A System Dynamics Model of Frozen Fish Supply Chain

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***Abstract*—The system dynamics methodology examines the intricate behaviors of complex systems through time, incorporating inventories, transfers, feedback cycles, lookup functions, and temporal delays. In fisheries systems, the interaction between resources and management entities is intricate, with the dynamics of fisheries significantly influencing the formulation of effective policies. Fisheries hold a vital position in Indonesia's economy, contributing to food security, nutrition, and the welfare of fishermen. Under Law Number 7 of 2016, the fisheries sector covers all activities, from resource management to the marketing of marine products. With its rich fishery resources, Indramayu Regency is a major contributor to West Java's fish production. TPI Karangsong, the hub of fishing activities in Indramayu, is a key player in the frozen fish supply chain, relying heavily on cold storage facilities to ensure product quality. Consequently, the system dynamics approach proves valuable in understanding the frozen fish supply chain by modeling the interactions between different variables and evaluating the impact of policies to improve fish quality. The system dynamics model in this study consists of six sub-models: fish at TPI, cold storage, refrigerated cabinets, total revenue, cash, and cold trucks. The simulation results provide policy recommendations to improve the quality of frozen fish at TPI Karangsong, namely the baseline scenario, cold truck scenario, cold truck scenario, truck and cold storage integration scenario, cold storage and fish catch drop integration scenario.**

***Keywords*—Supply chain; system dynamics; frozen fish; six sub-models; simulation; policy scenario**

I. Introduction

As a maritime nation where 70% of its territory is comprised of seas, Indonesia has substantial potential in the tourism and marine sectors, particularly in fisheries. The fisheries sector serves as a crucial contributor to the national economy by generating employment and supporting food security. By Law Number 7 of 2016 [1], the fisheries sector spans activities from pre-production to marketing, integrated within the fisheries business system. The rich diversity of fish resources is a core strength of Indonesian fisheries, with fishing operations governed by Law Number 45 of 2009 [2]. Additionally, the management of marine resources, both renewable and non-renewable, is regulated under Law Number 32 of 2014 [3]. The Marine Affairs and Fisheries Minister Regulation [4] outlines processing and product safety standards to maintain the competitiveness of Indonesian fishery products in global markets. Innovations in fish processing, whether through traditional or modern methods, are essential for adding value to fishery products and enhancing their global market position [5][6]. In Indramayu Regency, a major fisheries hub in West Java, over 35,000 fishermen produced 551,632.81 tons of fish in 2023, contributing 34.63% to West Java's total fishery production (BPS, 2022).

A company's competitive advantage can be improved through production efficiency, effective distribution, and the timely delivery of products to consumers [7][8]. Supply chain management (SCM) involves key factors such as technology utilization, customer satisfaction, supply chain unification, and inventory management are essential components, while competitive advantage is influenced by factors such as pricing, product quality, market readiness, and sales growth. A company's performance is evaluated through both financial and operational metrics [8]. While a stronger innovation strategy typically enhances operational performance, competitive advantage alone does not fully mediate the link between innovation strategy and overall company performance [9].

SCM is integral to the sustainability of food supply chains, particularly in minimizing food loss and addressing the challenges posed by climate change. The cold chain is essential for preserving the quality of perishable products, such as fish, during their transportation and storage [8]. Despite the significant obstacles faced by cold chain infrastructure in Indonesia, its successful implementation is essential for enhancing the fisheries sector's competitiveness in the global marketplace [10]. Moreover, the establishment of an efficient logistics system is imperative to bolster food security [11].

The complex structure of frozen fish distribution networks requires more than simplistic methods or single-cause solutions. Thus, there is a need for a framework that facilitates an understanding of the multifaceted issues within a systemic context [12] [13]. System dynamics is instrumental in illustrating the interconnections among suppliers, producers, and distribution networks. [14]. This approach underscores the importance of temporal factors in comprehending the overall behavior of a system, demonstrating how such a system can respond to external disturbances or align with the model's objectives (Coyle, 1997 in Wati et al., 2021). Furthermore, system dynamics highlights the influence of policies on system behavior (Richardson & Pugh III, 1997 in Wati et al., 2021) and facilitates the analysis of complex dynamics through the feedback mechanisms among system components [15]. The Causal Loop Diagram (CLD) is extensively used to design complex supply chains, including perishable products like frozen fish [16] [17] while [18] designed a sustainable supply chain model for the fisheries sector using a system dynamics approach.

TPI Karangsong is a leading fish distribution center in West Java, where the fisheries sector plays a vital role in promoting local economic development. Therefore, adequate cooling facilities are crucial to maintaining the quality of the distributed fish. This study aims to develop a system dynamics model that maps the frozen fish supply chain, expecting the simulation results to propose various policy scenarios that can potentially improve the quality of frozen fish products.

II. Related Works

A. Supply Chain Management (SCM)

There is integrates various entities collaborating to source raw materials transform into finished goods, deliver them to stores and then consumers [19][20]. Heizer et al. [21] Explain how a distribution network involves suppliers, manufacturers, distributors, and retailers, while Chopra and Meindl [22] emphasize the role of all stakeholders in meeting consumer demands. According to Apriani et al. [23], the interrelationship between goods, finances, and information is crucial. To optimize operations and enhance customer satisfaction, the supply chain mechanism must be effectively implemented through strong relationships with suppliers, efficient production processes, and excellent service [24] [25]. SCM is an integrated approach that efficiently Oversees the movement of products, finances, and insights from upstream to downstream to improve product quality, profitability, and organizational performance [26] [27] [28] [29]. Additionally, SCM enhances competitive advantage by driving efficiency in both production and distribution. [7] [8] [30].

B. System Dynamics (SD)

SD is initially presented by Forrester in the 1950s [31], who constructed a model to demonstrate the way policies influence the soundness of manufacturing systems [32], as well an advanced framework applied to model sophisticated feedback structures [33], making it highly valuable for analyzing interdisciplinary concerns [34]. Besides that, it can also identified using nonlinear relationships and feedback loops between system components, making it suitable for modeling complex socio-economic phenomena [35]. It enables the analysis of interactions among various processes at different levels, providing a holistic understanding of system behavior [15][36]. As part of systems theory, SD helps model nonlinearity through structural modeling incorporating feedback loops and time delays [37]. Key principles in the use of system dynamics include (1) building model structures that define system behavior, (2) integrating soft variables, and (3) interpreting mental models that provide substantial influence [38]. SD offers various benefits, such as visualizing causal links between variables, recognizing the effects of delays, and examining system responses to various scenarios (Zapata et al., 2019). In ecotourism management, Sjaifuddin's [39] model integrates biophysical, social, and economic variables simulated under multiple scenarios, while Utami et al. [40] highlight key response variables such as ecotourism revenue and mangrove rehabilitation. In production planning and control, Karaz et al. [41] emphasize the significance of dynamic interactions in evaluating the impact of dynamic management (MD) on construction projects. Similarly, Ismail et al. [42] focus on determining optimal Catch capacity to support the sustainability of Malaysian fisheries.

III. Methodology

The system dynamics model of the frozen fish supply chain in Karangsong is classified as a qualitative-quantitative research study and model-based simulation. This approach combines qualitative and quantitative analyses to understand complex systems and predict dynamic behaviors and feedback structures within the system. The study integrates qualitative and quantitative methods to capture system complexity and simulate time-series data [43] [44].

1) Qualitative research is employed to identify key variables, causal relationships, and behavioral dynamics that influence the frozen fish supply chain. Data are collected through interviews, observations, and discussions with stakeholders, such as fishermen, traders, and cooling facility managers.

2) A quantitative approach is applied during the modeling and simulation phase, using numerical data to construct an analytical model. This method consists of seven stages: problem identification, conceptualization, model formulation, behavior analysis, review, policy examination, and model application [17] [46].

3) The model-based simulation utilizes concepts such as stocks, flows, and feedback loops to describe the movement of materials, information, and policy influences within the system. The results of these simulations are used to evaluate policy scenarios that could enhance fish quality, stabilize supply, and increase income.

Integrating both qualitative and quantitative approaches enables this study to offer more comprehensive insights. By combining the narrative understanding from qualitative analysis with the predictive capabilities of quantitative simulation, the study provides more effective solutions for managing the sustainable frozen fish supply chain at TPI Karangsong. Using Vensim PLE 10.1.3 software, researchers can map variable relationships, analyze system structures, and simulate the dynamic behavior of the supply chain [29] [47].

The stages of building a system dynamics model in frozen fish supply chain system research are (Fig. 1):

1) Needs analysis: The initial step aims to identify the problems and needs of the system to be modeled.

2) Causal loop diagram: Used to map the cause-and-effect relationships between variables in the system, illustrating feedback loops that influence system dynamics.

3) Stock and flow diagram: A more detailed representation of the system, with stocks representing accumulation and flows regulating stock changes. This diagram models the quantitative dynamics of the system.

4) Simulation models: The development of system dynamics-based simulation models that enable the analysis of system changes over time.

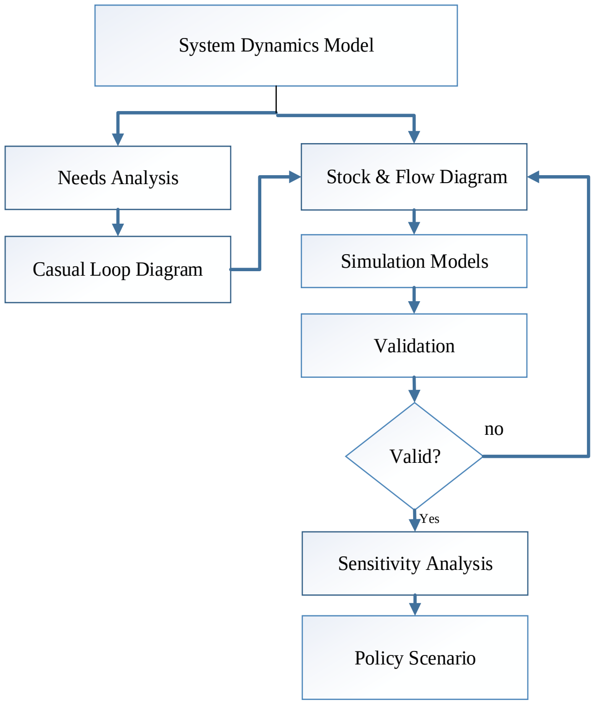

Fig. 1. Research steps.

5) Validation: Assessing the model's suitability against historical data or real-world conditions. The Pairwise Pearson Correlation method is used in system dynamics modeling or statistical models to evaluate the relationship between simulation results and actual data. Fish purchase data and fund allocation for fish purchases at one of the *Bakul* from 2021 to 2023 are used to calculate the validation. The formula is:

$$r = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i\overline{X})}{\sqrt{\sum_i^n (X_i - \overline{X})^2 \sum_i^n (Y_i - \overline{Y})^2}}$$

This method ensures that the simulation results can represent dynamics that correspond to the actual conditions of the modeled system.

1) Sensitivity analysis: After model validation, sensitivity analysis evaluates the impact of parameter changes on the model's results.

2) Policy scenario: The final stage involves using the model to test various policy scenarios to determine the best decision for improving system performance.

IV. Result and Discussion

This section is the completion stage in building a system dynamics model on the frozen fish supply chain and provides a selection of several policy scenarios obtained from the simulation results.

A. Results

The system dynamics model is a system modeling tool developed by Jay W. Forrester, which emphasizes feedback (closed loops) to understand the behavior as a whole. This model assumes that the system is always changing, with various activities influencing each other. Interrelated sub-models are used to achieve certain goals. The main variables in this model include Level (accumulated flow over time), Rate (flow rate), and Auxiliary (helping variables).

1) Needs analysis: This stage involves analyzing the needs of stakeholders in PPI Karangsong, such as:

a) Fishing port: The main location of fishing industry activities, equipped with safety and other supporting facilities.

b) Juragan: The main supplier of frozen fish and ship provider.

c) TPI Karangsong: fish auction place.

d) Fishermen: The main actors in fishing in the waters.

e) Bakul: Fish suppliers to ports, retailers, or consumers.

f) Consumers: Actors who utilize the catch.

g) Government: Through the Fisheries and Marine Service, regulates and manages fishing activities.

2) System identification: System identification is an approach used to comprehensively describe and analyze a system, often employing cause-and-effect diagrams or causal loop diagrams (CLD) to clarify the responses interactions across the variables within the system [48]. This methodology enables the identification of patterns or cycles in the system, facilitating more effective analysis and strategy design.

CLD are constructed based on research data, interviews, and literature reviews to accurately depict causal relationships [49]. In this study, the model is employed to understand of frozen fish supply chain dynamics, beginning with the auction at TPI Karangsong, continuing with storage in cold storage facilities, and culminating in distribution using refrigerated vehicles. This approach allows for analyzing the impact of decisions and related variables, ultimately aiming to improve supply chain efficiency.

The frozen fish supply chain system dynamics model simulation is conducted using Vensim PLE 10.1.13 software, and the CLD for frozen fish distribution is illustrated in Fig. 2.

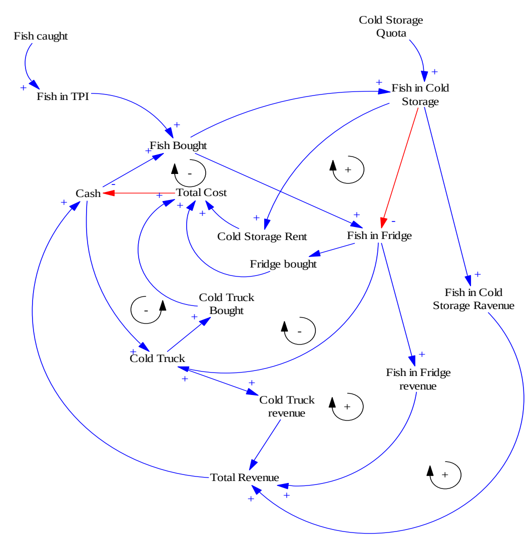

Fig. 2. Causal loop diagram.

Freezing and storage facilities for frozen fish products are crucial components in supporting the cold chain or supply chain system. These facilities help maintain the quality of fish products, enhance their added value, and ensure smooth distribution, price stability, and the availability of fishery products. As a result, the supply chain system can operate more efficiently and effectively.

3) Boundary model: The selection of model boundaries is a critical step in modeling, as it defines the scope of analysis relevant to the problem under investigation. These boundaries must encompass all cause-and-effect interactions within the frozen fish supply chain system to ensure a comprehensive representation. Effective decision-making in this supply chain depends on the model's accuracy and completeness, which directly influence the validity of the proposed decisions. The primary objective is to maintain product quality and safety throughout distribution, preventing any degradation that could negatively impact the selling price.

However, this model lacks a detailed analysis of the payback period, and risk analysis is not sufficiently addressed, limiting its ability to fully evaluate the financial feasibility and potential uncertainties associated with policy implementations.

4) System dynamics simulation flowchart structure: The simulation of system dynamics modeling results is used to observe behavior patterns and trends within the system, as well as the factors influencing it. However, Causal Loop Diagrams (CLD) have limitations in capturing the structure of stocks and flows in the system. To address this, a Stock & Flow Diagram (SFD) is employed, offering more detail and enabling more accurate simulations of system behavior. SFD incorporates the element of time, allowing for a more detailed analysis of interactions between variables. The frozen fish supply chain system is structured into six sub-models. These six sub-models enhance the system's overall analysis and simulation accuracy, as follows:

a) Frozen Fish Sub Model at TPI: Fig. 3 is a frozen fish sub-model at TPI Karangsong.

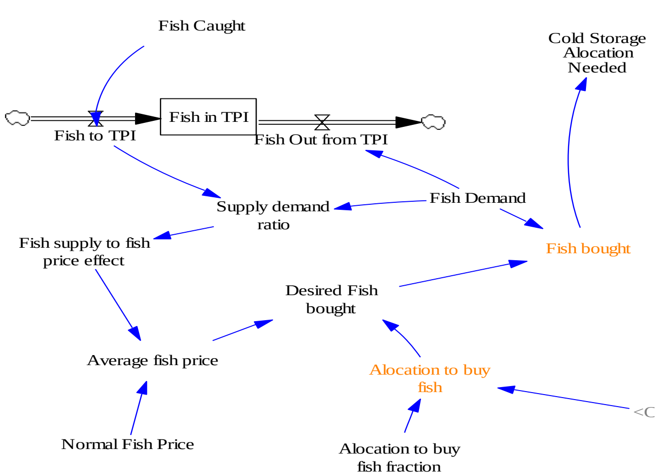

Fig. 3. Frozen fish sub model at TPI.

In this sub-model, frozen fish collected at the TPI represents a stock variable. Various types of frozen fish are auctioned at the TPI, and purchased by the *Bakul*, which reduces the stock of fish at the TPI. The supply-demand ratio is defined as the demand for fish relative to the availability of fish at the TPI. The average fish price is affected by the impact of fish supply on prices relative to the normal price level. The amount of fish purchased by the *Bakul* is determined by the allocation of funds available in the *Bakul's* cash reserves for buying frozen fish. The quantity of fish purchased then dictates the allocation of cold storage required.

b) Cold storage sub model: In this sub-model, the fish stored in cold storage is a stock variable. Fig. 4 is a sub-model of Cold storage at TPI Karangsong.

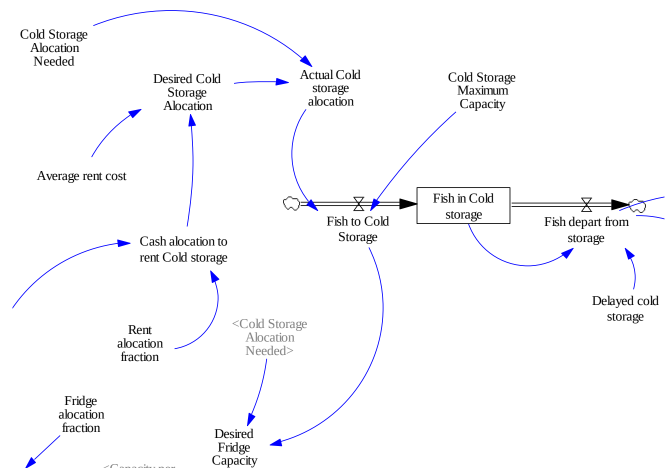

Fig. 4. Cold storage sub-model.

The purchased fish will initially be stored in cold storage. The allocation of fish that can be stored is determined by the cold storage's maximum capacity. The amount of fish stored will affect the cold storage rental cost, which will contribute to the total cost. If the cold storage reaches full capacity, the Bakul will store the excess frozen fish in a refrigerator, from which it will later be distributed.

c) Fish fridge sub model: In this sub-module, the stock variables are the number of refrigerators (Fish fridge) and fish stored in the Fish fridge. The simulation results of the Fish fridge sub-model are as shown in Fig. 5.

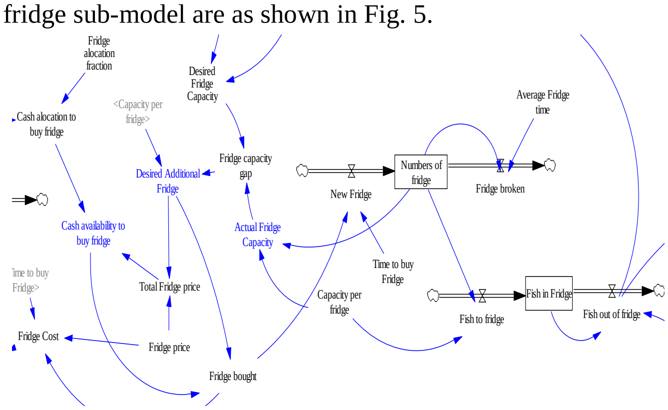

Fig. 5. Fish fridge sub model.

Fish that cannot be stored in cold storage must be placed in a refrigerator, although the quality will not be as well preserved as in cold storage. However, the *Bakul* must allocate funds to purchase the necessary refrigerators. The number of refrigerators required is determined by the amount of fish that exceeds the capacity of the cold storage. The need for additional refrigerators arises when a discrepancy exists between the desired and actual storage capacity to store the surplus fish.

d) Total revenue sub-model: Total income in this sub-model is calculated from how many frozen fish are in cold storage multiplied by the fish that come out of cold storage, plus income from fish in the fish fridge and those sent using cold trucks. The simulation results for total revenue are presented in Fig. 6.

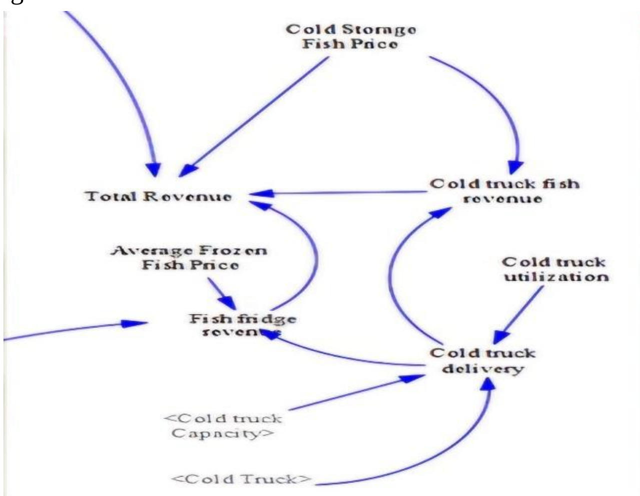

Fig. 6. Total revenue sub-model.

In this sub-model, it is assumed that all frozen fish purchased will be sold out. The assumption is that the price of frozen fish stored in cold storage is higher than that of fish stored in the Fish fridge. Then, frozen fish sent using a cold truck will maintain its quality to the maximum so that the selling price is the same as fish stored in the Fish fridge.

e) Sub model cash: Cash is a variable that increases due to income and decreases due to expenses. The total costs calculated in this model include cold storage rental costs, Fish fridge purchases and cold truck purchases (Fig. 7), so cash is income minus expenses.

f) Sub Model Cold truck: Cold trucks become stock variables in the sub-model (Fig. 8).

The cold truck is a model used for scenario simulations. In the baseline scenario, it is assumed that the *Bakul* does not own a cold truck, while in the subsequent scenario, the *Bakul* purchases a cold truck based on the amount of fish in the refrigerator and the availability of cash. The purchase of a cold truck depends on the cash allocation available to the *Bakul*. The procurement of the cold truck is determined by its capacity and the amount of fish in the refrigerator that needs to be transported. The price of the cold truck corresponds to the average market price, which varies depending on its specifications and capacity. The cold truck's role is to maintain the safety and quality of frozen fish during distribution, preventing quality degradation that typically occurs when using non-refrigerated trucks. This ensures that the fish delivered to consumers remains in optimal condition, enhancing consumer satisfaction and loyalty. The overall model is represented by a stock and flow diagram (Fig. 9).

5) Validation: Is conducted to verify that a model comprehensively achieves its objectives and accurately represents real system conditions. This process involves evaluating and testing the accuracy of the quantitative framework by comparing the outcomes of the dynamic system simulation against historical data. In this study, model validation was performed using a sample of Bakul who passed the normality test from the total population of Bakul at TPI Karangsong, Indramayu Regency. The assumption is that the Bakul consistently purchase frozen fish. Using data from 2021 to 2023, The following is data on demand for frozen fish in one of the Bakul, And normality data is (Fig. 10).

Based on historical data, the forecast results using linear trends for the number of fish purchased and fund allocation are as shown in Fig. 11. Table I shows demand of frozen fish in Bakul.

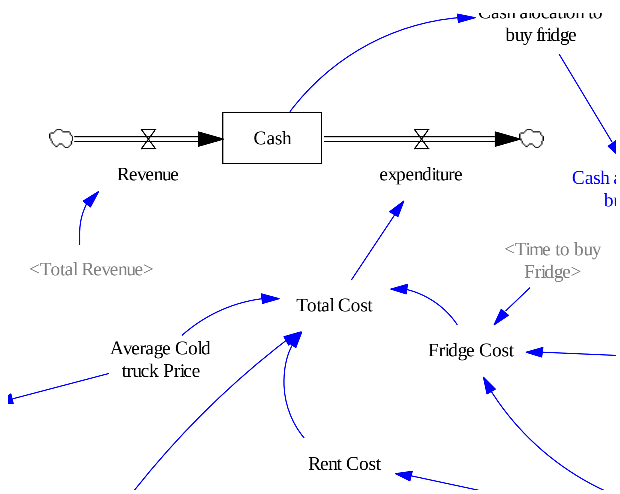

Fig. 7. Cash sub model.

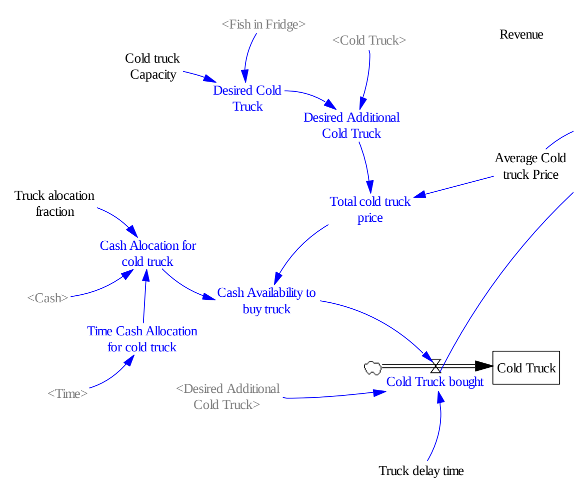

Fig. 8. Cold truck sub-model.

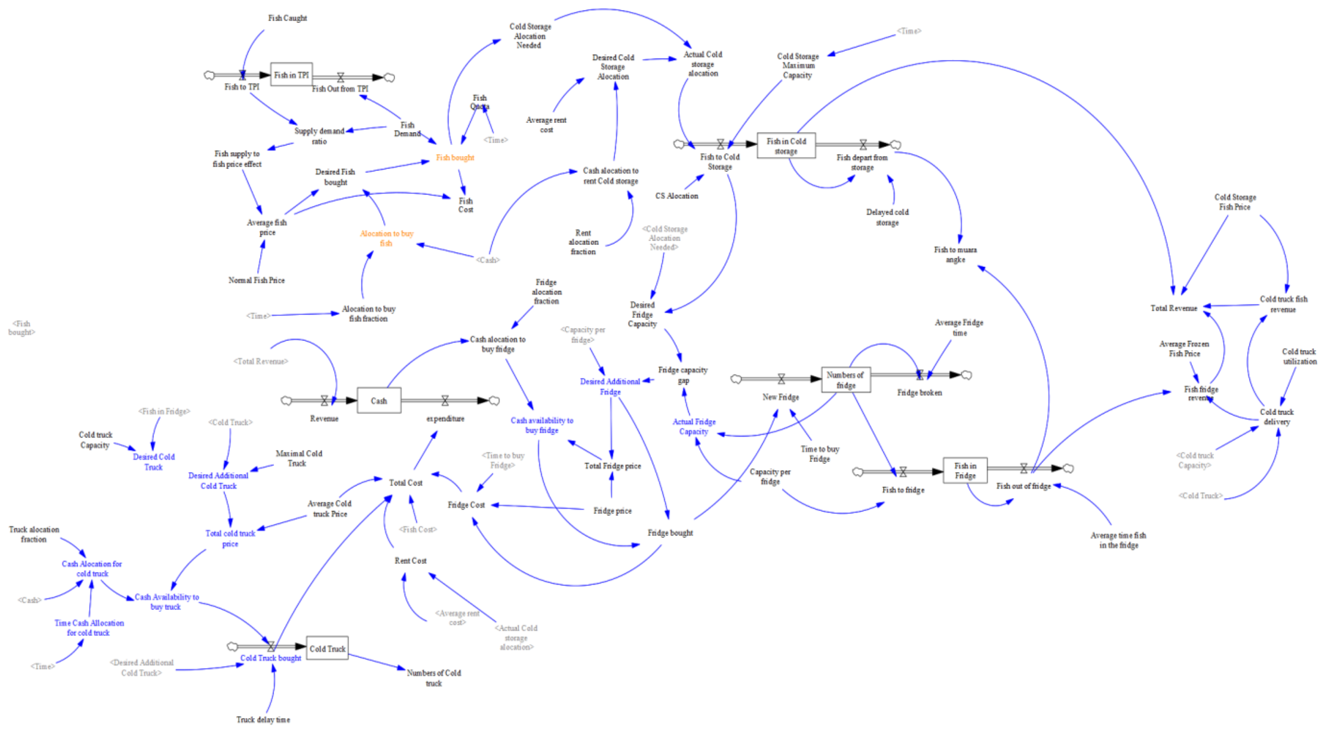

Fig. 9. SFD Frozen fish.

TABLE I. DEMAND OF FROZEN FISH IN BAKUL

Periode	Bought Fish (Kg.)	Forecast (Kg.)		Periode	Allocation to Buy Fish (Rp.)	Forecast (Rp.)
1	2,473	12,444		1	48,931,000	185,975,311
2	8,867	12,706		2	147,607,000	191,417,268
3	20,606	12,968		3	290,844,000	196,859,225
4	26,151	13,230		4	357,867,000	202,301,182
5	8,391	13,492		5	137,282,000	207,743,139
6	1,257	13,754		6	31,132,000	213,185,096
7	6,803	14,016		7	119,456,000	218,627,053
8	8,248	14,278		8	138,812,000	224,069,010
9	16,553	14,540		9	249,369,000	229,510,967
10	10,083	14,802		10	151,900,395	234,952,924
11	19,442	15,064		11	303,967,000	240,394,881
12	4,649	15,326		12	84,935,000	245,836,838
13	4,853	15,588		13	11,025,000	251,278,795
14	9,645	15,850		14	179,837,000	256,720,752
15	33,389	16,112		15	559,813,000	262,162,709
16	29,058	16,374		16	480,636,000	267,604,666
17	22,381	16,636		17	388,136,000	273,046,623
18	14,970	16,898		18	269,764,000	278,488,580
19	18,301	17,160		19	318,884,000	283,930,537
20	29,015	17,422		20	456,545,000	289,372,494
21	20,213	17,684		21	318,644,000	294,814,451
22	28,018	17,946		22	437,558,000	300,256,408
23	31,431	18,208		23	456,345,000	305,698,365
24	13,023	18,470		24	206,548,000	311,140,322
25	29,299	18,732		25	513,981,000	316,582,279

Periode	Bought Fish (Kg.)	Forecast (Kg.)
26	28,172	18,994
27	30,358	19,256
28	21,777	19,518
29	9,240	19,780
30	20,146	20,042
31	20,327	20,304
32	10,767	20,566
33	7,267	20,828
34	4,768	21,090
35		21,344.3
36		21,606.1
37		21,867.9
38		22,129.7
39		22,391.4
40		22,653.2
41		22,915.0
42		23,176.8
43		23,438.6
44		23,700.4
45		23,962.2
46		24,224.0
47		24,485.8
48		24,747.5
49		25,009.3
50		25,271.1

Periode	Allocation to Buy Fish (Rp.)	Forecast (Rp.)
26	532,323,000	322,024,236
27	511,786,000	327,466,193
28	392,037,000	332,908,150
29	171,705,000	338,350,107
30	358,203,000	343,792,064
31	360,188,000	349,234,021
32	189,555,000	354,675,978
33	125,478,000	360,117,935
34	75,005,000	365,559,892
35		371,001,849
36		376,443,806
37		381,885,763
38		387,327,720
39		392,769,677
40		398,211,634
41		403,653,591
42		409,095,548
43		414,537,505
44		419,979,462
45		425,421,419
46		430,863,376
47		436,305,333
48		441,747,290
49		447,189,247
50		452,631,204

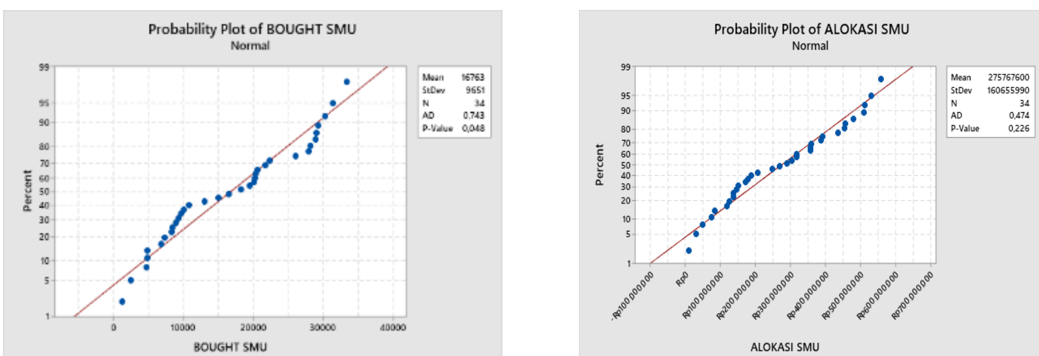

Fig. 10. Normal P Plot test.

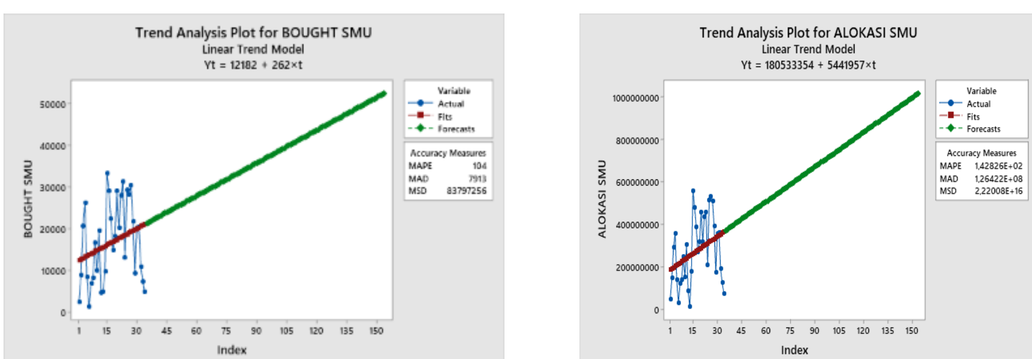

Fig. 11. Forecast results of the number of fish purchased and allocation of funds in one of the *Bakul*.

TABLE II. FORECAST ERROR

Method	Value
Bought Fish	
MAPE	104
MAD	7913
MSD	83797256
Allocation to buy Fish	
MAPE	1,42826E+02
MAD	1,26422E+08
MSD	2,22008E+16

From the forecast (Table II) results, Bakul experienced an increase in both the amount and allocation of funds. The results of data processing using MINITAB 19.1.1.0: The following are forecasting errors, namely:

Using the pairwise Pearson correlation method with a 95% confidence and a 5% significance level, the P-value for bought fish was 0.122, and for allocation to buy was 0.051, indicating that the data is valid for predicting future values at *Bakul*.

6) Sensitivity of system dynamics model: Sensitivity tests are conducted to measure how sensitive the model is to changes in input parameters or model structure so that it can understand its impact on model output. The results of this sensitivity test are behavioral changes, which are used to analyze the effects of interventions on the model. Sensitivity tests in this study include:

a) Functional intervention: Functional intervention entails modifying a specific parameter within the model. This study applies it to the parameter that represents the fish quantity at the TPI. The quantity of fish caught influences the amount of frozen fish purchased by the *Bakul* at the TPI. An increase or decrease in the number of fish will affect the cash allocation available to the *Bakul*.

b) Structural intervention: Structural intervention refers to changes made to the model by modifying the relationships that form its structure, aiming to assess their effects on the model's variables. In this study, structural intervention is implemented in the cold truck and cold storage sub-models. The purpose of acquiring a cold truck is to preserve the quality of frozen fish during transportation. In contrast, the increase in cold storage capacity is designed to ensure sufficient storage space.

The (3) three sub-models, namely the fish sub-model at TPI (functional intervention the cold truck sub-model, and the cold storage sub-model (structural intervention) have output sensitivity.

Sensitivity tests help identify various modeling scenarios by adjusting the model's parameters or structure. Thus, sensitivity tests allow researchers to explore various conditions and see how changes in a model's parameters or structure can influence its output.

7) Analysis of simulation results and policy scenarios: System dynamics models are essential tools for supporting practical decision-making, enabling policymakers to model different policy scenarios and assess the impact of each decision. This helps them select the most effective and efficient strategies for addressing complex and dynamic problems. The average price of frozen fish is often influenced by the availability of fish catches from the TPI. As fishing increases, the fish supply becomes more abundant. The harvested fish are then properly stored in cold storage to maintain the quality of frozen fish. Adequate cold storage allows frozen fish sales to occur throughout the year, stabilizing supply and creating more consistent demand and prices. The use of cold storage to preserve frozen fish quality is affected by several factors, including rental costs and storage capacity.

The simulation results produced three scenarios:

a) Cold truck procurement scenario: Simulation results in the Cold Truck Procurement Scenario as shown in Fig. 12.

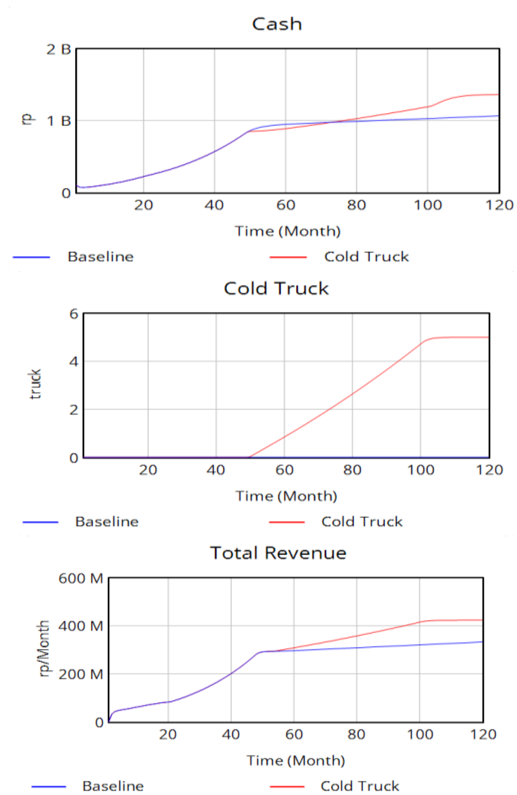

Fig. 12. Cold truck scenario simulation results.

The simulation results (Fig. 12) indicate that although there is a decrease in cash in the 50th month due to the purchase of cold trucks, revenue increases. Investing in cold trucks is essential to maintaining the quality of frozen fish during distribution, preventing price declines. Despite the high initial cost, cold trucks are a strategic investment that supports long-term cash growth through revenue from selling high-quality fish. With five cold trucks, the model positively impacts long-term financial performance, despite the initial outlay. Cold trucks ensure stable fish temperatures during transportation from cold storage to markets or restaurants, mitigating quality issues that arise from unrefrigerated shipments, particularly for travel distances exceeding four hours. Without cold trucks, fish quality deteriorates due to temperature fluctuations, thawing, microorganism growth, and texture damage, all of which reduce the fish's selling value, lead to economic losses, and diminish consumer satisfaction and trust. The procurement of cold trucks helps preserve fish quality, increase selling prices, and improve consumer satisfaction, making it a key solution for the sustainability of TPI Karangsong and the efficiency of distribution.

b) Cold truck and cold storage integration scenario: Simulation Results of Cold Truck and Cold Storage Integration Scenario as found in Fig. 13.

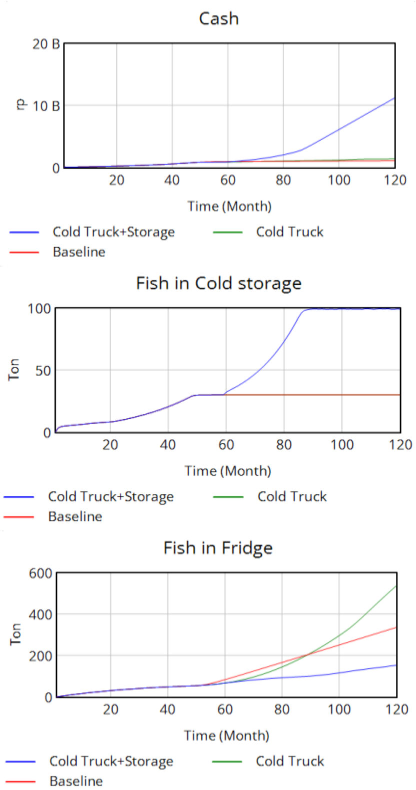

Fig. 13. Simulation results of cold truck and cold storage integration scenario.

This model illustrates how increasing cold storage capacity and using cold trucks for shipping can enhance storage efficiency, product quality, and revenue at TPI Karangsong. Expanding cold storage capacity and utilizing cold trucks are critical strategies for maintaining the quality of frozen fish during storage and distribution. Increased cold storage capacity allows fish to be kept under optimal conditions for extended periods, minimizing the risk of quality degradation from temperature instability. Cold trucks, with their efficient cooling systems, ensure stable fish temperatures during transportation from cold storage to the final distribution point. The integration of cold storage and cold trucks ensures that frozen fish are stored and distributed under ideal conditions, preserving freshness and quality.

Key impacts of this strategy include improved product quality and safety, which are essential for consumer health and compliance with industry regulations. Revenue increases are driven by the higher selling value of high-quality products, boosting both income and profitability. Operational efficiency is also enhanced due to reduced product spoilage during storage and distribution, lowering damage-related costs. Customer satisfaction improves as well, evidenced by a decrease in return rates and higher satisfaction scores, resulting from consistent product quality. The integration of cold trucks and cold storage not only preserves product quality but also enhances operational efficiency and customer satisfaction, supporting business stability and profitability. Furthermore, this strategy strengthens TPI Karangsong's reputation as a high-quality fish provider, contributing to local fishermen's income and welfare.

c) Cold truck, cold storage and fish catch drop integration scenario: Fig. 14 is a simulation results of the integration scenario of cold trucks, cold storage, and fish catch drop.

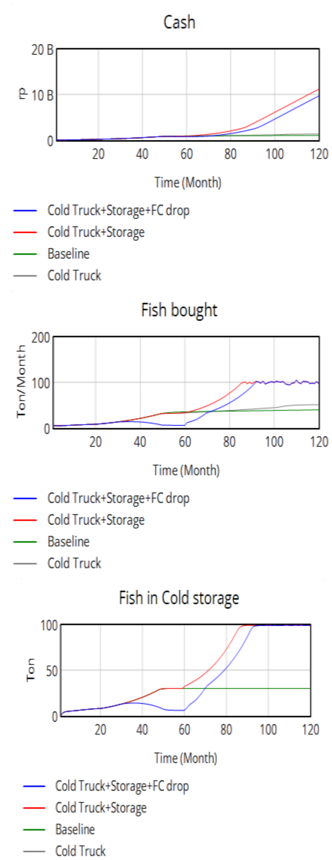

Fig. 14. Simulation results of the integration scenario of Cold Truck, Cold Storage, and Fish Catch Drop.

The simulation results indicate that a decrease in fish catch results in a decrease in the quantity of fish purchased, resulting in lower cold storage usage and reduced revenue. Although cash flow improved compared to the baseline, the increase was not as significant as it would be with stable fish catches. The integration of cold trucks and cold storage is a key strategy for optimizing the storage and distribution of frozen fish, ensuring product quality and safety from the point of catch to the final consumer. By increasing cold storage capacity, fish can be kept under optimal conditions for extended periods, minimizing the risk of quality degradation due to temperature fluctuations. Cold trucks maintain stable fish temperatures during distribution, preserving freshness and quality.

This strategy involves three main components: the fish catch drop, cold storage, and cold trucks. The fish catch drop refers to the initial phase where freshly caught fish are transferred to temperature-controlled facilities to slow spoilage. Cold storage maintains fish at low temperatures to preserve quality over time, reducing microbiological and enzymatic activity. Cold trucks ensure stable temperatures are maintained during transport, safeguarding product integrity.

While this integration enhances operational efficiency and product quality, the decline in fish catch still negatively impacts revenue and shipment volume. However, cash flow improved compared to the baseline, indicating that the strategy mitigates some of the negative effects of reduced fish catches, though overall revenue remains lower. The integration of cold trucks and cold storage is vital for maintaining product quality, improving supply chain efficiency, and enhancing consumer satisfaction, while also helping to reduce the impact of catch fluctuations on TPI Karangsong's revenue and operations.

B. Discussion

Additionally, this research highlights that the system dynamics model for the frozen fish supply chain generates several policy scenarios aimed at enhancing fish quality and improving fishermen's welfare. Policies should promote the effective, efficient, and sustainable utilization of all available natural resources within the country [30]. The policy scenarios are as follows:

1) Scenario 1: Baseline: Describes the current state without additional policies. It provides a picture of how variables develop without changes or interventions, helping to identify potential problems and the need for corrective action to achieve desired goals in the future.

2) Scenario 2: Cold Truck Procurement: The procurement of cold trucks is intended to maintain the stable temperature of frozen fish during transportation, ensuring the preservation of fish quality. With better product quality, the selling price of fish increases, and consumer satisfaction is ensured. Cold trucks are essential for transporting frozen fish from cold storage to markets, restaurants, or distributors. Trucks with a minimum capacity of 2.9 tons and a temperature range between -20°C and +10°C must be used for deliveries exceeding four hours, while non-refrigerated trucks are prohibited. Although this investment results in an initial cash reduction, it leads to increased revenue and maintains product quality, making it a strategic decision. Routine maintenance is necessary to extend the lifespan of cold trucks to up to 10 years, ensuring sustainable operations.

The use of cold trucks is crucial for preserving product quality, reducing losses, and ensuring consumer satisfaction and trust.

3) Scenario 3: Integration of Cold truck and Cold storage: The integration of cold trucks and cold storage is a strategic policy in the distribution of frozen fish to maintain product quality and improve operational efficiency. This integration allows temperature stability from storage to delivery, reduces the risk of product damage, and increases customer satisfaction. Increasing cold storage capacity requires significant investment and government support. The use of cold trucks in distribution ensures that product temperatures are maintained throughout the supply chain, contributing directly to increased revenue and product sales value. Operational efficiency is improved through better coordination and integrated inventory management, reducing product transfer times and adjusting shipments to market demand. The success of this policy can be measured through increased revenue, reduced return rates, and customer satisfaction. In addition, this integration also reduces product damage, meets food safety standards, and improves business sustainability with better energy efficiency and supply chain management.

4) Scenario 4: Integration of Cold Truck, Cold Storage, and Fish Catch Drop: The integration of fish catch reduction, cold storage, and cold trucks aims to maintain optimal temperature and quality of frozen fish throughout the supply chain while enhancing operational efficiency and customer satisfaction. This policy combines all elements of the cold chain [45] to ensure product quality and safety from catch to consumer. The fish catch reduction strategy involves determining the timing and location of catches based on fish population data, along with using monitoring technology to improve catch efficiency. After processing, the fish are stored in cold storage at sub-zero temperatures, focusing on maintaining stable temperatures throughout the facility. Cold trucks are employed during distribution to preserve temperatures during transport, using efficient cooling systems and regular maintenance. Companies must also adhere to food safety standards at every stage. The success of this policy will be evaluated based on product quality, operational efficiency, return rates, and customer satisfaction.

This study offers significant advantages in supporting policy decision-making for the frozen fish supply chain. First, applying a system dynamics approach enables holistic and integrated analysis, capturing interactions among supply chain components, such as the impact of investment in cold trucks and cold storage on fish quality and income. Second, the proposed policy simulations provide insights into various relevant scenarios, including a baseline scenario without intervention for comparison and a scenario involving cold truck and cold storage investments, demonstrating the potential for increased income and selling prices through improved fish quality. Third, this model facilitates predicting the long-term effects of policies, particularly in scenarios involving fish catch declines, aiding in understanding income stability challenges amid reduced catches. Additionally, the approach supports formulating evidence-based improvement strategies tailored to the needs of local fisheries stakeholders, contributing to sustainable solutions. By integrating simulation results with model-based decision-making, this study enhances its relevance in promoting the sustainability of the fisheries supply chain in TPI Karangsong and surrounding areas.

V. Conclusion

The study utilizes a system dynamics approach to simulate the frozen fish supply chain, the simulation results in several policy scenarios. The baseline scenario without intervention shows no significant changes. The cold truck procurement scenario increases income, despite requiring initial investment. Meanwhile, the integration of cold trucks and cold storage helps maintain fish quality and increases selling prices. In the final scenario, which combines cold trucks, cold storage, and a reduction in fish catches, fish quality is preserved, though the income is still affected by the catch decline.

Future research will explore the potential of new technologies, such as IoT for real-time temperature monitoring and blockchain for transparent tracking, to improve the supply chain model's accuracy. Additionally, the sub-models should be supported by a microservice-based IT roadmap, starting with small programs that evolve into larger modules.

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