MIXED-INTEGER LINEAR PROGRAMMING MODEL FOR PRODUCTION PLANNING AND LABOR ALLOCATION IN THE MELON FARM

Aekachai Pantong[1] and Sirikarn Chansombut[2]

[1]Ph.D. Student, Faculty of Logistics and Digital Supply Chain, Naresuan University, Thapo Sub-district, Muang District, Phitsanulok, 65000, Thailand, aekachaip65@nu.ac.th

[2]Lecturer, Faculty of Logistics and Digital Supply Chain, Naresuan University, Thapo Sub-district, Muang District, Phitsanulok, 65000, Thailand, sirikarnc@nu.ac.th

ABSTRACT

This research investigates the optimization of the melon supply chain, aiming to minimize production costs through the development of a mixed-integer linear programming (MILP) model. The framework addresses key inefficiencies in current practices, such as suboptimal cultivation scheduling, inefficient labor allocation, and excessive reliance on outsourced workers, by integrating critical decision variables, including planting schedules, harvesting timelines, and workforce planning. The proposed model enables systematic and data-driven management of greenhouse farming operations. Computational experiments using Premium Solver V2023 demonstrate the model's practical effectiveness, achieving a total production cost of 134,400 THB, which represents a 10.16% reduction compared to manual planning, while maintaining production efficiency. These results highlight the potential of mathematical optimization in supporting sustainable agricultural practices and enhancing decision-making processes. Ultimately, the framework functions as a valuable decision-support tool for both farmers and agribusiness managers in optimizing resource allocation and production.

KEYWORDS: Melon Supply Chain, Production planning, Labor allocation, MILP

1. Introduction

Melon (*Cucumis melo*), a fruit classified within the same botanical group as cantaloupe, is celebrated for its sweet flavor and distinctive aromatic profile. These attributes have significantly contributed to its widespread popularity in Thailand. Recent data indicates that the total area dedicated to melon cultivation in Thailand is approximately 1,761.28 rai (1 rai = 0.395 acres) [1]. The feasibility of melon cultivation across multiple provinces is largely attributed to the adoption of closed greenhouse systems by farmers. These systems enable precise control over environmental conditions and production variables, thereby enhancing both yield and product quality.

This research uses data from the Community Enterprise of the Melon Farmers' Group in Ban Nongkang, Chang Ngam Subdistrict, Nong Ya Sai District, Suphan Buri Province. The melon production process involves several critical stages, including strategic planning, cultivation, harvesting, raw material procurement, and labor resource allocation. Labor inputs are sourced from a combination of in-house farm labor and external contracted labor, which can be flexibly deployed across all stages of production. The labor allocation problem in melon farms arises from a shortage of labor during the harvest period, as the melon harvesting season coincides with the harvest seasons of other agricultural crops that also require external contract labor, leading to competition for limited labor resources. Given the interdependence of these stages, effective planning is essential to ensure operational efficiency. Inefficient planning can result in increased operational costs and reduced overall productivity, highlighting the need for a systematic approach to production management.

The application of the mixed-integer linear programming (MILP) model represents a significant advancement in agricultural supply chain optimization. It provides a structured methodology for addressing challenges related to resource allocation, seasonal variability, and time-sensitive operations. Furthermore, the model serves as a decision-support tool, enabling farmers and producers to make informed decisions that enhance both economic and operational outcomes.

This research applies supply chain management principles to address the complexities inherent in melon production planning. Specifically, a MILP model is proposed to optimize the entire production process. Using real-world data from the case study group, the model integrates key activities such as seed procurement, planting, harvesting, and labor resource allocation at each stage of production. By consolidating these processes into a unified framework, the model aims to minimize total operating costs while ensuring that melon production aligns with customer demand.

2. Related work

Supply chain management (SCM) is a strategic framework that helps coordinate and collaborate between different parts of the supply chain network. It encompasses the movement of raw materials, information, and financial resources, with the primary goal of meeting customer demand while improving the overall efficiency of the supply chain [2]. Among the tools used in SCM, mathematical models have become key instruments for solving complex optimization problems. These models have gained significant attention in academic research because they provide structured solutions to complex challenges, especially in agricultural food production planning [3].

In agricultural food production planning, mathematical models have been successfully applied to improve raw material procurement and production processes. For example, in the walnut processing industry [4], integrated planning frameworks have been developed to align raw material procurement with production schedules, ensuring that products meet customer demands effectively. Models have been applied to solve labor allocation problems. For example, Wishon [5] developed an optimization model for a farm's growing and labor acquisition schedules. Similarly, harvest planning has been widely studied in industries with time-sensitive operations. Sugarcane harvesting, for instance, has been analyzed to meet the needs of the sugar manufacturing sector [6]. Since sugarcane has a limited harvesting window, good planning is crucial to reduce operational costs and maximize yield. Similarly, apple harvesting [7] has been explored to meet year-round customer demand, thereby ensuring a steady supply of fresh produce. Effective harvest planning not only cuts costs but also improves the responsiveness and efficiency of the supply chain. A comprehensive review by Soto-Silva [8] highlights the growing trend of using mathematical models to address challenges in agricultural supply chains. The findings show the increasing importance of these models in improving operational efficiency and enhancing sustainability in agriculture.

This research aims to develop a MILP model as a decision-support tool for optimizing melon production planning. The model integrates key processes across the entire supply chain, including melon seed procurement, cultivation, harvesting, and labor allocation in melon farming. By combining these processes into a single framework, the model uses real-world data and seeks to align melon production with customer demand while minimizing total operational costs. Its primary objective is to reduce costs related to resource utilization, labor allocation, and logistics, thereby improving the overall efficiency of the supply chain.

3. Problem description

The melon production planning process is intricate, requiring the involvement of multiple stakeholders across various stages, including seed sourcing, cultivation, crop maintenance, and harvesting. The general flow diagram of the melon production process is shown in Figure 1, and the steps involved in the process are described below.

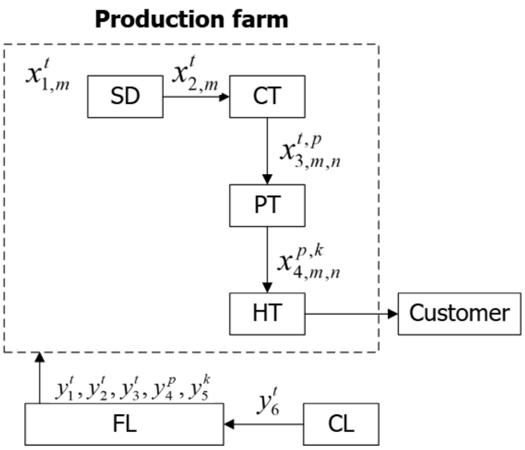

Figure 1 The Production Process for Melons on a Farm

The melon cultivation process begins with the procurement of high-quality melon seeds from suppliers ($x^t_{1,m}$). Farmers germinate melon seeds in seedling trays (SD), achieving a germination rate of approximately 95%. Once the seedlings reach 10 days of age ($x^t_{2,m}$), they are transplanted into growing beds during the Cultivating stage (CT), within a controlled greenhouse environment. Ten days after transplantation, farmers prune the branches and leaves of the melon plants to ensure healthy growth and optimize resource allocation.

Thirty days after pruning, the melon plants enter the flowering stage and become ready for pollination ($x^{t,p}_{3,m,n}$). The pollination process (PT) typically spans about 3 days. After successful pollination, melon plants that have reached at least 75 days of age ($x^{p,k}_{4,m,n}$) are considered mature and ready for harvest (HT). The optimal harvesting window is within 5 days to ensure peak quality and freshness. To meet customer expectations, the melons must be harvested at least one day before delivery.

The entire process, starting from the initial germination of melon seeds through to the final harvesting of mature melons, necessitates the active involvement of both internal farm labor (FL) ($y_1^t, y_2^t, y_3^t, y_4^p, y_5^k$) and externally contracted labor (CL) (y_6^t). Given the multifaceted constraints inherent in melon production planning, such as resource limitations, labor availability, and environmental uncertainties, meticulous scheduling of planting, harvesting, and labor allocation becomes critical to ensuring operational efficiency and maximizing resource utilization.

4. Mathematical model

The model was formulated as a MILP problem, as described below. It comprises several key components: indices and sets, decision variables, parameters, constraints, and an objective function. Each of these components is crucial for defining the problem and ensuring efficient optimization.

4.1 Model assumptions

This research utilized data collected from the community enterprise of melon growers in Ban Nong Khang, Suphan Buri Province, Thailand, as a case study. The development of the model was guided by the following assumptions:

1) The time horizon considered in this study is one year (365 days), with the problem-solving process starting on the first day of January (t = 1).

2) It is specified that melon seedling cultivation requires 10 days, pollination occurs when the plants reach 30 to 32 days of age after greenhouse planting, and harvesting takes place when the plants are between 75 and 80 days old.

3) Each greenhouse can be harvested only once during each harvesting season.

4) At the commencement of the calculation, no Work in Process (WIP) inventory exists in any process.

4.2 Mathematical Notation

The details of the mathematical model are presented in Table 1.

Table 1 Mathematical Notation Used in the Model

Indices and sets			
$t \in T$	set of cultivating periods	$m \in M$	set of a group of melon farmers
$p \in P$	set of pollinating periods	$n \in N$	set of a group of melon greenhouses
$k \in K$	set of harvesting periods		
Parameters			
RaT_1	germination rate of melon seeds	CoT_1	cost of seeds
RaT_2	worker rate in the seedlings sector	CoT_2	cost of seeding
RaT_3	planting rate per greenhouse	CoT_3	cost of cultivating
RaT_4	worker rate in the cultivating area	CoT_4	cost of pollinating
RaT_5	worker rate in the pruning sector	CoT_5	cost of harvesting
RaT_6	worker rate in the pollinating sector	CoT_6	cost of farm laborers
RaT_7	worker rate in the harvesting area	CoT_7	cost of contracted laborers
RaT_8	melon yield rate	DeM^k	demand of melon in period *k*
CaP_1	total number of farm laborers		
Decision Variables			
$x_{1,m}^t$	number of seeds planted in period *t* by famer *m*		
$x_{2,m}^t$	number of seedlings planted in period *t* by farmer *m*		
$x_{3,m,n}^{t,p}$	equal to 1 if cultivating in period *t* and pollinating in period *p* by farmer *m* in greenhouse *n* and 0 otherwise.		
$x_{4,m,n}^{p,k}$	equal to 1 if pollinating in period *p* and harvesting in period *k* by farmer *m* in greenhouse *n* and 0 otherwise.		
y_1^t	number of laborers working in the seedlings sector in period *t*		
y_2^t	number of laborers working in the cultivating area in period *t*		
y_3^t	number of laborers working in the pruning sector in period *t*		
y_4^p	number of laborers working in the pollinating sector in period *p*		
y_5^k	number of laborers working in the harvesting area in period *k*		
y_6^t	number of contracted laborers acquired in period *t*		

4.3 Objective function

The Objective function minimizes is the sum of seeding cost ($C^{Seeding}$), cultivating cost ($C^{Cultivating}$), pollinating cost ($C^{Pollinating}$), harvesting cost ($C^{Harvesting}$), and Outsourcing cost ($C^{Outsourcing}$). The total cost of the objective function is defined by Equation (1) as follows:

Minimize:

$$Z = C^{Seeding} + C^{Cultivating} + C^{Pollinating} + C^{Harvesting} + C^{Outsourcing} \quad (1)$$

The seeding cost is defined as the total of the seeds cost and the labor cost in the seedlings sector, which can be calculated using Equation (2) as:

$$C^{Seeding} = CoT_1 \sum_{t \in T} \sum_{m \in M} x_{1,m}^{t} + CoT_6 \sum_{t \in T} y_1^{t} \quad (2)$$

The cultivating cost is defined as the total of the seedlings cost, the cultivating cost, and the labor cost in the cultivating area, which can be calculated using Equation (3) as follows:

$$C^{Cultivating} = CoT_2 \sum_{t \in T} \sum_{m \in M} x_{2,m}^{t} + CoT_3 \sum_{t \in T} \sum_{p \in P} \sum_{m \in M} \sum_{n \in N} x_{3,m,n}^{t,p} + CoT_6 \sum_{t \in T} y_2^{t} \quad (3)$$

The pollinating cost is defined as the total of the pollinating cost and the labor cost in the pruning and pollinating sectors, which can be calculated using Equation (4) as follows:

$$C^{Pollinating} = CoT_4 \sum_{t \in T} \sum_{p \in P} \sum_{m \in M} \sum_{n \in N} x_{3,m,n}^{t,p} + CoT_6 \left(\sum_{t \in T} y_3^{t} + \sum_{t \in T} y_4^{t} \right) \quad (4)$$

The harvesting cost is defined as the total of the harvesting cost and the farm laborers cost in the harvesting area, which can be calculated using Equation (5) as follows:

$$C^{Harvesting} = CoT_5 \sum_{p \in P} \sum_{k \in K} \sum_{m \in M} \sum_{n \in N} x_{4,m,n}^{p,k} + CoT_6 \sum_{k \in K} y_5^{k} \quad (5)$$

The outsourcing cost, which is the total cost of contracted laborers, can be calculated using Equation (6) as follows:

$$C^{Outsourcing} = CoT_7 \sum_{k \in K} y_6^k \quad (6)$$

4.4 Constraints

The required quantities of resources for melon seedling cultivation can be calculated using constraint Equation (7), as this process requires a 10-day period.

$$RaT_1 x_{1,m}^t \geq x_{2,m}^{t+10}; \forall_{t \in T, m \in M} \quad (7)$$

Constraint Equation (8) determines the labor input required in the seedlings sector.

$$RaT_2 \sum_{m \in M} x_{1,m}^t \leq y_1^t; \forall_{t \in T} \quad (8)$$

Constraint Equation (9) determines the number of seedlings used daily in the melon cultivation process.

$$x_{2,m}^t = RaT_3 \sum_{p \in P} \sum_{n \in N} x_{3,m,n}^{t,p}; \forall_{t \in T, m \in M} \quad (9)$$

Constraint Equation (10) assumes that planting greenhouses are not reused.

$$\sum_{t \in T} \sum_{p \in P} x_{3,m,n}^{t,p} \leq 1; \forall_{m \in M, n \in N} \quad (10)$$

Constraint Equation (11) determines the labor input required in the cultivating area.

$$RaT_4 \sum_{p \in P} \sum_{m \in M} \sum_{n \in N} x_{3,m,n}^{t,p} \leq y_2^t; \forall_{t \in T} \quad (11)$$

The maintenance process for melon plants involves pruning melon branches and leaves 10 days after planting, as described in Equation (12), which determines the labor input required for pruning.

$$RaT_5 y_2^t = y_3^{t=t+10}; \forall_{t \in T} \tag{12}$$

Constraint Equation (13) determines the labor input required in the pollinating sector.

$$RaT_6 \sum_{t \in T} \sum_{m \in M} \sum_{n \in N} x_{3,m,n}^{t,p} \leq y_4^p; \forall_{p \in P} \tag{13}$$

Once melons reach reproductive maturity (30 days), pollination can begin and must be completed within 3 days. The harvest period for melons is 75–80 days, as defined by Equations (14) and (15).

$$\sum_{p \geq t+30}^{p \leq t+32} x_{3,m,n}^{t,p} = \sum_{p \geq t+30}^{p \leq t+32} \sum_{k \geq t+75}^{k \leq t+80} x_{4,m,n}^{p,k}; \forall_{t \in T, m \in M, n \in N} \tag{14}$$

$$\sum_{t \in T} x_{3,m,n}^{t,p} = \sum_{k \in K} x_{4,m,n}^{p,k}; \forall_{p \in P, m \in M, n \in N} \tag{15}$$

Constraint Equation (16) assumes that harvesting greenhouses are not reused.

$$\sum_{p \in P} \sum_{k \in K} x_{4,m,n}^{p,k} \leq 1; \forall_{m \in M, n \in N} \tag{16}$$

Constraint Equation (17) determines the labor input required for the harvesting area.

$$RaT_7 \sum_{p \in P} \sum_{m \in M} \sum_{n \in N} x_{4,m,n}^{p,k} \leq y_5^k; \forall_{k \in K} \tag{17}$$

The harvested melon yield must meet customer demand, and harvesting must be completed one day prior to customer pickup, as defined by Equation (18).

$$RaT_8 \sum_{p\in P} \sum_{m\in M} \sum_{n\in N} x_{4,m,n}^{p,k=k-1} \geq DeM^k ; \forall_{k\in K} \tag{18}$$

Constraint Equation (19) determines the maximum labor capacity based on the availability of farm and contracted laborers.

$$y_1^t + y_2^t + y_3^t + y_4^p + y_5^k \leq CaP_1 + y_6^t ; \forall_{t\in T, p\in P, k\in K}, t = p = k \tag{19}$$

Constraint Equations (20) and (21) define the variable types.

$$x_{1,m}^t, x_{2,m}^t, y_1^t, y_2^t, y_3^t, y_4^p, y_5^k, y_6^t \geq 0 \, and \, Integer ; \forall_{t\in T, p\in P, k\in K, m\in M} \tag{20}$$

$$x_{3,m,n}^{t,p}, x_{4,m,n}^{p,k} \in \{0,1\} ; \forall_{t\in T, p\in P, k\in K, m\in M, n\in N} \tag{21}$$

5. Case study

The melon production process consists of systematic stages: seedling propagation, cultivation and maintenance, and harvesting. The supply chain involves intermediaries who collect the harvested produce for further distribution. The developed mathematical model was tested using the Premium Solver V2023 [9]. However, the solver encountered computational limitations due to the excessive number of decision variables and constraints, exceeding its capacity to derive an optimal solution. To validate the model's accuracy, the researchers conducted a case study simulation by reducing the production planning horizon (Figure 2)

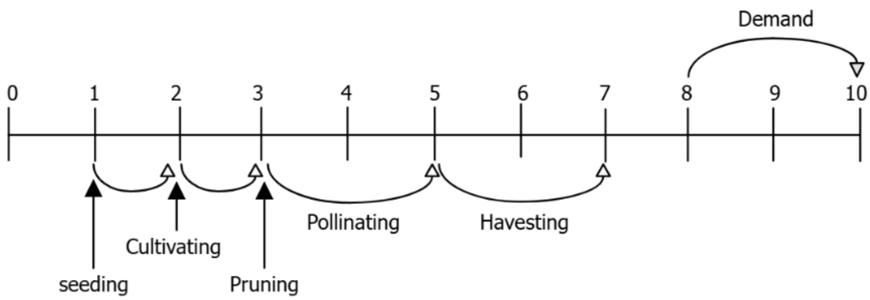

Figure 2 Melon Production Planning Horizon Timeline

The following components systematically structure the proposed melon cultivation framework.

1) Seedling:

- Propagation commences in Period 1 (duration: 1 period).

2) Cultivating:

- Transplanting to greenhouses is conducted upon completion of the seedling stage.
- Pruning is initiated after the plants have spent 1 period in the greenhouse.

3) Pollinating:

- Initiated when melons reach 3 periods of age.
- Must be completed within a 2-period window.

4) Harvesting:

- Permitted once melons attain an age of ≥ 5 periods.
- Must be finalized within 2 periods after eligibility.

5) Demand Fulfillment:

- Harvested melons must meet customer demand specifications.
- Harvesting must be completed 1 period before customer pickup.

In this case study, the production planning framework uses real-world data from over 700 greenhouse farms to define the scope and scale of the problem by reducing the number of decision variables (Table 2), while incorporating key input data and parameters (Table 3) to ensure the plan meets consumer demand (Table 4). Notably, the reduction in dataset size for model testing did not compromise the model's performance. The resulting melon production plan accurately reflects optimal planting and harvesting quantities and fully satisfies customer demand.

Table 2 Size of the Test Problem

Number of cultivating periods	10
Number of pollinating periods	10
Number of harvesting periods	10
Number of farmers	3
Number of greenhouses	7

Table 3 Input Data and Parameter Values

Parameter	Value
RaT_1	95%
RaT_2	1/1,040 for worker rate in the seedlings sector
RaT_3	800 plants per greenhouse
RaT_4	3 workers per greenhouse per day
RaT_5	1/3 of the laborers are working in the cultivating area.
RaT_6	1 worker per greenhouse per day
RaT_7	3 workers per greenhouse per day
RaT_8	1,140 kilograms per greenhouse
CaP_1	35 workers
CoT_1	6 baht per seed
CoT_2	1 baht per seeding
CoT_3	8,175 baht per greenhouse
CoT_4	3,000 baht per greenhouse
CoT_5	1,520 baht per greenhouse
CoT_6	355 baht per worker per day
CoT_7	450 baht per worker per day

Table 4 Demand for Melon (kilograms)

k	DeM^k	k	DeM^k
1	0	6	0
2	0	7	0
3	0	8	3,420
4	0	9	1,140
5	0	10	2,280

6. Results and discussion

In this study, the researchers employed Premium Solver to compute the optimal solution. The results of the mixed-integer linear programming (MILP) model were applied to melon production planning, encompassing cultivation, pollination, fertilization, and harvesting, as well as labor resource allocation. The detailed outcomes are presented in Tables 5 and 6.

Table 5 Optimized Values of the Decision Variables

t,p,k	$x_{1,m}^t$			$x_{2,m}^t$			y_1^t	y_2^t	y_3^t	y_4^p	y_5^k	y_6^t
	$m=1$	$m=2$	$m=3$	$m=1$	$m=2$	$m=3$						
1	1,685	0	0	0	0	0	2	0	0	0	0	0
2	0	0	1,685	1,600	0	0	2	6	0	0	0	0
3	0	0	0	0	0	1,600	0	6	2	0	0	0
4	0	1,685	0	0	0	0	2	0	2	2	0	0
5	0	0	0	0	1,600	0	0	6	0	1	0	0
6	0	0	0	0	0	0	0	0	2	1	0	0
7	0	0	0	0	0	0	0	0	0	0	12	4
8	0	0	0	0	0	0	0	0	0	2	4	0
9	0	0	0	0	0	0	0	0	0	0	8	0
10	0	0	0	0	0	0	0	0	0	0	0	0

Table 6 Optimized Decision Variables for Melon Greenhouse Operations

m,n	Farmers 1	m,n	Farmers 2	m,n	Farmers 3
1,1	$x_{3,m,n}^{t=2,p=4}=1$ $x_{4,m,n}^{p=4,k=7}=1$	2,1	Not selected	3,1	$x_{3,m,n}^{t=3,p=6}=1$ $x_{4,m,n}^{p=6,k=7}=1$
1,2	$x_{3,m,n}^{t=2,p=4}=1$ $x_{4,m,n}^{p=4,k=7}=1$	2,2	$x_{3,m,n}^{t=5,p=8}=1$ $x_{4,m,n}^{p=8,k=9}=1$	3,2	$x_{3,m,n}^{t=3,p=5}=1$ $x_{4,m,n}^{p=5,k=8}=1$
		2,3	$x_{3,m,n}^{t=5,p=8}=1$ $x_{4,m,n}^{p=8,k=9}=1$		

Remark: The remaining decision variables take the value 0.

This production planning model provides an effective scheduling approach for melon cultivation. For example, when presented with a customer demand of 2,280 kg in period k=10 (see Table 3), the model generates a production plan (Table 4) that involves procuring 1,685 seeds in period t=4 , cultivating 1,600 healthy seedlings by period t=5 , transplanting them into greenhouses managed by Farmer 2 during the same period (Table 5) using Greenhouse 2 and Greenhouse 3, conducting pollination in period p=8 , and achieving a harvest of 2,280 kg in period k=9 . This schedule precisely fulfills the demand while maintaining the critical one-period buffer between harvest and delivery. A comprehensive review of the overall production plan confirms that customer demand is fully satisfied, highlighting the model's practical applicability and efficient management of the production timeline. The optimized total production cost amounts to 134,400 THB, representing a 10.16% reduction compared to manual planning, which incurs a cost of 149,600 THB.

7. Conclusions

This study shows that using a mathematical model can help melon farmers plan their work better. Instead of making decisions based on experience or guesswork, the model helps farmers schedule planting, harvesting, and labor use in a more organized and efficient way. It reduces total production costs by 10.16% and lowers the need for outsourced workers, which makes farm operations more stable and easier to manage.

The results suggest that even small farms can benefit from using optimization tools. The model can also be adapted for other crops with similar growing patterns. In future research, we will focus on expanding the model's scope to include additional components of the melon supply chain, improving its ability to handle real-life challenges such as weather variability and demand uncertainty, and developing enhanced scenario analysis capabilities for various operational conditions.

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Author's Profile

Aekachai Pantong, Ph.D. Student at Faculty of Logistics and Digital Supply Chain, Naresuan University, Thapo Sub-district, Muang District, Phitsanulok, 65000, Thailand. Email: aekachaip65@nu.ac.th
Domain: Logistics and Supply Chain Management, Optimization

Sirikarn Chansombut, Lecturer at Faculty of Logistics and Digital Supply Chain, Naresuan University, Thapo Sub-district, Muang District, Phitsanulok, 65000, Thailand. Email: sirikarnc@nu.ac.th
Domain: Production planning and scheduling, Optimization, Mathematical modeling, Simulation modeling, Metaheuristics

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