Jurnal Ilmu Kehutanan
https://jurnal.ugm.ac.id/v3/jik/
ISSN: 01264451 (print); EISSN: 24773751 (online)

Predicting Timber Demand for the Shipyard Industry in Batang, Central Java, Indonesia Using System Dynamics Modeling

Prediksi Permintaan Kayu untuk Industri Galangan Kapal di Batang, Jawa Tengah, Indonesia Menggunakan Pemodelan Dinamika Sistem

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RESEARCH ARTICLE

DOI: 10.22146/jik.v20i1.22686

MANUSCRIPT:
Submitted : 1 July 2025
Revised : 15 March 2026
Accepted : 31 March 2026
Published : 29 June 2026

KEYWORD
system dynamics, fisheries fleet capacity, wood supply chain, marine resource management, sustainable timber supply

KATA KUNCI
dinamika sistem, kapasitas armada perikanan, rantai pasok kayu, pengelolaan sumber daya kelautan, pasokan kayu berkelanjutan

ABSTRACT

Indonesia's wooden shipbuilding industry faces pressure from rising fisheries targets and unstable timber supplies. Batang Regency, a prominent shipyard cluster in Indonesia, relies on tropical hardwoods such as bengkirai and merbau as the main raw material for shipbuilding. More fishing, under Maximum Sustainable Yield (MSY) and Total Allowable Catch (TAC) policies, will strain timber resources. This research developed a dynamic simulation model to estimate future timber demand for Batang's wooden shipyards, using data from 21 shipyards and fisheries, timber, MSY, and TAC statistics (2014–2018). Implemented in Powersim Studio 10 and validated using the Mean Absolute Percentage Error (MAPE) by comparing simulated outputs with historical observations. The model estimated cumulative timber use of 52,035 m^3 (an average of 10,407 m^3/year) for 2014–2018. Projections show demand rising to 42,293 m^3 by 2035 (0.93% of national output), with high accuracy (MAPE <5%). Integrating fisheries and timber data, the model supports sustainable planning for Indonesia's wooden shipbuilding industry.

INTISARI

Industri galangan kapal kayu Indonesia menghadapi tekanan dari meningkatnya target produksi perikanan nasional dan fluktuasi produksi kayu. Kabupaten Batang, yang merupakan salah satu klaster galangan kapal kayu terbesar di Indonesia, sangat bergantung pada kayu tropis seperti bengkirai dan merbau sebagai bahan baku utama industri galangan kapal. Peningkatan kapasitas penangkapan ikan melalui kebijakan Maximum Sustainable Yield *(MSY) dan* Total Allowable Catch *(TAC) akan meningkatkan tekanan terhadap ketersediaan bahan baku kayu. Penelitian ini bertujuan untuk mengembangkan model simulasi dinamis untuk memprediksi kebutuhan kayu pada industri galangan kapal di Kabupaten Batang dengan menggunakan data dari 21 galangan kapal aktif, serta data sekunder mengenai produksi perikanan, MSY, TAC, dan produksi kayu nasional pada periode 2014–2018. Simulasi dilakukan menggunakan* Powersim Studio 10 *dan divalidasi dengan metode* Mean Absolute Percentage Error *(MAPE) melalui perbandingan antara hasil simulasi dan data historis. Model menghasilkan estimasi penggunaan kayu kumulatif dari 2014–2018 sebesar 52.035 m^3 (10.407 m^3/tahun). Proyeksi model menunjukkan peningkatan kebutuhan kayu sebesar 42.293 m^3 pada tahun 2035 (0,93% dari produksi nasional), dengan akurasi yang tinggi (MAPE <5%). Informasi yang diperoleh dari pemodelan ini dapat digunakan untuk perencanaan bahan baku guna mendukung industri galangan kapal kayu yang berkelanjutan.*

Introduction

Wood is an important raw material widely used in various industries in Indonesia, including construction, furniture, and shipbuilding. As a renewable natural resource, wood plays a crucial role in supporting industrial activities, infrastructure development, and economic growth. Industries that rely significantly on natural resources as primary inputs are highly sensitive to fluctuations in raw material availability, making efficient resource management essential to ensure production stability and long-term sustainability (Chopra et al. 2019; Rossini et al. 2023). In this context, the availability and use of timber resources become important factors influencing the performance of wood-based industries.

One industry that heavily relies on timber resources is the shipbuilding sector, particularly traditional wooden shipyards. In many maritime regions, including Indonesia, wooden vessels are still commonly utilized in small- and medium-scale fisheries and coastal transportation because of their lower production costs, accessibility of raw materials, and suitability for conventional shipbuilding methods (Ikhsan 2017; Kafalı et al. 2018; Anjum et al. 2022). The construction of traditional vessels requires substantial amounts of timber as the primary structural material, making wood availability an important factor in sustaining shipyard operations (Ikhsan 2017; Anjum et al. 2022). Shipyards also play a strategic role in supporting maritime economic activities through vessel construction, maintenance, and repair services (Putra et al. 2023).

Timber utilization in shipbuilding is directly associated with production activities and industrial demand. Higher vessel production generally increases timber requirements, while fluctuations in ship orders may influence the level of raw material consumption. In many shipbuilding industries, production activities are commonly implemented under a make-to-order system, where manufacturing processes begin only after customer orders are confirmed (Cuong et al. 2020). Under this production pattern, the continuity and availability of timber supply become essential to maintain production stability and operational efficiency within the shipbuilding industry (Chopra et al. 2019; Ivanov 2020). Limitations or disruptions in timber supply may therefore affect production planning, increase operational costs, and reduce supply chain performance.

In Indonesia, one of the major clusters of traditional wooden shipyards is located in Batang Regency, Central Java. This region has numerous small- scale and medium-scale shipyards that produce wooden fishing vessels for regional and national markets. The shipyard commonly uses tropical hardwood species, such as bengkirai, merbau, laban, and mixed hardwoods due to the durability and resistance to marine environmental conditions (Anjum et al. 2022). Consequently, shipbuilding activities contribute to continuous timber consumption and create pressure on forest resources over time.

At the same time, timber supply in Indonesia has experienced fluctuations due to regulatory changes, forest governance policies, and market dynamics. National forestry statistics show variations in log production over time, reflecting changes in resource management and utilization policies (Erwinsyah et al. 2017; Badan Pusat Statistik 2023; Food and Agriculture Organization 2024). On a broader scale, global assessments also show increasing pressure on forest resources due to rising demand for wood-based products and land-use change (Food and Agriculture Organization 2020). These conditions emphasize the importance of understanding timber demand patterns in industries that rely significantly on forest resources (Hoogstra-Klein & Meijboom 2021).

The dynamics of timber demand in shipbuilding industries are influenced by multiple interacting factors, including production capacity, industrial activities, and resource availability. In some cases, shipbuilding activities are also indirectly influenced by developments in related sectors, such as fisheries, which require vessels as supporting infrastructure (Ardiyani et al. 2019; Food and Agriculture Organization 2024). These interactions create a complex system where changes in one component may affect others over time. However, traditional analytical approaches often focus on static conditions and may not fully capture these dynamic relationships (Yoshimura et al. 2025).

System-oriented approaches have increasingly been applied to analyze complex industrial systems involving interconnected variables and feedback interactions (Rizqi 2019). Among these approaches, system dynamics modeling has been widely utilized to examine nonlinear relationships, feedback structures, and time-dependent changes within industrial and supply chain systems (Geissdoerfer et al. 2018; Rebs et al. 2019). Recent studies have demonstrated the applicability of system dynamics in evaluating industrial sustainability, manufacturing systems, and maritime supply chain management under dynamic conditions (Saraji & Sharifabadi 2017; Praharsi et al. 2020; Chen et al. 2022). Nevertheless, most previous studies have primarily emphasized production efficiency, policy evaluation, or institutional interactions, while limited attention has been given to timber demand dynamics within shipbuilding industries.

Research concerning timber demand in traditional shipyard industries remains relatively limited, particularly studies that integrate production activities with long-term resource availability through dynamic analysis. Existing studies generally focus on estimating material consumption, forecasting industrial production, or describing supply chain structures without comprehensively examining how timber demand may change over time under varying production conditions (Gejo-García et al. 2022). Consequently, there is still limited understanding regarding the influence of fluctuations in ship production on future timber demand patterns. This gap is important because the absence of dynamic demand analysis may result in less accurate projections of timber requirements and may affect the sustainability of raw material supply for wood-based shipbuilding industries. Inadequate understanding of demand dynamics can also reduce the effectiveness of production planning, timber allocation, and long-term resource management strategies.

Although system dynamics approaches have been applied in maritime industries and supply chain analysis (Saraji & Sharifabadi 2017; Praharsi et al. 2020), this research generally focuses on industrial processes or institutional interactions rather than specifically addressing timber demand as a critical resource constraint in shipbuilding industries. Consequently, the role of timber as a limiting factor in the shipyard production system remains insufficiently explored. Based on the description above, this research aimed to develop a dynamic simulation model to predict future timber demand in the wooden shipyard industry in Batang Regency. By integrating empirical data from shipyard industries with a modeling approach, the results provide a clearer understanding of timber demand dynamics and offer a practical basis for improving resource planning and ensuring the long-term sustainability of timber supply in wood-based industries.

Methods

Research Area

This research location was in Batang Regency, Central Java, Indonesia, one of the major clusters of traditional wooden shipyards. The region has 21 active shipyards that produce wooden vessels for domestic markets (Dinas Perindustrian Perdagangan Koperasi dan UMKM Kabupaten Batang 2018). The concentration of shipyards created a localized production system in which vessel production and timber demand were closely linked. Therefore, Batang Regency provided an appropriate setting for analyzing timber consumption in the wooden shipbuilding industry.

Research Design

This research employed a mixed-methods: qualitative and quantitative to develop a dynamic simulation model to estimate timber demand for Batang's wooden shipyards. The qualitative system analysis was applied to understand the mechanisms and behavior of the system. Specifically, quantitative analysis measured vessel production, timber consumption, and material efficiency. A modeling approach represented the relationship between ship production and timber demand over time. As a result, this approach enabled the analysis of interactions among variables and long-term system behavior (Qudrat-Ullah 2020).

Data Collection and Sources

Data were collected between May 2019 and March 2020 using structured interviews, field observations, and document review. A census approach was applied by including all 21 shipyards in Batang Regency to ensure full representation of the industry (Creswell & Creswell 2018). Primary data collection used structured interviews with shipyard owners or production managers. The interview questions captured key aspects of production characteristics, timber utilization, material conversion, supply and procurement, and operational constraints which directly correspond to the variables analyzed in the results section. To improve clarity and transparency, the interview guide questions were grouped into several aspects as presented in Table 1. Field observations validated production processes and material usage. Secondary data originated from official publications, including national timber production statistics, fisheries-related data, and regional economic reports. The integration of primary and secondary data allowed the model to capture both industrial activities and broader resource conditions (Ivanov 2020).

Estimation of Timber Requirements and Material Efficiency

Timber requirements were estimated based on field measurements and interviews with 21 shipyards. Timber volume was measured in m^3 and converted into weight when necessary, using wood density values commonly applied in shipbuilding material assessment (Anjum et al. 2022). Timber demand was calculated for different vessel classes to capture variations in material requirements. Material efficiency evaluation used a yield indicator that compared output and input during processing. This indicator reflected the efficiency with which raw logs were converted into usable shipbuilding materials.

Model Development

The prediction model represented the relationship between ship production and timber demand. The process involved identifying key variables, defining system boundaries, and determi-ning how variables interact over time. Conceptual relationships among variables were initially identified to describe how changes in ship production affect timber consumption and availability. These relation-ships were then translated into a simulation model implemented in Powersim Studio version 10 (Gejo-García et al. 2022). The model comprised variables representing production activities, timber availability, and supporting para-meters derived from historical data. These variables were categorized into internal system components and external parameters, allowing the simulation of system behavior over time.

Table 1. Data collection aspects and interview questions

No.	Aspect	Description	Key Questions
1	Production Characteristics	Ship production activities	1.What types and sizes (GT) of vessels are produced? 2.How many vessels are produced annually? 3.Which vessel size is produced most frequently? 4.How long does it take to build each vessel class?
2	Timber Utilization	Timber types and volume used in ship construction	1.What types of timber are used in ship construction? 2.How much timber is required for each vessel class? 3.Which timber species are used for structural and non-structural components? 4.How does vessel size affect timber requirements?
3	Material Conversion	Timber processing efficiency and material loss	1.What is the conversion rate from logs to processed timber? 2.How much material loss occurs during cutting and shaping? 3.What is the estimated total efficiency from logs to finished ship structures? 4.At which stage does the highest material loss occur?
4	Supply and Procurement	Timber Sourcing, Logistics, and Supply Chain	1.Where is timber sourced from (region/supplier)? 2.How is timber transported to the shipyard? 3.How is the procurement process conducted? 4.Is there a buffer stock maintained by suppliers? 5.What other materials are required, and where are they sourced from?
5	Production Records	Historical data and timber cost structure	1.Are there records of annual production and timber consumption? 2.What is the average price per species? 3.What is the estimated timber cost for each vessel class? 4.How significant is timber cost compared to total production cost?
6	Operational Constraints	Challenges affecting production and timber supply	1.What challenges are faced in timber availability? 2.How does timber supply affect production schedules? 3.Are there limitations related to capital, labor, or production space? 4.How do fluctuations in demand affect production decisions?

Model Evaluation

Model evaluation compared the simulated results with the observed data. The deviation measure used was the Mean Absolute Percentage Error (MAPE), which expresses prediction error as a percentage (Hyndman & Athanasopoulos 2018). MAPE values were interpreted using standard criteria, where lower values indicate higher accuracy. A value below 5% shows high accuracy, while values between 5% and 10% represent acceptable accuracy. This evaluation ensured that the model was reliable for analyzing timber demand and generating future projections.

Sensitivity Analysis

The sensitivity analysis evaluated how changes in key parameters affect model outcomes. Parameters such as timber growth rate, production rate, and vessel damage rate were tested to assess the impact on system behavior. This analysis helped identify critical variables and evaluate model robustness under different conditions (Rebs et al. 2019).

Model Application and Simulation

The model utilized historical data from 2014 to 2018. Primary data collected from the shipyard were integrated with secondary statistical data to accurately represent system conditions. The model then estimated actual timber consumption and simulated future timber demand. This simulation facilitated the analysis of trends, patterns, and potential imbalances between timber supply and demand over time. Figure 1 summarizes the procedures of the research.

Result and Discussion

Characteristics of the Shipbuilding Industry

Fisheries Capacity, Catch Production, and Vessel Requirement

The demand for wooden fishing vessels is closely related to developments in the capture fisheries sector, as fleet capacity is influenced by marine resource potential and sustainable harvest limits (Ardiyani et al. 2019; Food and Agriculture Organization 2024). Therefore, fisheries indicators such as fishing fleet size, catch production, Maximum Sustainable Yield (MSY), and Total Allowable Catch (TAC) became important variables in analyzing timber demand in the shipbuilding industry. National fisheries data showed that the number of operating vessels declined significantly during 2014–2015, mainly due to regulatory reforms, including the moratorium on fishing licenses (Kementerian Kelautan dan Perikanan Republik Indonesia 2024). This moratorium reduced fleet size, it contributed to improved fisheries resource conditions, as reflected by increasing MSY and TAC values. However, the actual fish catch remained below the allowable catch level, ranging from 64% to 78% of the TAC, indicating that fisheries resources have not been fully used. One possible explanation is the limited number of vessels capable of operating effectively, particularly in offshore areas. This condition suggests that increasing fishing fleet capacity may be necessary to optimize resource utilization. When this increase occurs through the construction of wooden vessels, it will directly lead to higher timber demand in the shipbuilding industry. Therefore, fisheries variables constitute an external driver of future timber demand.

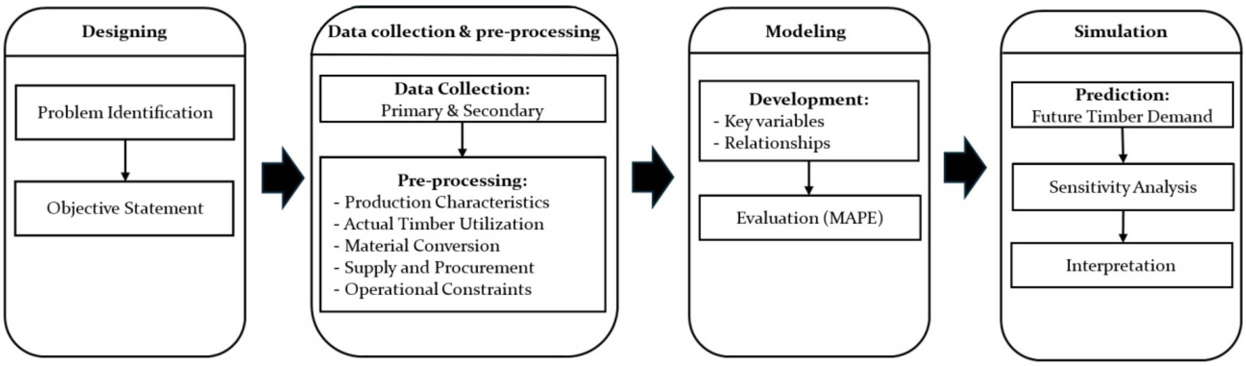

Figure 1. Systematic workflow of the timber demand prediction for the shipyards industry in Batang Regency

Ship Production and Vessel Characteristics

The wooden shipbuilding industry in Batang Regency represents one of the largest traditional shipyard clusters in Indonesia, with 21 active shipyards recorded in 2019. This industry plays an important role in supporting small-scale maritime activities, particularly in providing vessels for fisheries and coastal economic sectors (Ikhsan 2017; Kafalı et al. 2018; Anjum et al. 2022). Historically, shipbuilding development in Batang has been closely linked to the growth of the fisheries industry (Kementerian Kelautan dan Perikanan Republik Indonesia 2018). Ship production reached its peak between 2005 and 2007, when approximately 500 wooden vessels were produced annually. However, in the last decade, production has fluctuated and generally declined due to several structural constraints, including limited capital investment, restricted production areas, increasing competition among shipyards, and unstable demand from fishing operators. As a result, many shipyards have partially shifted their activities toward vessel repair and docking services.

Shipbuilding activities in Batang follow a make-to-order production system, in which vessel construction begins only after a confirmed order and an initial down payment of approximately 25% of the vessel price is received. This system reduces inventory risk but creates a direct dependency between production activities and raw material demand. Consequently, timber consumption fluctuates in line with annual vessel production.

Ship production serves as the main driver of timber demand, as wooden vessels require substantial volumes of structural materials (Ikhsan 2017; Anjum et al. 2022). Based on primary data collected from 21 shipyards, annual ship production during 2014–2018 showed moderate fluctuations, decreasing from 65 vessels in 2014 to 58 in 2017, before increasing to 87 in 2018. These variations reflect changes in market demand, particularly those associated with fisheries activities and vessel replacement cycles.

Vessels produced in Batang shipyards are classified into several size categories, namely 29 GT, 30 GT, 55 GT, 80 GT, and 100 GT. Among these categories, 30 GT vessels dominate production due to their balance between operational capacity and investment cost. Larger vessels require higher capital and longer construction time, resulting in lower production frequency. Differences in vessel size directly influence timber requirements, as larger vessels require greater hull dimensions and more extensive structural components.

The timber requirement per vessel varies significantly across classes. Based on field measurements, a 29 GT vessel requires approximately 107 m^3 of timber, while 30 GT, 55 GT, 80 GT, and 100 GT vessels require around 110 m^3, 203 m^3, 205 m^3, and 370 m^3/unit, respectively. These values represent gross timber requirements prior to processing losses. By combining vessel production data and class-based timber requirements, the average timber requirement per vessel (weighted by production composition during 2014–2018) is estimated at approximately 174.5 m^3. This average reflects the dominance of 30 GT vessels in production, and the relatively lower frequency of large-vessel construction.

Timber Conversion Efficiency

The shipbuilding process consists of two main stages, namely log processing and structural assembly. Field measurements indicate that the conversion efficiency from logs to processed timber beams is approximately 70%, implying that around 30% of the raw material volume is lost during cutting and shaping. A similar efficiency level is observed during the assembly stage. Consequently, the overall conversion efficiency from logs to finished ship structures is approximately 49%. This indicates that only about 0.49 m^3 of usable timber is obtained from each cubic meter of logs. The conversion factor is therefore a critical parameter for understanding material utilization in the shipbuilding process, as it reflects inherent losses during production.

Timber Species and Material Characteristics

Shipyards in Batang Regency used several tropical hardwood species, including bengkirai (*Shorea laevis*), merbau (*Intsia bijuga*), laban (*Vitex pubescens*), and mixed hardwoods. These species were selected for their mechanical strength and durability in marine environments. Bengkirai is primarily used for critical structural components, such as hull planking and keel structures, due to its high density (approximately 0.91 g/cm^3) and durability. Merbau is commonly used for internal structural components, while laban and mixed hardwoods are used for secondary and non-structural elements. The combination of these timber species reflects the shipbuilders' strategy to balance structural performance with cost efficiency.

Timber Cost Structure

Timber prices varied significantly depending on species. Based on supplier data, bengkirai timber was priced at approximately IDR 15,000,000/m^3, while merbau, laban, and mixed hardwoods were priced at IDR 8,000,000, IDR 4,500,000, and IDR 2,500,000/m^3, respectively. For example, constructing a 30 GT vessel required approximately 110 m^3 of timber, consisting of 25 m^3 of bengkirai, 25 m^3 of merbau, 20 m^3 of laban, and 40 m^3 of mixed hardwoods. Based on these values, the estimated timber cost for a 30 GT vessel reached approximately IDR 765 million. Timber costs increased significantly for larger vessels, reaching up to IDR 2.5 billion for 100 GT vessels. These values represented only raw material costs and did not include labor, logistics, or equipment installation.

Supply Chain Structure

The wooden shipbuilding industry in Batang Regency operated within a supply chain comprising multiple actors, including timber suppliers, shipyards, and vessel buyers. Timber originated from forest production areas in Kalimantan and Papua and were transported through major ports before reaching Batang. Material, financial, and information flows were interconnected within this system. Buyers initiated production through down payments, enabling the shipyards to procure raw materials. Shipyards then coordinated timber specifications and quantities with suppliers. This structure reflected a typical supply chain system in resource-based industries, where coordination between upstream and downstream actors is essential for ensuring efficient production and resource availability (Chopra et al. 2019; Ivanov 2020).

Actual Timber Consumption

Timber was the primary material used in wooden ship construction due to its strength, durability, and resistance to marine environments (Anjum et al. 2022). Based on field data, total timber consumption in Batang Regency's shipyards during the period 2014–2018 reached approximately 52,035 m^3, with an average annual consumption of 10,407 m^3. Timber consumption fluctuated in line with ship production levels. The lowest consumption occurred in 2016, corresponding to reduced production, while higher consumption was observed in years with increased shipbuilding activity. Timber supply during the same period reached approximately 59,840 m^3, slightly exceeding actual consumption. This difference was maintained intentionally by suppliers as buffer stock to compensate for material losses during transportation and processing. These results show that, under current conditions, timber supply is relatively sufficient to meet industrial demand. However, the close relationship between production and consumption suggested that future increases in ship production may significantly increase timber demand (Solana 2023).

Model Development

Key Variables and Their Relationships

The prediction of timber demand started with identifying the main variables that influence the system. In this research, timber demand was determined by the interaction between ship production, timber availability, and fisheries development. Fisheries data showed that although the number of operating vessels declined due to regulatory policies, fish stock conditions improved, as reflected by increasing MSY and TAC. However, actual fish catches remained below the allowable level, showing that fisheries resources have not been fully used. This gap suggested that future increases in fishing fleet capacity may be needed to optimize resource utilization. Since wooden vessels were still widely used, this potential increase in vessel demand became an important driver of timber demand in the shipbuilding industry.

Conceptual Model

To understand how the main variables interact, the relationships within the system were mapped, as illustrated in Figure 2. This representation showed how changes in one variable influenced the others over time and served as the basis for the prediction model. The relationships were represented using a Causal

Loop Diagram (CLD), a commonly used tool for describing feedback structures in complex systems (Rebs et al. 2019). The CLD shows the interactions between marine resource potential, vessel production activities, and timber availability in the wooden shipbuilding industry. The system consists of three main interaction patterns.

First, an increase in marine resource potential leads to higher vessel demand, which stimulates ship production and elevates timber consumption. Second, as the number of vessels increases, vessel damage also rises, creating a need to replace vessels and maintain production. Third, timber availability acts as a limiting factor, where increasing production leads to higher timber demand, which may eventually constrain production when supply becomes insufficient. These interactions show that timber demand is not only driven by production activities but also regulated by resource availability and fleet dynamics. The presence of both reinforcing and balancing mechanisms shows that the system operates dynamically, with continuous feedback between variables (Rebs et al. 2019).

Structured Model

After identifying the relationships among variables (Figure 2), the next step was to translate these interactions into a quantitative, structured simulation model to represent the interaction between timber supply, vessel production, and fisheries-related variables over time. The model integrated key components of the system, including marine resource potential, vessel production, operational vessel stock, and timber availability. Vessel production was expressed in timber volume equivalent (m^3) to maintain consistency with timber demand representation, which was measured in m^3/year and reflected the volume of wood required for shipbuilding activities. In this study, vessel demand, vessel production, and vessel requirement were expressed in terms of timber equivalent (m^3), representing the volume of wood required to construct vessels, rather than the number of unit vessels. This approach is used to maintain consistency with the overall objective of analyzing timber demand in the shipbuilding industry. The optimal vessel requirement was the estimated number of fishing vessels needed to sustainably utilize fisheries

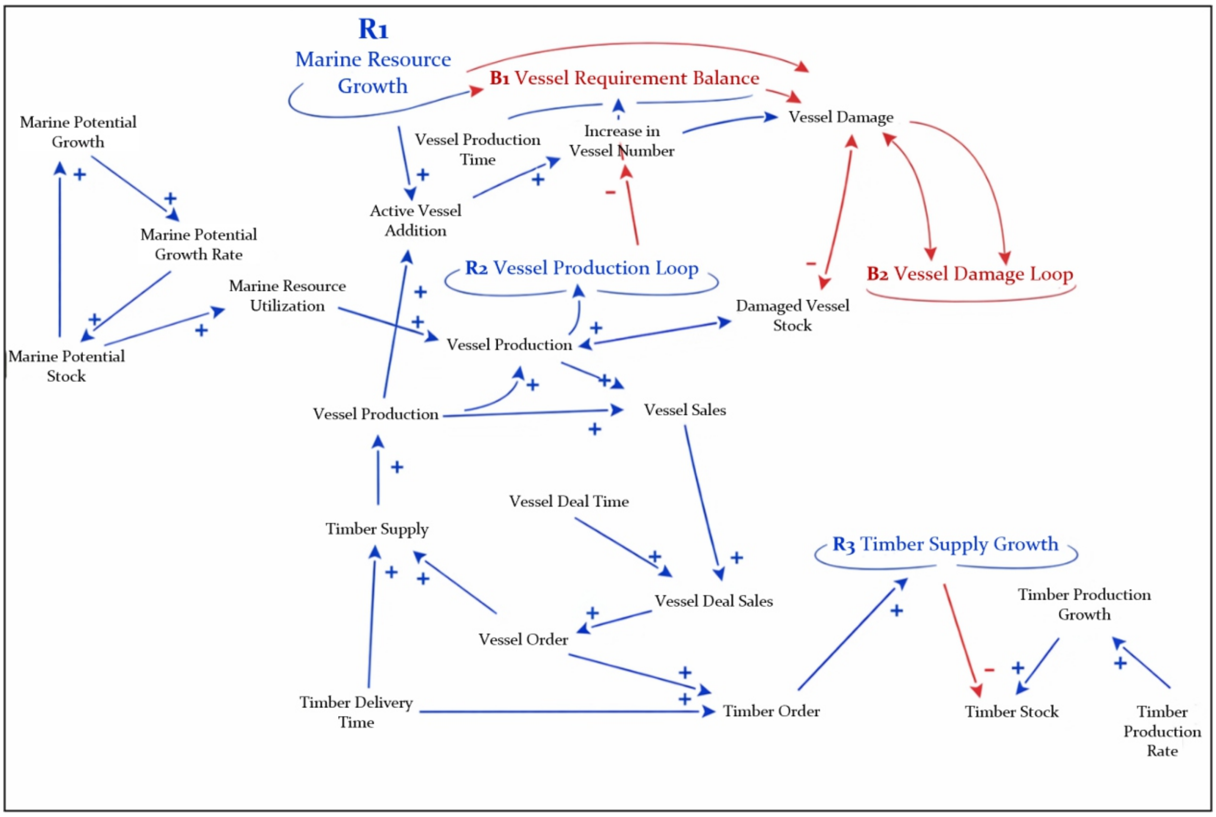

Figure 2. Causal loop diagram of the timber demand system in the wooden shipbuilding industry

resources, based on the Total Allowable Catch (TAC). This value was derived by comparing the TAC with the average productivity per vessel. These components were connected through relationships that describe how changes in one variable influence others, allowing the system to be analyzed dynamically (Figure 3). By translating conceptual relationships into a structured model, the system could simulate future conditions and analyze how timber demand evolves over time.

Model Evaluation

Model evaluation is important to ensure that the model can represent actual system behavior before being used for prediction. The evaluation compared simulated values with observed data for key variables, including timber supply, timber demand, and operational vessel stock during the period 2014–2018. The level of deviation between simulated and observed values was measured using MAPE, which expresses prediction error as a percentage (Hyndman & Athanasopoulos 2018).

Table 2 shows the comparison between simulated outputs and observed data for the key variables (timber supply, timber demand, and operational vessel stock) in the period 2014–2018. The results show that the simulated values closely follow observed data across all key variables. For the timber supply variable, the absolute percentage error ranged between 0.013 and 0.174, resulting in a MAPE value of 4.94%, indicating that the model could reproduce the historical behavior of timber supply with relatively small deviation. Similarly, the validation results for operational vessel stock showed a MAPE value of 6.84%, which remains within the acceptable range for system dynamics model validation. Although the MAPE value was slightly higher than that of other variables, the operational vessel stock model adequately represented fleet dynamics. The overall MAPE remains low, indicating that the model captures the general trend effectively.

Aside from numerical validation, Table 3 compares trends in observed fishing fleet data with those of simulated operational vessels. Due to differences in classification, official data include vessels with a capacity of 20 GT, while the model represents vessels with a capacity of 29–100 GT. Therefore, the comparison focuses on general trends rather than absolute values. The higher magnitude in

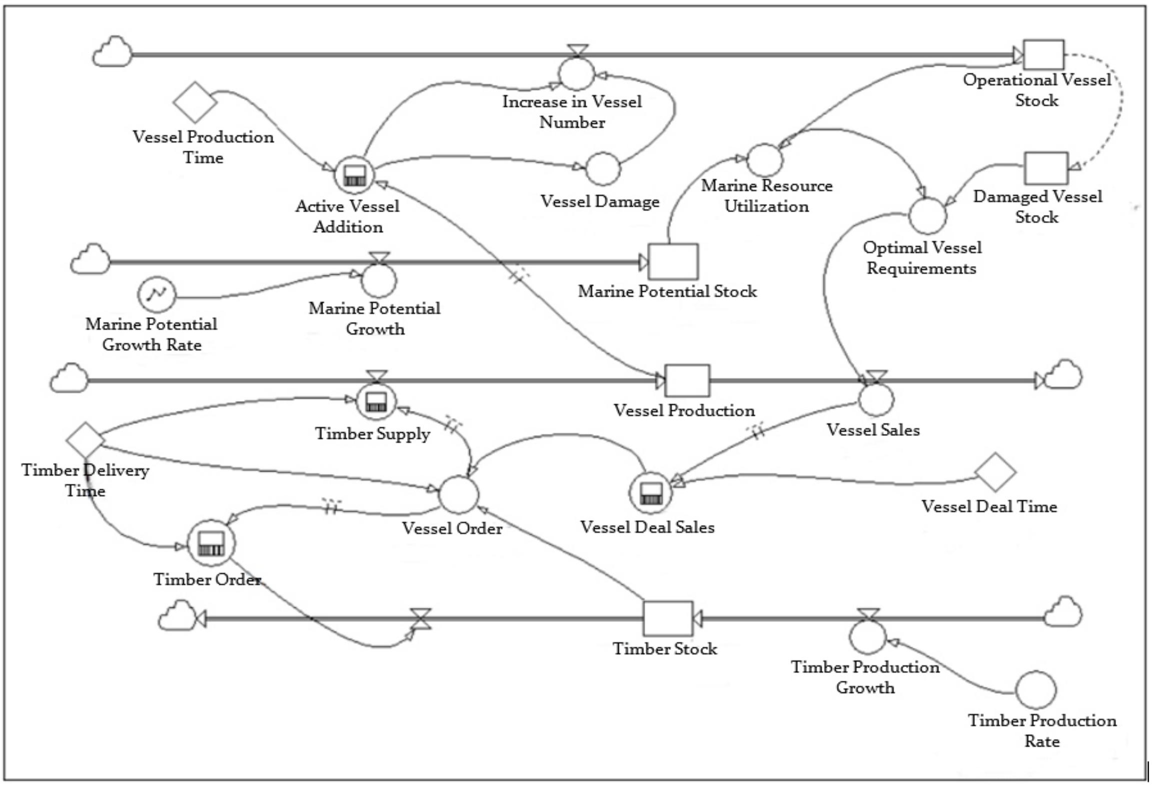

Figure 3. Stock flow diagram of wooden fishing vessel production system

Table 2. MAPE of key variables

Key Variable	Data	Wood Supply (m^3) by Year				
		2014	2015	2016	2017	2018
Timber Supply	Observed	12,606	12,276	8,960	10,813	12,309
	Simulation	12,412	12,499	8,848	10,528	10,162
	Absolute Average	0.015	0.018	0.013	0.026	0.174
	MAPE			0.0494		
Timber Demand	Observed	11,460	11,160	8,145	9,830	11,190
	Simulation	12,420	11,295	8,545	10,655	11,397
	Absolute Average	0.0838	0.0121	0.0491	0.0839	0.0185
	MAPE			0.0495		
Operational Vessel Stock	Observed	7,000	6,200	6,000	6,500	6,800
	Simulation	7,000	6,960	6,933	6,876	6,843
	Absolute Average	0.000	0.123	0.155	0.058	0.006
	MAPE			0.0684		

Table 3. Trend comparison between official fishing fleet data and simulated operational vessels

Data	Vessel Unit by Year				
	2017	2018	2019	2020	2021
Actual (20–100 GT)	31,610	35,810	20,144	21,413	18,486
Simulation (29–100 GT)	6,695	6,618	6,783	6,770	6,715

the observed data was mainly due to the inclusion of smaller vessel classes. Previous research also indicated that fleet estimation should consider vessel characteristics and the potential of marine resources within specific fisheries management areas (Ardiyani et al. 2019).

Overall, the validation results showed that the model could reproduce historical system behavior with acceptable accuracy. The consistency between simulated and observed trends suggested that the model can represent the interactions among timber supply, ship production, and fishing fleet dynamics. This capability provided a useful basis for identifying potential imbalances between timber supply and industrial demand and supporting decision-making related to resource planning and shipyard production management. Therefore, the validated model was considered reliable for further simulation. The subsequent section presents the simulation results for the period of 2014–2040.

Simulation for Predicting Future Demand

Based on the validation results, the model is considered sufficiently accurate to represent the system's behavior. Therefore, the model can be used to simulate future conditions and analyze how timber supply and demand evolve. Figure 4 depicts the dynamic interaction between timber supply, timber demand, and vessel production within the system over the period 2014–2040. During the initial period, timber supply and vessel production remained relatively stable, fluctuating between approximately 8,000 and 15,000 m^3/year, indicating a relatively balanced relationship between timber availability and ship production. Minor fluctuations occurred during this period, reflecting variations in production demand and resource availability. The system operated under relatively stable conditions, where timber supply is sufficient to meet production needs without significant pressure.

Figure 4 presents the dynamic simulation of timber supply, vessel production, and optimal vessel requirements for the period 2014–2040. From 2022 onwards, vessel production gradually increased, followed by a corresponding rise in timber demand. This pattern indicated that increasing vessel requirements, driven by improving fisheries conditions, directly influence shipbuilding activities and timber consumption. During the period 2025–2027, vessel production reached intermediate peaks, reflecting periods of intensified shipbuilding activity. Timber supply also increased during this phase. However, its growth was relatively slower than timber demand, suggesting pressure on timber availability.

Towards 2028–2029, both timber supply and vessel production showed a slight decline, indicating a temporary adjustment within the system. A more pronounced transition occurs around 2030, when

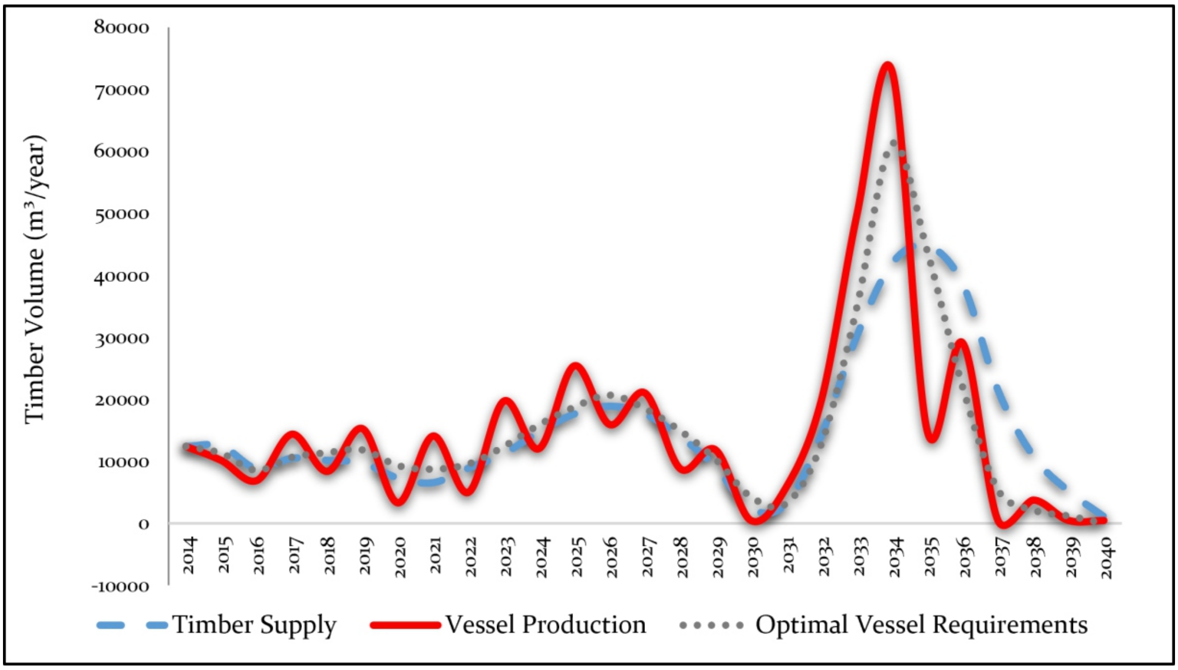

Figure 4. Dynamic simulation of timber supply, vessel production, and optimal vessel requirements (2014–2040)

vessel production and timber demand decreased significantly. This decline represented a temporary contraction phase, which might be associated with limitations in timber supply or adjustments in vessel demand.

The system then entered its most critical phase between 2033 and 2035. During this period, vessel production reached its highest levels, demanding more than 70,000 m^3/year of timber for this level of production. This peak reflected a substantial expansion in shipbuilding activities, driven by increased fleet requirements. Timber supply also increased, but demand rose even more rapidly, leaving limited timber availability to constrain the system. This imbalance indicated a potential supply deficit during peak production periods, highlighting the need for proactive resource planning.

Following this peak, vessel production declined sharply, while timber demand gradually decreased. This pattern suggested the completion of fleet expansion and the beginning of system stabilization. Timber supply also decreased over time; however, the gap between supply and demand became smaller, indicating a gradual return to a more balanced condition. By the period 2038–2040, the system approached a relatively stable state, characterized by lower production levels and reduced pressure on timber resources.

Overall, the simulation results demonstrated that the shipbuilding system operates as a dynamic, cyclical system in which timber supply, vessel production, and fisheries-driven demand continuously interact over time. The significant peak observed in the early 2030s underscored the risk of supply pressure when timber availability failed to keep pace with demand.

From a managerial perspective, these findings suggest that shipyard operators and policymakers should anticipate periods of high timber demand by strengthening supply planning, improving material efficiency, and exploring alternative raw materials. In addition, better coordination between the forestry and fisheries sectors is necessary to ensure that fleet expansion plans are aligned with sustainable timber availability. Without such coordination, rapid increases in vessel production may lead to resource constraints that could disrupt both industrial activities and long-term sustainability. Therefore, integrating timber resource management with shipbuilding production planning is essential to support the stable and sustainable development of the shipbuilding industry (Praharsi et al. 2020).

Sensitivity Analysis

The sensitivity analysis was conducted to evaluate how changes in key variables influence system behavior, as the simulation results depend on several

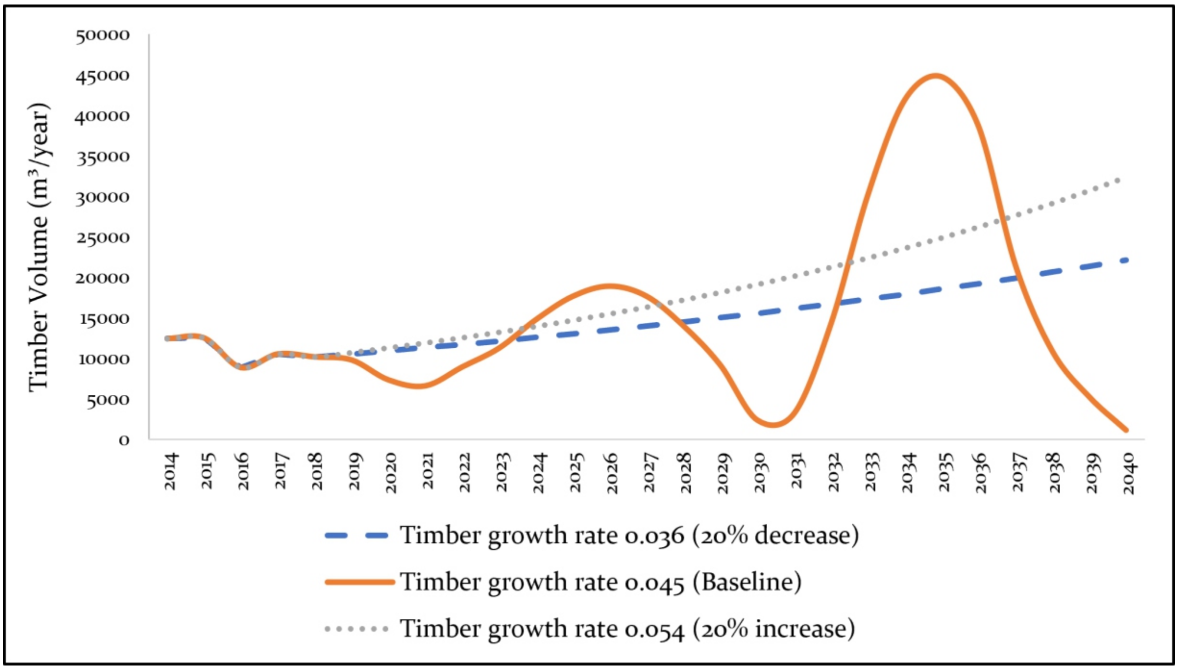

Figure 5. Sensitivity of timber supply (m^3/year) on timber growth rate

critical parameters. This step is essential for identifying variables with the most significant impact on timber supply, vessel production, and overall system dynamics.

Effect of Timber Growth Rate on Timber Supply

The first sensitivity analysis examines the effect of timber growth rate on timber supply. The results show that variations in timber growth rate significantly influence the long-term trajectory of timber supply. In the baseline scenario (using the current timber growth rate), timber supply fluctuates over time, particularly during the period 2028–2035, when it increases sharply before declining again (Figure 5). This fluctuation reflects the dynamic interaction between timber availability and vessel production demand within the system. Higher timber growth rates lead to a more sustained increase in timber availability, while lower growth rates constrain supply growth and reduce system resilience under increasing demand pressure.

The difference between scenarios becomes more pronounced in the long term. Under the higher-growth-rate scenario, timber supply continues to increase steadily, indicating sufficient resource regeneration to support future demand. In contrast, the lower-growth-rate scenario shows a slower increase, suggesting potential limitations in timber availability under higher production pressure. These findings indicate that timber growth rate plays a determining role in long-term supply adequacy, particularly under increasing demand conditions, where insufficient regeneration may constrain system stability.

Effect of Marine Potential Growth Rate on Vessel Demand

The second sensitivity analysis examines how changes in marine potential growth rate affect vessel demand, an important driver of timber consumption. Figure 6 shows the sensitivity of vessel demand to variations in the marine potential growth rate. Three scenarios were tested by adjusting the variable by ±20% of the baseline value: 0.123 (low), 0.154 (baseline), and 0.185 (high). The results show a consistent upward trend across all scenarios, indicating that vessel demand increases over time as marine resources are utilized more intensively. However, the magnitude of increase differs across scenarios, where the higher growth rate produces a steeper trajectory, while the lower growth rate results in a more gradual increase.

The results reveal that higher marine potential growth rates lead to a gradual increase in vessel demand, reflected in higher timber requirements. Conversely, lower growth rates result in slower growth

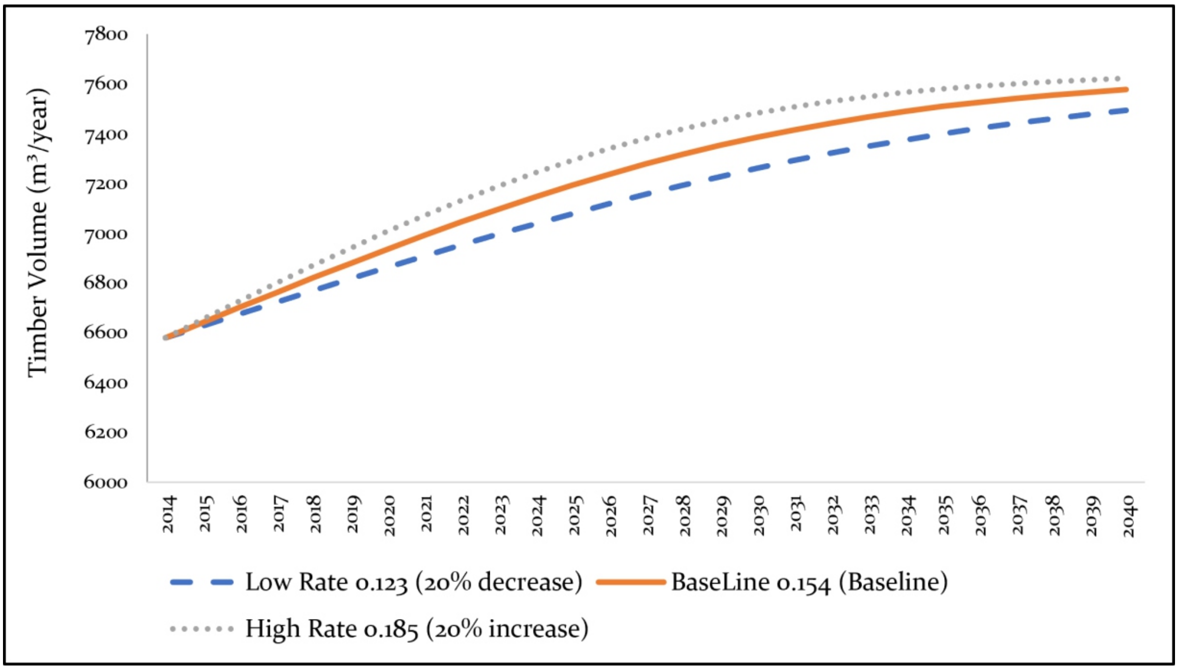

Figure 6. Sensitivity of vessel demand (m^3/year) to marine potential growth rate

of timber demand. The differences between scenarios become more pronounced after 2025, indicating that the influence of marine resource potential streng-thens over the long term. Despite these differences, the overall pattern remains stable without abrupt fluctuations. These results highlight that marine resource potential acts as an external demand driver, gradually shaping vessel production dynamics, rather than inducing structural changes in system behavior.

Effect of Vessel Damage Rate on Vessel Demand

The final sensitivity analysis examines the effect of vessel damage rate on vessel demand, representing replacement demand within the system. Vessel damage rate is defined as the proportion of vessels requiring replacement per year (unit/year), which is converted into timber equivalent demand (m^3/year) by multiplying it by the average timber requirement per vessel (174.5 m^3/unit). Three scenarios were tested: a lower damage rate (0.16), a baseline (0.20), and a higher damage rate (0.24). This analysis captures how variations in vessel deterioration intensity influence long-term replacement requirements within the ship-building system. Changes in the vessel damage rate directly affect the frequency of vessel replacement, which, in turn, determines total timber demand.

The results presented in Figure 7 show that vessel demand increases consistently across all scenarios as the vessel damage rate increases. The higher-damage-rate scenario produces the highest level of vessel demand throughout the simulation period, followed by the baseline and the lower scenario. This confirms that the vessel damage rate has a direct and proportional influence on replacement demand within the system. A key observation from Figure 7 is that the curves' overall shapes remain identical across all scenarios, with nearly parallel trajectories. This indicates that variations in the vessel damage rate do not alter the system's structural behavior but instead serve as a scaling factor that adjusts the magnitude of demand without altering its temporal dynamics.

In the early simulation period, differences between scenarios are relatively small. However, as time progresses, the gap between scenarios becomes increasingly pronounced, reflecting the cumulative nature of vessel deterioration, in which small differen-ces in damage rates accumulate into larger long-term variations in replacement demand.

Despite these differences in magnitude, all scenarios exhibit similar fluctuation patterns over time. These fluctuations reflect the interaction between vessel aging, replacement timing, and production cycles within the system. Periodic increa-ses and decreases in demand occur consistently across all scenarios, indicating that the system's behavior remains stable under varying levels of vessel damage

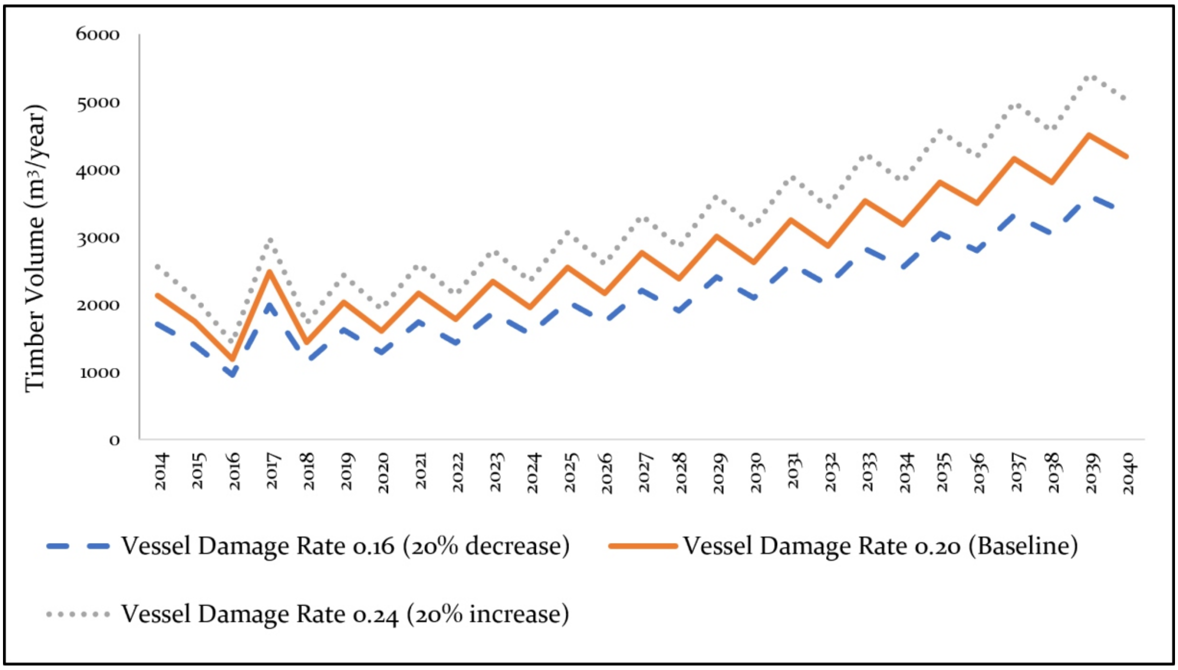

Figure 7. Sensitivity of vessel demand (m^3/year) on vessel damage rate

intensity.

Overall, the results indicate that the vessel damage rate is a key determinant of the scale of replacement demand in shipbuilding systems. However, it does not alter the underlying system dynamics, which remain governed by cyclical vessel replacement processes. This suggests that improvements in vessel durability and maintenance practices would primarily reduce the magnitude of timber demand rather than fundamentally changing its temporal pattern. These findings reinforce the importance of vessel durability in moderating long-term pressure on timber resources.

Limitations

This research focused on timber demand in the wooden shipbuilding industry and the relationship with production activities. Economic variables such as production costs and timber prices were not included, and ecological dynamics were not explicitly modeled. Despite these limitations, the model provides useful insights into timber demand and the interactions between industrial activities and resource availability.

Conclusion

This research analyzed annual timber consumption and projected future timber demand in the traditional shipbuilding industry of Batang Regency, Central Java, using a system dynamics model. Empirical analysis showed that timber consumption was closely related to ship production activities, with an average annual consumption of approximately 10,407 m^3 during the observation period. Variations in vessel size, production volume, and material efficiency directly determined timber demand. Model validation indicated an acceptable accuracy, with MAPE values below 10% for all key variables, suggesting the model is reliable for long-term analysis.

Simulation results indicate that timber demand is affected by both current production levels and long-term interactions among fisheries industry development, vessel demand, and resource availability. The model forecasts a substantial rise in vessel production and timber demand in the early 2030s, with a peak projected around 2034 to 2035. During this period, timber supply is expected to fall short of demand, potentially placing considerable pressure on timber resources unless corrective measures are implemented. Sensitivity analysis further identifies timber growth rate, marine resource potential, and vessel damage rate as key parameters influencing system behavior.

These results provide a dynamic model for understanding timber demand in traditional shipbuilding industries. However, several limitations should be acknowledged. The model does not include economic variables, such as timber prices or production costs, nor does it explicitly represent forest regeneration processes or detailed fisheries stock dynamics. This research suggests incorporating these aspects to improve projection accuracy and support more comprehensive resource management strategies.

Acknowledgment

The authors are grateful for the support and cooperation of the Association of Shipbuilding Industries in Batang Regency, Central Java, for providing valuable information and serving as key resource persons in this research.

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