor 3 is slightly reduced (see Fig. 15).

Table 11. Effects of the upper limit of inventory at the manufacture on the average total cost per period.*

Case	U_1	U_2	U_3	T	n_1	n_2	n_3	TC_p
1	24,000	3,000	900	13	13	2	2	10,123
2	22,000	2,600	800	10	10	5	2	10,153
3	20,000	2,200	700	10	10	5	2	10,163
4	18,000	1,800	600	10	10	5	2	10,176
5	16,000	1,400	500	10	10	5	2	10,208

* Note that the units of U_i, T, n_i, and TC_p are kg, days, unitless, and THB, respectively.
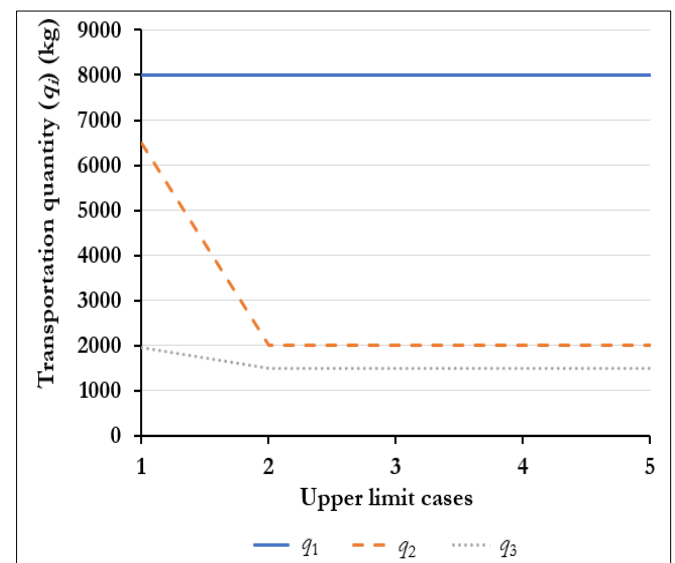

Fig. 15. Effects of the upper limit of inventory at the manufacture on transportation quantity.
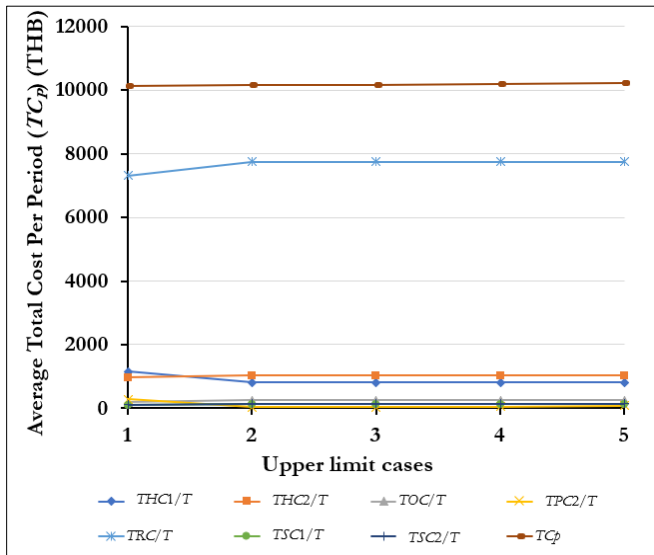
Fig. 16. Average total cost per period when changing the upper limit of inventory at the manufacturer.

6.4. Optimizing the Entire Supply Chain vs. Individual Member

The proposed VMI model optimizes the total cost per period of the entire supply chain and the best solution is $(T, n_1, n_2, n_3) = (13, 13, 2, 2)$ with the best cost per period of 10,123 Baht as shown in Table 6.

A sub-model is constructed considering only total cost of each vendor and allow each vendor to solve for the best value of n_i independently. In the sub-model, it has a parameter, which is the production cycle time of manufacturer (T). T is fixed at 13 because it is the best value suggested by the proposed VMI model and T is decided by the manufacturer. When the sub-model is solved independently for each vendor, the best solution is obtained with $(n_1, n_2, n_3) = (13, 2, 2)$. This result indicates that when each vendor is allowed to make decision independently to optimize own total cost. The solution is the same as the solution obtained by the proposed VMI model that minimize total cost of the entire supply chain. It concludes that the proposed VMI model does not force vendors to scarify to maximize benefit of the entire supply chain based on the current cost structure of this case study.

7. Conclusions and Further Studies

This paper develops a vendor-managed inventory model to satisfy the special characteristics of the instant noodle supply chain in Thailand, which has not been addressed before by past works. The special characteristics are as follows. The first stage is multiple suppliers, which may be traders or producers while the second stage is a manufacturer of instant noodles. Moreover, transportation from the first stage to the second stage can be performed using small- and/or medium-sized trucks. A medium-sized truck has a lower

unit cost of transportation than a small-sized truck. These characteristics cannot be handled by the existing VMI models.

Data of the case study is collected from an instant noodle company in Thailand. The developed VMI model is applied to the instant noodle supply chain, and the experimental results are reported. The experimental results reveal that the proposed VMI model can determine reasonable solutions and suggest how to effectively manage the VMI system.

This paper has both theoretical and practical contributions. The theoretical contributions are as follows.

1. The proposed VMI model is specially developed to match the characteristics of the instant noodle supply chain in Thailand, which cannot be handled directly by the available VMI models in the literature.

2. Although the proposed VMI model is developed for a single product, it can be easily extended to handle multiple products, given that the production capacity is sufficient. For example, product A is produced by the manufacturer for 13 days $(T = 13)$ in a month. Then, the manufacturer switches to produce product B for 10 days $(T = 10)$ in that month. Therefore, the VMI problem for producing products A and B by this supply chain can be considered and solved separately.

The practical contributions of this paper are managerial insights obtained from the experimental results, which are presented as follows.

1. The sensitivity analysis of the T variable, how this variable affects other decision variables, the average total cost per period, and all cost components presented in Section 6.1 are useful for the instant noodle supply chain. This indicates that setting the best value of the production cycle time of the manufacturer (T) results in the lowest average total cost per period. However, when the T value is reduced from the best value, the average total cost per period is slightly increased. In contrast, when the T value is increased, the average total cost per period is highly increased. Therefore, the supply chain is motivated to implement the lean concept by reducing the T value to reduce the production batch size and raw material inventory at the manufacturer, which is the main member of the instant noodle supply chain.

2. The transportation cost is the highest cost component of the supply chain in the case study, as shown in Sections 6.1 to 6.3. Most companies in Thailand use trucks with multiple sizes for

3. transportation, dependent on the amount of materials. Trucks of different sizes have a different transportation cost per trip. The proposed VMI model allows trucks of different sizes to be used. Therefore, the transportation cost in the model is much more accurate and practical than a model with only one truck size. This issue is the major practical contribution of the proposed VMI model.

4. The effects of the penalty cost and the upper limit of raw material inventory at the manufacturer on the best solutions and cost components (presented in Section 6.3) are beneficial for the supply chain. Setting different penalty costs and upper limits do not significantly affect the average total cost per period of the supply chain since the proposed VMI model is effective for determining the best decision variables (T, and n_i), to minimize the average total cost per period. Therefore, when the manufacturer would like to reduce the inventory level of raw materials, the penalty cost may be set at a relatively high level or the upper

limits may be set at relatively low levels, without significantly affecting the average total cost per period of the entire supply chain.

5. The proposed VMI model that minimizes total cost of the entire supply chain give the solution which is the same as the solution form the model that minimize cost of vendors independently. Thus, the manufacturer of the instant noodle supply chain does not take advantage of the vendors.

The proposed VMI model is limited in that it needs crisp or constant parameters. However, the customer demand for the instant noodle company is affected by its marketing promotions and competitor promotions. Thus, this is a highly uncertain environment. A further study is needed to extend the VMI model to handle uncertain or fuzzy demand situations. The fuzzy demand under pessimistic, most likely, and optimistic situations should be estimated. An extended VMI model should be developed to determine a robust solution that maximizes the expected total cost per period of all situations.

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