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Research article

A Mixed-Integer Linear Programming Approach for the Sustainable Design and Planning System of Marine Shrimp Aquaculture Supply Chain Network

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Abstract

Pacific white shrimp (*Litopenaeus vannamei*) is a marine shrimp species introduced by the Department of Fisheries for experimental farming. It is currently being considered as a viable alternative to tiger prawn farming, which faces challenges such as slow growth rates. Concurrently, some farmers have independently adopted white shrimp aquaculture and reported notable success, including higher production rates compared to tiger prawns. As a result, many farmers have transitioned to white shrimp farming. However, given that white shrimp is a relatively new species in Thailand's aquaculture sector, farmers continue to face significant challenges in farm management, fry hatchery procurement, pond rotation, feeding, production inputs, harvesting, and transportation. These difficulties are primarily due to the absence of a structured farm management plan, which hinders farmers from achieving consistent, high-quality yields. To address these challenges, this research employs a mixed-integer linear programming (MILP) model to design and optimize the white shrimp aquaculture supply chain network. The model targets key aspects such as selecting fry hatchery dealers, managing farms (including shrimp pond rotation for continuous production), streamlining aquaculture operations, and optimizing shrimp harvesting for sale at shrimp floating raft markets. The primary objective is to maximize farmers' profits from shrimp aquaculture. The results indicate that the proposed MILP model functions effectively as a decision-support tool, achieving an 11.52% increase in profit compared to traditional manual planning methods.

Keywords: white shrimp aquaculture; production planning; supply chain network; mixed-integer linear programming

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1. Introduction

Pacific white shrimp (*Litopenaeus vannamei* Boone) is a species of marine shrimp that has been introduced and cultivated in Thailand as a replacement for tiger prawn, which currently faces growth-related challenges. This shift has contributed to the increasing adoption of white shrimp aquaculture, driven by its higher yield potential compared to tiger prawn. Consequently, many farmers have transitioned to raising white shrimp (Department of Fisheries, 2015a). However, as white shrimp is a relatively new species in Thailand's aquaculture sector, some farmers face difficulties in sourcing high-quality fry, managing farming practices, and providing suitable feed. These challenges often lead to slower growth rates and increased vulnerability to disease, ultimately resulting in shrimp being sold at lower market prices (Coastal Aquaculture Research and Development Office, 2006).

A study of white shrimp aquaculture among farmer groups in Bang Khun Sai Subdistrict, Ban Laem District, Phetchaburi Province, revealed that most farmers face significant challenges in areas such as farm management, fry hatchery procurement, pond rotation, shrimp feed, production factors, harvesting, and transportation. These difficulties largely stem from the absence of comprehensive farm management planning that encompasses the entire production process—from fry hatchery procurement and feed acquisition to the timely transportation of shrimp to appropriate shrimp floating rafts. As a result, farmers struggle to manage shrimp aquaculture effectively, leading to inconsistencies in produce quality and reduced production outcomes. In response, the Department of Fisheries has established criteria for marine shrimp aquaculture in accordance with Good Aquaculture Practice (GAP) standards. This initiative aims to elevate shrimp farming to a standard that fosters consumer trust and supports the development of export-quality agricultural products. Under the GAP system, three core areas are evaluated: aquaculture management, feeding and production factors, and harvesting (Department of Fisheries, 2015b). Therefore, there is a critical need for tools that support efficient and effective farm management planning, enabling farmers to produce high-quality products that meet GAP standards at the lowest possible cost.

The agricultural food supply chain network (AFSCN) refers to the production and delivery of agricultural products from the point of origin to the point of consumption through a series of stages. Each stage adds specific value to the final product (Yadev et al., 2022). Furthermore, the AFSCN is a sophisticated and complex system due to the involvement of numerous intermediaries in various processes. Today's AFSCN is also expected to be flexible, offering diverse options for end consumers, ranging from processed food to fresh produce (Zhu et al., 2018). However, the AFSCN faces challenges such as information asymmetry, limited industrialization, and inadequate management, which contribute to inefficiencies in the supply chain (Kamble et al., 2020). As a result, addressing supply chain network planning issues has become critical to improving overall efficiency (Vazquez et al., 2021). A well-planned supply chain network can help farmers maintain product quality, which is crucial to operational efficiency. For instance, in marine shrimp aquaculture, effective farm management design and planning are essential. These practices enable farmers to manage their operations systematically, ensuring product quality and compliance with consumer standards.

In this study, we focused on developing supply chain network principles to design and plan the complexities of white shrimp aquaculture. Specifically, we applied a mixed-integer linear programming (MILP) model. The outcomes of the model are expected to provide a practical tool for farmers to optimize total profit surplus and establish a sustainable supply chain network for white shrimp farming. By doing so, we aim to offer an effective and efficient solution to the challenges faced by the farmers in the increasingly competitive agricultural sector (Mohammed & Wang, 2017). The proposed model addresses key components of the entire farming processes, including fry hatchery selection, farm management practices such as pond rotation for continuous production, aquaculture management during the grow-out period, and shrimp harvesting for sale at shrimp floating rafts. Overall, this research contributes to the development of effective and sustainable supply chain network planning practices for white shrimp aquaculture, which is essential for the continued growth and success of this important agricultural sector.

Today's consumers are highly attentive to sustainable and circular approaches in the design of agricultural food supply chain networks (Farooque et al., 2019), as agriculture plays a vital role in every society by supporting food production and sustaining the global population. However, agricultural production systems and their associated supply chain network components face various challenges, which are further intensified by global water scarcity caused by climate change (Mamoudan et al., 2023). These challenges lead to negative consequences, such as rising food prices and increased food waste. Higher food prices disproportionately impact vulnerable populations and pose a significant threat to food security (Saetta & Caldarelli, 2020). Additionally, key challenges in managing agricultural supply chain networks include the short shelf life, perishability, and seasonality of agricultural products, which require significant effort to maintain product quality. Therefore, efficient supply chain network planning is essential for addressing these issues and ensuring that products reach consumers in a timely and cost-effective manner (Tsolakis et al., 2014).

Over the past decade, agricultural supply chain network planning has been receiving increasing attention from researchers (Ahumada & Villalobos, 2011). A major focus has been the development of effective planning tools, with mathematical models playing a prominent role. These models are increasingly applied to optimize agricultural production planning, improving both efficiency and profitability while ensuring the freshness and availability of perishable products. Previous research aimed at improving supply chain network planning in agricultural food sector was focused on analyzing supply chain structures and enhancing logistics management across the production, processing, and distribution stages (Saetta & Caldarelli, 2020). To support these efforts, researchers developed mathematical programming models to assist in optimizing supply chain network planning. Limpianchob (2015; 2017) proposed a supply chain network planning for tangerines and aromatic coconuts in Thailand. These studies examined system that integrated production planning and harvest scheduling using MILP. Jaigirdar et al. (2023) formulated a mathematical model to address the challenges in quantifying cold storage and transportation for fresh fruits such as guava and lime, aiming to minimize associated storage and transportation costs. Ahsan & Dankowicz (2019) focused on production planning by optimizing seed planting schedules. Similarly, Albornoz et al. (2020) developed a fertilization planning model to ensure adequate nutrient content in the soil for crop cultivation. In addition, Wu and Tanaka (2025) formulated a MILP model to address the perishable inventory control problem.

Several studies have focused on supply chain network planning in fisheries and aquaculture through the application of mathematical models. Managing fisheries remains a highly complex challenge, primarily due to the imperative of ensuring sustainability within these systems (Limpianchob et al., 2020). Nevertheless, after more than 40 years of applying mathematical models to fisheries management, it is both reasonable and timely to review successful cases to evaluate past performance, identify current challenges, and determine future research directions (Bjørndal et al., 2004). For example, Larkin and Sylvia

(1999) presented a model for determining the optimal harvest timing based on fish quality, using intrinsic quality estimation to inform management decisions. Mistiaen and Strand (1998) developed an optimality conditions model for feeding rates and harvest timing in Greece under the assumption that the output price was piecewise linear in weight. Handayani et al. (2021) proposed a MILP model aimed at improving traceability and reducing costs in Indonesia's fish feed industry. Similarly, Purnomo et al. (2022) developed a mathematical model to enhance traceability in a closed fish farming supply chain network. MILP models have also been applied to the supply chain of giant freshwater prawn, as presented by Limpianchob et al. (2020; 2022), focusing on optimal scheduling of aquaculture operations encompassing the entire marine shrimp supply chain network. Overall, these studies highlight both the importance and complexity of supply chain network planning in the agricultural sector, underscoring the need for effective mathematical models and optimization methods to support informed decision-making.

Although existing literature addresses supply chain network planning for agricultural products, notable research gaps remain—particularly in the area of production planning within aquaculture supply chain network design. There is clear evidence that no prior studies have focused specifically on the design and planning of white shrimp farm management covering the entire supply chain network. This gap may be attributed to the relatively recent establishment of white shrimp farming in Thailand, which has been in development for less than 20 years (Department of Fisheries, 2015a). Farmers still lack adequate tools to support their operations and improve the efficiency of farm management across the supply chain. To address this gap, the present study applies a mixed-integer linear programming model to design and plan the white shrimp farm supply chain network. The primary objective is to optimize farm management efficiency in marine shrimp aquaculture. This proposed model functions as a decision-support tool, enabling farmers to effectively design and manage their entire supply chain network in order to maximize overall operational profitability.

Bang Khun Sai Subdistrict, Ban Laem District, Phetchaburi Province is an area known for its high density of shrimp farms due to mineral-rich soil ideal for white shrimp aquaculture. The supply chain network structure of white shrimp aquaculture was analyzed. This structure is represented as a network diagram, shown in Figure 1, and includes the following components:

Farmers initiate the aquaculture process by contacting hatchery dealers to inquire about the availability of fry for purchase. Based on the information received, they decide which dealers from ($HaTD_i^t$). There are two types of fry hatchery dealers: those who do not provide transportation services to the farm (I_D) and middlemen who both sell fry and offer transportation services to the farm (I_{DM}). If farmers choose dealers who do not offer transportation services, they are responsible for arranging their own vehicles to transport the fry from the dealership to the farm. In practice, most farmers tend to purchase fry from dealers they are familiar with and who are located nearby.

Simultaneously, farmers begin preparing the ponds for white shrimp cultivation and place orders for shrimp feed and nutritional supplement feed from vendors. Seawater is pumped through filter bags, disinfected using concentrated potassium permanganate, and left to settle for three days. During this period, essential equipment is also installed, including blowers, water-beating propellers, and waste removal devices. There are four types of shrimp feed ($FeED_{fs}{}^t$) used for raising white shrimp and one type of nutritional supplement ($SuLPp_v{}^t$). As with fry procurement, farmers typically purchase these supplies from familiar and trusted vendors.

When the fry arrive at the farm, they are placed in a nursery pond to rest and acclimate for approximately 3-4 days. After this period, the fry are transferred to the prepared shrimp pond ($PoND_p^t$), with each pond capable of accommodating around 100,000 fry. Farmers begin feeding the fry with Shrimp Feed No. 1 during the first week after stocking. Feed No. 2 is introduced in the second week, followed by Feed No. 3 from weeks three to eight. From the ninth week until harvest, Feed No. 4 is provided four times daily using an automatic feeder. In addition to the regular feed, protein-based nutritional supplements are administered every two weeks until harvest. Throughout the grow-out period, farmers actively manage water quality by adding fresh water to the pond every three days and removing shrimp waste from the center of the pond every two days. These practices help maintain optimal conditions for shrimp growth and health.

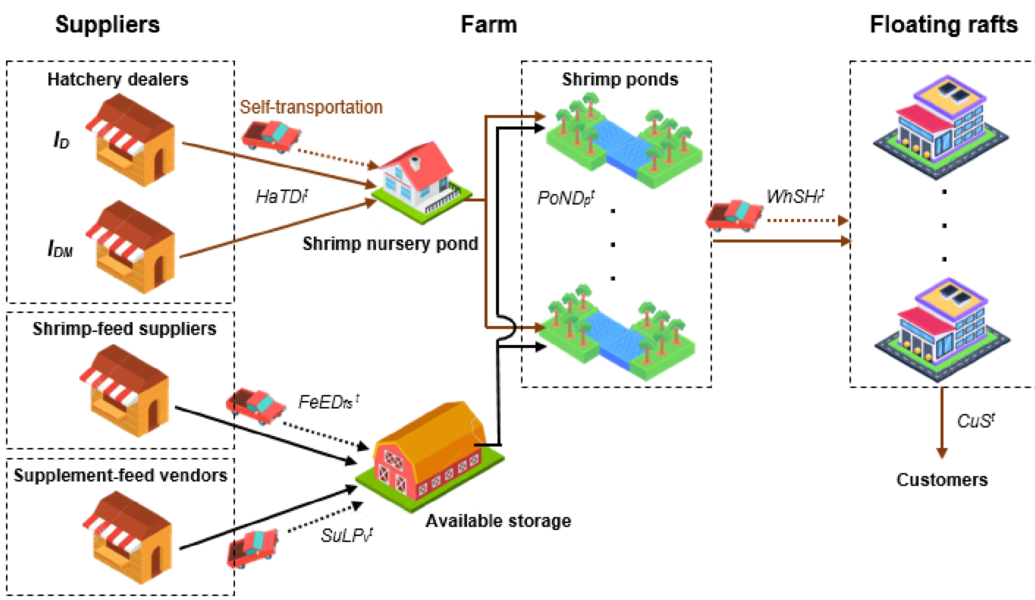

Figure 1. SCN configuration of white shrimp aquaculture in the case study

When the white shrimp reach approximately two months of age, farmers activate pond aerators to increase oxygen levels, particularly at the bottom of the pond. By the third month, the shrimp typically reach the desired market size and are ready for harvest. At this stage, farmers hire laborers (LaB^t) to assist with the harvesting process. The primary equipment used is a net, which is dragged across the pond in a single pass from one end to the other to minimize stress and reduce the risk of disease or mortality among the shrimp. After harvesting, the white shrimp ($WhSH_r^t$) are immediately placed in ice buckets to preserve freshness and then transported to the purchasing platform in Samut Sakhon Province for sale.

2. Materials and Methods

In this study, real-world data from white shrimp farmers in Bang Khun Sai Subdistrict, Ban Laem District, Phetchaburi Province, were used as a case study. The development of the mathematical model was based on the following assumptions:

1) All breeding ponds are available to stock fry at any point during the aquaculture period. The fry are assumed to be of uniform quality, though their selling prices vary depending on the dealer.

2) Fry hatchery dealers who provide transportation services to farms ($i \epsilon I_{DM}$) include transportation costs in the selling price of the fry.

3) Factors such as climate, seasonal variation, and disease outbreaks affecting white shrimp aquaculture are excluded from the evaluation of model variables.

4) At the start of the model calculation, there are no leftover materials from previous aquaculture cycles (e.g., shrimp feed).

The following section outlines the sets of variables, the objective function, and the constraints of the proposed model.

2.1 Indices and sets

AT the set of aquaculture periods, t = 1,...,$AT,$
FED the set of shrimp-feed types, f = 1,...,$FED,$
I_D the set of hatchery dealers without delivery service, i = 1,...,$I_D,$
I_{DM} the set of middlemen with delivery service, i = 1,...,$I_{DM},$
MOD the set of transportation methods, m = 1,...,$MOD,$
PND the set of shrimp ponds, p = 1,...,$PND,$
RAF the set of shrimp floating rafts, r = 1,...,$RAF,$
SUP the set of shrimp-feed suppliers, s = 1,...,$SUP,$
VEN the set of nutritional supplement-feed vendors, v = 1,...,$VEN.$

2.2 Decision variables

The determination of decision variables represents farm management, feeding, production factors, and the harvesting of products in each period ($\forall t \in AT$), as outlined below:

CuS^t total production of white shrimp during each period t (kg)
$FeED_{fs}{}^t$ quantity of shrimp feed of type f ordered from supplier s at time period t (kg)
$HaTD_i^t$ quantity of fry ordered from dealer i during time period t, $i \epsilon I_D \cup I_{DM}$ (shrimps)
LaB^t total amount of labor used to catch white shrimp during each time period t (person)
$SuLP_v{}^t$ quantity of nutritional supplement feed ordered from vendor v during time period t (kg)
$TrFD_s{}^t$ number of truck trips required for shipping shrimp feed from supplier s during time period t (trips)
$TrHD_i^t$ number of truck trips required for shipping fry from dealer i, $i \epsilon I_D$ during time period t (trips)
$TrSD_v{}^t$ number of truck trips required for shipping nutritional supplement feed from vendor v during time period t (trips)
$TrWD_{mr}{}^t$ number of truck trips required for shipping shrimp to shrimp floating raft r with transportation method m during time period t (trips)
$WhSH_r{}^t$ quantity of white shrimps delivered to shrimp floating raft r during time period t (kg)

In addition, we defined binary decision variables in this mathematical model to identify which shrimp ponds farmers must use to breed fry during each aquaculture period. Another variable was defined to enable farmers to decide on transporting white shrimp to the shrimp floating rafts during each time period, as outlined below:

$$PoND_p^t = \begin{cases} 1, \text{ if pond } p \text{ is utilized for aquaculture in time period } t \\ 0, \text{ otherwise} \end{cases}$$

$$ShRR_r^t = \begin{cases} 1, \text{ if shrimp floating raft } r \text{ is established in time period } t \\ 0, \text{ otherwise} \end{cases}$$

2.3 Parameters

In this section, we will define the parameters used in mathematical modeling, including the following data:

$CapD_r^t$ maximum quantity of white shrimp that shrimp floating raft r can purchase during time period t (kg)
$CapF_f$ maximum capacity of shrimp feed of type f per pond (kg/pond)
$CapFV_{fs}$ maximum selling capacity of shrimp feed of type f by supplier s (kg)
$CapH_i$ maximum selling capacity of fry of each hatchery dealer i, $i \in I_D \cup I_{DM}$ (shrimps)
$CapP_p$ maximum capacity of fry that farmers can stock in each pond p (fry/pond)
$CapS$ maximum capacity of nutritional supplement feed per pond (kg/pond)
$CapSP_v$ maximum selling capacity of supplement feed by vendor v (kg)
$CapTF$ maximum shrimp feed shipping capacity per trip (kg)
$CapTH$ maximum fry shipping capacity per trip (shrimps)
$CapTS$ maximum nutritional supplement feed shipping capacity per trip (kg)
$CapTW_m$ maximum shipping capacity of shrimp per trip using transportation method m (kg)
$CosFS_{fs}$ cost of shrimp feed of type f from supplier s (THB/kg)
$CosHA_i$ cost of fry purchased from dealer i, $i \in I_D \cup I_{DM}$ (THB/shrimp)
$CosLB$ cost of labor (THB/person)
$CosPO_p$ cost of shrimp pond management for each pond p (THB/pond)
$CosSU_v$ cost of nutritional supplement feed from vendor v (THB/kg)
$CosTF_s$ unit transportation cost from shrimp feed supplier s (THB/trip)
$CosTH_i$ unit transportation cost from fry hatchery dealer i, $i \in I_D$ (THB/trip)
$CosTS_v$ unit transportation cost from nutritional supplement feed vendor v (THB/trip)
$CosTW_{mr}$ unit transportation cost from the farm to the shrimp floating raft r by transportation method m (THB/trip)
RoG^t growth rate of white shrimp aquaculture during time period t (calculated as the average yield per pond of white shrimp from 2021 to 2023)
RoL_p number of laborers working for harvesting in pond p
$ShrP_r^t$ selling prices of white shrimp from the shrimp floating raft r during time period t (THB/kgr)

To enhance understanding of the proposed model formulation, Figure 2 illustrates the dependencies between the decision variables in white shrimp aquaculture and the stage of supply chain network planning. The objective of the model is to maximize the total profit surplus and improve supply chain network efficiency for white shrimp aquaculture, while accounting for the effects of the multi-period and multi-stage production planning.

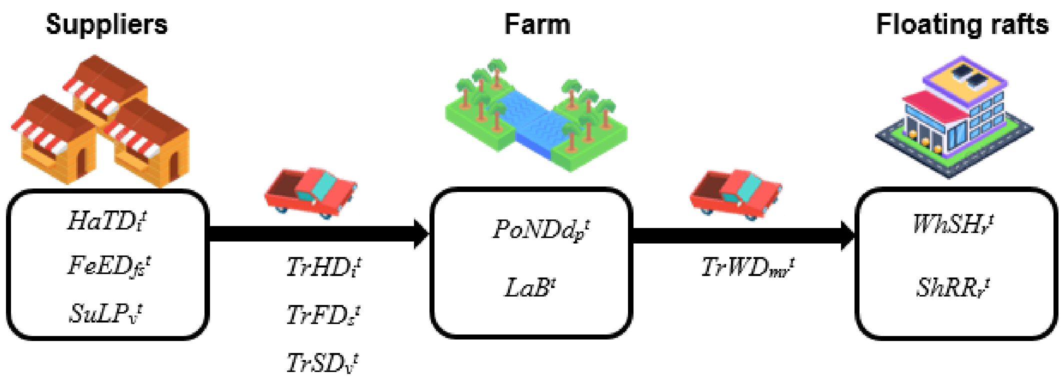

Figure 2. A conceptual diagram of the decision variables in the white shrimp aquaculture supply chain network

2.4 Objective function

In this research, we developed an objective function designed to support farmers in efficiently managing white shrimp aquaculture across the entire supply chain network, with the aim of maximizing total profit surplus. The system encompasses planning for fry procurement, shrimp pond selection, the choice of feed and nutritional supplements, shrimp harvesting, and the selection of appropriate vehicles for delivery to shrimp floating rafts. The overarching goal is to optimize sales revenue while ensuring customer satisfaction. The objective function incorporates the following components:

$$Max\ z = \text{Net revenue - Annual total cost} \tag{1}$$

From the objective function, net revenue is defined as the total income generated from selling white shrimp to shrimp floating rafts ($WhSH_r^t$), as illustrated below:

$$\text{Net revenue} = \sum_{r \in RAF} \sum_{t \in AT} WhSH_r^t \bullet ShRP_r^t \tag{1.1}$$

In the second term, annual total cost is defined as the overall expenses incurred in white shrimp aquaculture, including five types of costs: shrimp pond management cost (c^{Ope}), fry purchasing cost (c^{Hat}), shrimp feed and nutritional supplements cost (c^{Fed}), labor cost (c^{Lab}), and transportation cost (c^{Trn}), as follows:

$$\text{Annual total cost} = c^{Ope} + c^{Hat} + c^{Fed} + c^{Lab} + c^{Trn} \tag{1.2}$$

2.4.1 Shrimp pond management cost (c^{Ope})

This refers to the costs incurred when farmers utilize shrimp ponds to stock fry during the aquaculture period. These costs include pond preparation, care and maintenance, and other necessary expenses. The total cost varies based on the size of the pond, as follows:

$$c^{Ope} = \sum_{p \in PND} \sum_{t \in AT} PoND_p^t \bullet CosPO_p \tag{1.2.1}$$

2.4.2 Fry purchasing cost (c^{Hat})

This refers to the costs incurred when farmers purchase fry from hatchery dealers during the aquaculture period, as outlined below:

$$c^{Hat} = \sum_{i \in I_D \cup I_{DM}} \sum_{t \in AT} HaTD_i^t \bullet CosHA_i \quad (1.2.2)$$

2.4.3 Shrimp feed and nutritional supplement cost (c^{Fed})

This refers to the cost of four types of shrimp feed and nutritional supplements used throughout the aquaculture period, detailed as follows:

$$c^{Fed} = \sum_{f \in FED} \sum_{s \in SUP} \sum_{t \in AT} FeED_{fs}^t \bullet CosFS_{fs} + \sum_{v \in VEN} \sum_{t \in AT} SuLP_v^t \bullet CosSU_v \quad (1.2.3)$$

2.4.4 Labor cost (c^{Lab})

This refers to the labor costs incurred by farmers for hiring workers to harvest white shrimp, as detailed below:

$$c^{Lab} = \sum_{t \in AT} LaB^t \bullet CosLB \quad (1.2.4)$$

2.4.5 Transportation cost (c^{Trn})

Transportation costs occur throughout the white shrimp aquaculture period and encompass four stages: transporting fry from hatchery dealers (if farmers purchase from a supplier that does not provide transportation services, requiring them to arrange and cover the costs themselves), transporting four types of shrimp feed, transporting nutritional supplements, and transporting shrimp to floating rafts for sale.

$$c^{Trn} = \sum_{i \in I_D} \sum_{t \in AT} TrHD_i^t \bullet CosTH_i + \sum_{s \in SUP} \sum_{t \in AT} TrFD_s^t \bullet CosTF_s + \sum_{v \in VEN} \sum_{t \in AT} TrSD_v^t \bullet CosTS_v + \sum_{m \in MOD} \sum_{r \in RAF} \sum_{t \in AT} TrWD_{mr}^t \bullet CosTW_{mr} \quad (1.2.5)$$

2.5 Constraints

The constraints of the mathematical model used for designing and planning the white shrimp aquaculture supply chain network are formulated to achieve the following objectives: effectively meeting customer demand, maximizing total profit surplus for farmers, and ensuring compliance with Good Aquaculture Practice (GAP) standards as set by the Department of Fisheries. These constraints include:

The operational limitations associated with managing each shrimp pond throughout the aquaculture period, as specified in constraints (2)-(5).

$$\sum_{t \in AT} PoNDd_p^t \leq 4, \forall p \in PND \quad (2)$$

Constraint (2) specifies that each shrimp pond must be used exactly four times over the course of the aquaculture period.

Constraint (3) ensures a continuous supply of white shrimp during peak selling periods by requiring farmers to stock at least one batch of shrimp fry in each aquaculture cycle.

$$\sum_{p \in PND} PoND_p^t \geq 1, t = 1,...,10 \tag{3}$$

The farmers in the case study avoid stocking fry during the winter season due to low water temperatures, which inhibit shrimp growth and increase mortality risk. Accordingly, constraint (4) is established to prohibit fry stocking during the winter period, as follows:

$$\sum_{p \in PND} PoND_p^t = 0, t = 11,...,13 \tag{4}$$

Typically, once fry is stocked in a pond, it takes approximately three months (90 days) for white shrimp to reach harvest size. Therefore, if pond *p* is selected for aquaculture in period *t*, it cannot be reused for next three months, until the shrimp are harvested and sold to the shrimp floating rafts. This condition is defined in constraint (5).

$$\sum_{a=0}^{2} PoND_p^{t+a} \leq 1, \forall p \in PND, t = 1,...,10 \tag{5}$$

The following section outlines the key processes involved in white shrimp aquaculture. It begins with farmers selecting a pond for fry stocking, followed by pond preparation activities such as improving pond conditions and disinfecting seawater before releasing the fry. Once stocked, farmers manage the aquaculture process over a three-month period to ensure the shrimp reaches the desired size and quality required by customers. These processes are detailed by constraints (6)-(19).

$$\sum_{i \in I_D \cup I_{DM}} HaTD_i^t \geq \sum_{p \in PND} PoND_p^t \bullet CapP_p, \forall t \in AT \tag{6}$$

$$HaTD_i^t \leq CapH_i, \forall i \in I_D \cup I_{DM}, \forall t \in AT \tag{7}$$

and

$$HaTD_i^t \leq TrHD_i^t \bullet CapTH, \forall i \in I_D, \forall t \in AT \tag{8}$$

Constraints (6) and (7) define the total quantity of fry that a farmer must purchase from hatchery dealers in each period, ensuring that this amount does not exceed the maximum allocation permitted by each dealer during the same period. Constraint (8) states that if a farmer purchases fry from a dealer who does not provide transportation services ($i \in I_D$), the farmer must independently arrange transportation to the farm.

Farmers begin feeding prepared food to fry starting from the first week after stocking and continue until harvest. Four types of feed are used to support shrimp growth, administered four times per day through automatic feeding machines. Constraints (9)-(11) determine the quantity of feed to be purchased from suppliers and the number of truck trips required to transport the feed to the farm.

$$\sum_{s \in SUP} FeED_{fs}^{t} \geq \sum_{p \in PND} PoND_{p}^{t} \bullet CapF_{f} \ , \forall f \in FED, \forall t \in AT \tag{9}$$

$$FeED_{fs}^{t} \leq CapFV_{fs} \ , \forall f \in FED, \forall s \in SUP, \forall t \in AT \tag{10}$$

and

$$\sum_{f \in FED} FeED_{fs}^{t} \leq TrFD_{s}^{t} \bullet CapTF \ , \forall s \in SUP, \forall t \in AT$$

(11)

Additionally, farmers administer protein-based nutritional supplements to enhance the weight and body fullness of white shrimp. The quantity of supplements required for purchase from vendors is determined by constraints (12)-(14).

$$\sum_{v \in VEN} SuLP_{v}^{t} \geq \sum_{p \in PND} PoND_{p}^{t} \bullet CapS, \forall t \in AT \tag{12}$$

$$SuLP_{v}^{t} \leq CapSP_{v}, \forall v \in VEN, \forall t \in AT \tag{13}$$

and

$$SuLP \leq TrSD_{v}^{t} \bullet CapTS \ , \forall v \in VEN, \forall t \in AT \tag{14}$$

White shrimps are ready for harvest after approximately three months of cultivation. The model determines the appropriate size and quality of the shrimp to meet customer requirements. For harvesting, farmers use nets to collect all shrimp from each pond in a single operation to minimize stress and maintain product quality. The quantity of white shrimp harvested, and the labor required in each time period are defined in constraints (15) and (16).

$$\sum_{p \in PND} PoND_{p}^{t} \bullet CapP_{p} \bullet RoG^{t} = \sum_{r \in RAF} WhSH_{r}^{t+3} \ , t = 1,\ldots,10 \tag{15}$$

and

$$LaB^{t} \geq \sum_{p \in PND} PoND_{p}^{t} \bullet RoL_{p}, \forall t \in AT \tag{16}$$

The quantity of white shrimp transported to each shrimp floating raft, along with the number of truck trips and types of vehicles chosen by farmers for transportation, is specified in constraints (17) and (18).

$$WhSH_{r}^{t} \leq ShRR_{r}^{t} \bullet CapD_{r}^{t} \ , \forall r \in RAF, \forall t \in AT \tag{17}$$

and

$$WhSH_{r}^{t} \leq \sum_{m \in MOD} TrWD_{mr}^{t} \bullet CapTW_{m} \ , \forall r \in RAF, \forall t \in AT \tag{18}$$

Finally, constraint (19) specifies the total quantity of white shrimp that farmers can harvest in each period, ensuring a consistent supply of shrimp for sale to the shrimp floating rafts throughout the aquaculture period.

$$\sum_{r \in RAF} WhSH_{r}^{t} = Cus^{t}, \forall t \in AT \tag{19}$$

$$PoND_p^t, ShRR_r^t \in \{0,1\}, \forall p, \forall r, \forall t \quad (20)$$

$$CuS^t, FeED_{fs}^t, SuLP_v^t, WhSH_r^t \geq 0, \forall f, \forall s, \forall v, \forall r, \forall t \quad (21)$$

$$HaTD_i^t, LaB^t \geq 0 \text{ and integer}, \forall i, \forall t \quad (22)$$

$$TrFD_s^t, TrHD_i^t, TrSD_v^t, TrWD_{mr}^t \geq 0 \text{ and integer}, \forall s, \forall i, \forall v, \forall m, \forall r, \forall t \quad (23)$$

3. Results and Discussion

Using the mixed-integer linear programming (MILP) model presented in the previous section, we employed the CPLEX Solver within GAMS Studio (Version 47.5.0) to develop a mathematical model. The propose of this model is to support the planning and management of white shrimp farms across the entire supply chain network, with the objective of identifying the optimal solution.

3.1 Result of case study

The results of the mixed-integer linear programming (MILP) model were applied to design and plan the supply chain network for white shrimp aquaculture in a case study. This process includes fry hatchery selection, farm management, farming operations, and shrimp harvesting for sale at shrimp floating rafts. The primary objective is to maximize the total profit surplus for farmers while satisfying customer demand. A summary of the numerical results from the case study is presented in Table 1.

Table 1. The computational results of case study

Computational Results	
1)Total profit surplus	1,064,637 THB
2) Total decision variables	859 variables
2.1) Binary variables	195 variables
2.2) Integer variables	468 variables
2.3) Linear variables	196 variables
3) Total Constraints	4,119 constraints
4) Computational period	112.22 seconds
5) Gap tolerance	0.1%

From Table 1, the optimal total profit surplus of the operation is 1,064,637 THB per year, achieved with a gap tolerance of 0.1% and a calculation time of only 112.22 seconds, demonstrating the high quality of the integer results obtained. Compared to manual planning, which yielded a total net profit of 941,990 THB per year, the model demonstrates an increase of 122,647 THB annually, representing an 11.52% improvement in net profit (Figure 3).

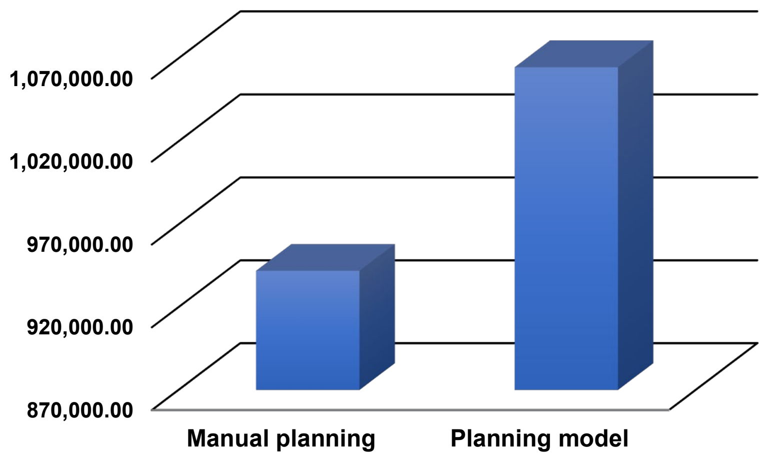

Figure 3. The comparison of total net profit results before and after implementing the model

An analysis of the results from the mathematical model revealed that the increase in total profit surplus was achieved through the efficient and strategic design of the supply chain network, leading to an overall cost reduction of approximately 6.55% compared to the pre-model scenario. The most significant cost savings were observed in shrimp feed and nutritional supplements, which originally totaled 270,000 THB. After implementing the model, these costs decreased to 259,200 THB, representing a 4.00% reduction. The model was designed to encourage farmers to purchase from suppliers located farther away but offering lower prices compared to nearby suppliers. While transportation costs increased, the overall expense for shrimp feed and nutritional supplements was significantly reduced by sourcing from distant suppliers with lower prices, ultimately resulting in substantial cost savings.

In summary, the results of the mathematical model effectively demonstrate its capability to design and plan a supply chain network system for white shrimp aquaculture. The model facilitates efficient farm management, optimized farming operations, informed selection of suitable production factors, and the fulfillment of customer demand, all while ensuring compliance with Good Agricultural Practices (GAP) standards.

3.2 Sensitivity analysis

This section presents a sensitivity analysis to examine the impact of various parameters on the mathematical model (Yousefi-Babadi et al., 2017) and to evaluate their effects under different conditions. Additional costs, including shrimp pond management, fry hatchery procurement, shrimp feed and nutritional supplements, labor, and transportation, were increased by 10% to 50% to assess their impact on total profit surplus (Bilgen & Ozkarahan, 2007). The results of the sensitivity analysis, along with the percentage differences in net profit for each cost type, are shown in Table 2. Labor costs were excluded from this study due to their relatively minor variations compared to other costs.

Table 2. The computational results of case study

Percentage Change	Increasing Shrimp Pond Management Cost		Percentage Change	Increasing Fry Purchasing Cost	
	Solution (THB)	Change in profit (%)		Solution (THB)	Change in Profit (%)
10	1,055,637.00	0.85	10	1,055,187.00	0.89
20	1,046,637.00	1.69	20	1,045,737.00	1.78
30	1,037,637.00	2.54	30	1,036,287.00	2.66
40	1,028,637.00	3.38	40	1,026,837.00	3.55
50	1,019,637.00	4.23	50	1,017,387.00	4.44
Percentage Change	**Increasing Shrimp Feed and Supplements Cost**		**Percentage Change**	**Increasing Transportation Cost**	
	Solution (THB)	**Change in Profit (%)**		**Solution (THB)**	**Change in Profit (%)**
10	1,034,750.00	2.81	10	1,062,837.00	0.17
20	1,004,864.00	5.61	20	1,061,037.00	0.34
30	947,978.10	8.41	30	1,059,237.00	0.51
40	945.091.00	11.23	40	1,057,437.00	0.68
50	915,205.50	14.04	50	1,055,636.00	0.85

Table 2, which shows that the sensitivity analysis results, indicates that total profit surplus is most sensitive to changes in the cost of shrimp feed and nutritional supplements, followed by the costs of fry hatchery procurement and pond management, respectively. Conversely, transportation costs have a relatively lower impact on net profit. For example, a 10% increase in transportation costs results in only a 0.17% decrease in net profit, whereas a 10% increase in shrimp feed and nutritional supplement costs leads to a 2.81% decrease in net profit (Figure 4).

These findings highlight that the cost of shrimp feed and nutritional supplements has a significant impact on the total net profit, making it a critical component of the cost structure in white shrimp aquaculture. The high influence of feed costs stems from the need for farmers to use multiple types of shrimp feed, with prices varying by supplier. Therefore, implementing efficient and well-planned purchasing strategies for feed and nutritional supplements is essential for farmers seeking to minimize costs and improve profitability.

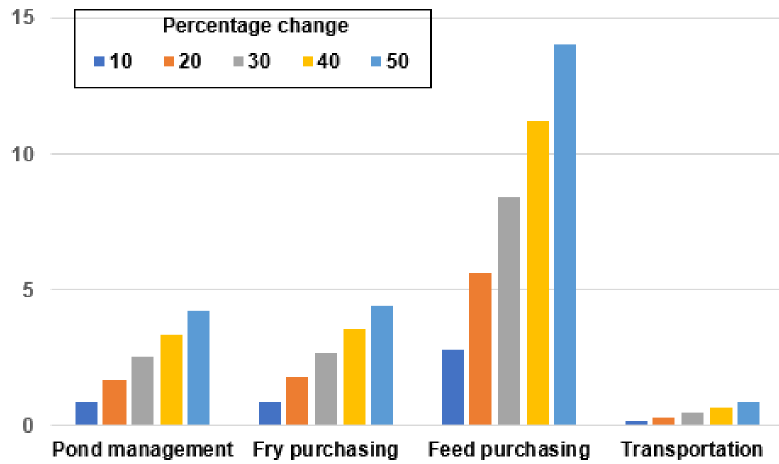

Figure 4. Comparison of the percentage change in total profit surplus when costs increase.

4. Conclusions

In this research, the study focused on the challenges of designing and planning a supply chain network system for white shrimp aquaculture, using a case study group of farmers in Bang Khun Sai Subdistrict, Ban Laem District, Phetchaburi Province. Data collection revealed that farmers encountered various issues in farm management, including fry hatchery procurement, pond rotation, shrimp feeding, production factors, harvesting, and transportation. These challenges hindered their ability to manage shrimp farming effectively, resulting in difficulties in producing high-quality and consistent products.

This research developed a mixed-integer linear programming model to design and plan the supply chain network for white shrimp farming. The data used for analysis were derived from actual aquaculture operations. The mathematical model accounted for various constraints associated with shrimp farming, ensuring compliance with the GAP standards established by the Department of Fisheries. This approach guaranteed the model's accuracy and practicality for real-world application. The CPLEX Solver program, implemented using the GAMS Studio language (Version 47.5.0), was employed to determine the optimal solution. The results achieved a tolerance value of just 0.1% from the optimal solution. The proposed design and planning of the white shrimp farming supply chain network proved to be highly efficient, yielding a total net profit that was 11.52% higher than the previous system without the model.

To enhance the comprehensiveness of the white shrimp supply chain management planning system and ensure its relevance to current conditions, future research will focus on planning the transportation of fry from dealers to farms. This aspect is critical, as dealers pack fry in plastic bags filled with seawater and pressurized with oxygen gas to keep them alive. Farmers generally have only 4-6 h to transport these bags before the fry perish. Without effective transportation planning, the fry may die during transit, forcing farmers to purchase additional fry to replace the loss, thereby increasing operational costs.

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6. Authors' Contributions

Wannarat Bunnun, Pinyatorn Meewassana, and Sukanya Chaiphantho: Problem identification, methodology development, model creation, implementation, and manuscript preparation. Chaimongkol Limpianchob: Research supervision, literature review, and manuscript revision.

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7. Conflicts of Interest

The authors declare that no conflicts of interest exist.

References

Ahsan, Z., & Dankowicz, H. (2019). Optimal scheduling and sequencing for large-scale seeding operations. *Computers and Electronics in Agriculture, 163*, Article 104728. https://doi.org/10.1016/j.compag.2019.01.052

Ahumada, O., & Villalobos, J. R. (2011). Operational model for planning the harvest and distribution of perishable agricultural products. *International Journal of Production Economics, 133*(2), 677-687. https://doi.org/10.1016/j.ijpe.2011.05.015

Albornoz, V. M., Veliz, M. I., Ortega, R., & Ortiz-Araya, V. (2020). Integrated versus hierarchical approach for zone delineation and crop planning under uncertainty. *Annals of Operations Research*, *286*, 617-634. https://doi.org/10.1007/s10479-019-03198-y

Bilgen, B., & Ozkarahan, I. (2007). A mixed-integer linear programming model for bulk grain blending and shipping. *International Journal of Production Economics*, *107*(2), 555-571. https://doi.org/10.1016/j.ijpe.2006.11.008

Bjørndal, T., Lane, D. E., & Weintraub, A. (2004). Operational research models and the management of fisheries and aquaculture: a review. *European Journal of Operational Research, 156*(3), 533-540. https://doi.org/10.1016/S0377-2217(03)00107-3

Coastal Aquaculture Research and Development Office. (2006). *Knowledge management of white shrimp hatchery according to GAP standards*. Department of Fisheries. Bangkok.

Department of Fisheries. (2015a). *How to successfully raise shrimp during a severe EMS/AHPND outbreak*. Department of Fisheries. Bangkok.

Department of Fisheries. (2015b). *Evaluation criteria for marine shrimp farms according to GAP standards.* Department of Fisheries ,Bangkok.

Farooque, M., Zhang, A., & Liu, Y. (2019). Barriers to circular food supply chains in China. *Supply Chain Management: An International Journal*, *24*(5), 677-697. https://doi.org/10.1108/SCM-10-2018-0345

Handayani, D. I., Masudin, I., Rusdianayah, A., & Suharsono, J. (2021). Production-distribution model considering traceability and carbon emission: A case study of the Indonesian canned fish food industry. *Logistics*, *5*(3), Article 59. https://doi.org/10.3390/logistics5030059

Jaigirdar, S. M., Das, S., Chowdhury, A. R., Ahmed, S., & Chakrabortty, R. K. (2023). Multi-objective multi-echelon distribution planning for perishable goods supply chain: A case study. *International Journal of Systems Science: Operations and Logistics*, *10*(1), Article 2020367. https://doi.org/10.1080/23302674.2021.2020367

Kamble, S. S., Gunasekaran, A., & Gawankar, S. A. (2020). Achieving sustainable performance in a data-driven agriculture supply chain: A review for research and applications. *International Journal of Production Economics, 219*, 179-194. https://doi.org/10.1016/j.ijpe.2019.05.022

Larkin, S. L., & Sylvia, G. (1999). Intrinsic fish characteristics and intraseason production efficiency: A management-level bio-economic analysis of a commercial fishery. *American Journal of Agricultural Economics, 81*(1), 29-43. https://doi.org/10.2307/1244448

Limpianchob, C. (2015). A mixed integer linear programming model for optimal production planning in tangerine supply chain. *Kasetsart Journal (Natural Science), 49*(6), 1001-1011.

Limpianchob, C. (2017). Integrated of harvesting and production planning in aromatic coconut supply chain using mixed integer linear programming. *International Journal of Operational Research, 30*(3), 360-374. https://doi.org/10.1504/IJOR.2017.087277

Limpianchob, C., Sasabe, M., & Kasahara, S. (2020). A push strategy optimization model for a marine shrimp farming supply chain network. *International Journal of Operational Research, 39*(2), 262-277. https://doi.org/10.1504/IJOR.2020.109757

Limpianchob, C., Sasabe, M., & Kasahara, S. (2022). A multi-objective optimization model for production and transportation planning in a marine shrimp farming supply chain network. *International Journal of Operational Research, 45*(1), 1-28. https://doi.org/10.1504/IJOR.2022.125727

Mistiaen, J. A., & Strand, I. (1998). Optimal feeding and harvest time for fish with weight-dependent process. *Marine Resource Economics*, *13*(4), 231-246. https://doi.org/10.1086/mre.13.4.42629239

Mamoudan, M. M., Jafari, A., Mohammadnazari, Z., Nasiri, M. M. N., & Yazdani, M. (2023). Hybrid machine learning-metaheuristic model for sustainable agri-food production and supply chain planning under water scarcity. *Resources, Environment and Sustainability, 14*, Article 100133. https://doi.org/10.1016/j.resenv.2023.100133

Mohammed, A., & Wang, Q. (2017). The fuzzy multi-objective distribution planner for a green meat supply chain. *International Journal of Production Economics, 184*(2), 47-58. https://doi.org/10.1016/j.ijpe.2016.11.016

Purnomo, M. R. A., Wangsa, I. D., Rizky, N., Jauhari, W. A., & Zahria, I. (2022). A multi-echelon fish closed-loop supply chain network problem with carbon emission and traceability. *Expert Systems with Applications*, *210*, Article 118416. https://doi.org/10.1016/j.eswa.2022.118416

Saetta, S., & Caldarelli, V. (2020). How to increase the sustainability of the agri-food supply chain through innovations in 4.0 perspective: a first case study analysis. *Procedia Manufacturing, 42*, 333-336. https://doi.org/10.1016/j.promfg.2020.02.083

Tsolakis, N. K., Keramydas, C. A., Toka, A. K., Aidonis, D. A., & Iakovou, E. T. (2014). Agri-food supply chain management: a comprehensive hierarchical decision-making framework and a critical taxonomy. *Biosystems Engineering*, *120*(4), 46-64. https://doi.org/10.1016/j.biosystemseng.2013.10.014

Vazquez, D. A. Z., Fan, N., Teegerstrom, T., Seavert, C., Summers, H. M., Sproul, E., & Quinn, J. C. (2021). Optimal production planning and machinery scheduling for semi-arid farms. *Computers and Electronics in Agriculture, 187*, Article 106288. https://doi.org/10.1016/j.compag.2021.106288

Wu, Y., & Tanaka, S. (2025). Perishable inventory control with backlogging penalties: A mixed-integer linear programming model via two-step approximation. *Computer and Operations Research, 176*, Article 106953. https://doi.org/10.1016/j.cor.2024.106953

Yadev, V. S., Singh, A. R., Gunasekaran, A., Raut, R. D., & Narkhede, B. E. (2022). A systematic literature review of the agro-food supply chain: Challenges, network design, and performance measurement perspectives. *Sustainable Production and Consumption, 29*, 685-704. https://doi.org/10.1016/j.spc.2021.11.019

Yousefi-Babadi A., Tavakkoli-Moghaddam, R., Bozorgi-Amiri, A., & Seifi, S. (2017). Designing a reliable multi-objective queuing model of a petrochemical supply chain network under uncertainty: a case study. *Computers and Chemical Engineering*, *100*(5), 177-197. https://doi.org/10.1016/j.compchemeng.2016.12.012

Zhu, Z., Chu, F., Dolgui, A., Chu, C., Zhou, W., & Piramuthu, S. (2018). Recent advances and opportunities in sustainable food supply chain: a model-oriented review. *International Journal of Production Research, 56*(17), 5700-5722. https://doi.org/10.1080/00207543.2018.1425014