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Supply Chain Sustainability Risk Assessment to Support Supply Chain Resilience Improvement Using House of Risk (HoR) and Interpretive Structural Modeling (ISM) at PT XYZ

Qhintara Febriana Putri Wahyono[a,*], Farida Pulansari[b], Isna Nugraha[c]

[a]Department of Industrial Engineering, Faculty of Engineering, Universitas Pembangunan Nasional “Veteran” Jawa Timur.
Email: 22032010141@student.upnjatim.ac.id.
[b]Department of Industrial Engineering, Faculty of Engineering, Universitas Pembangunan Nasional “Veteran” Jawa Timur.
Email: farida.ti@upnjatim.ac.id.
[c]Department of Industrial Engineering, Faculty of Engineering, Universitas Pembangunan Nasional “Veteran” Jawa Timur.
Email: isna.nugraha.ti@upnjatim.ac.id.

Abstract

Supply chain activities in the shipbuilding industry have high complexity, which may generate sustainability risks and affect the company’s supply chain resilience. This study aims to assess sustainability risks in the supply chain and formulate mitigation strategies toward supply chain resilience at PT XYZ. The methods employed in this study are House of Risk and Interpretive Structural Modeling. The analysis results identified 24 risk events and 30 risk agents, with additional works as the main priority risk agent having an Aggregate Risk Potential value of 945. The most effective mitigation strategy identified is project coordination meetings based on a master schedule, with an Effectiveness to Difficulty Ratio value of 3,846.67. The results of Interpretive Structural Modeling indicate that knowledge, visibility, risk management culture, and trust are the main driving elements in supporting the company’s supply chain resilience. Based on the synthesis of both analyses, mitigation strategies are focused on improving planning, cross-divisional coordination, and organizational learning across three phases: pre-disruption, during disruption, and post-disruption. This study is expected to provide strategic recommendations to support the strengthening of the company’s supply chain resilience.

Keywords: House of risk; interpretive structural modeling; shipbuilding industry; supply chain resilience; sustainability risk

1. Introduction

Supply Chain Management (SCM) is a system that integrates suppliers, manufacturers, and customers through the flow of goods, information, and financial resources to achieve operational efficiency [1]. As business environments become increasingly dynamic and complex, companies are no longer focused solely on operational efficiency but are also required to consider sustainability aspects in managing their supply chains. This condition has encouraged the development of Sustainable Supply Chain Management (SSCM), which emphasizes the integration of economic, social, and environmental dimensions into supply chain activities [2]. Through SSCM implementation, companies are expected not only to optimize performance and reduce costs but also to ensure that operational activities remain environmentally responsible and socially sustainable. However, the practical implementation of sustainable supply chain management remains challenging due to the presence of uncertainties and disruptions across supply chain processes.

Risk is generally defined as an uncertain event that may create either positive or negative impacts on organizational objectives. In the managerial context, risks emerge due to variability in internal and external conditions, such as fluctuating demand, price instability, supplier unreliability, and operational disruptions [3]. Within supply chain management, risk refers to factors that potentially disrupt the continuity of activities across the supply chain network, from upstream suppliers to downstream customers [4]. These risks can negatively affect the movement of materials, information, and services, thereby reducing the efficiency and effectiveness of business operations. Furthermore, one source of risk may trigger multiple disruption events simultaneously, making supply chain risk management increasingly complex. If not properly mitigated, these disruptions may reduce operational performance and weaken a company’s ability to maintain resilience under uncertain conditions.

The increasing uncertainty and complexity of interconnected supply chain activities have encouraged organizations to recognize supply chain resilience as a strategic capability. Supply chain resilience refers to the

*Corresponding author. Tel.: +62-857-7378-2129
Jl. Rungkut Madya, Gn. Anyar, Kec. Gn. Anyar, Surabaya
Jawa Timur, Indonesia 60294

capability of a supply chain system to anticipate potential disruptions, cope with their effects, resume normal operations, and adapt to evolving conditions while preserving operational continuity [5]. A resilient supply chain enables organizations to minimize the adverse effects of disruptions and sustain performance despite uncertainty. Nevertheless, resilience cannot be achieved solely through reactive corrective actions but requires proactive identification, prioritization, and mitigation of potential risks throughout the supply chain network. Accordingly, effective risk management becomes a critical enabler in supporting the long-term resilience and sustainability of organizational supply chain systems [6].

The shipbuilding industry represents one of the industrial sectors with highly complex supply chain structures due to the involvement of numerous stakeholders, long production lead times, project-based manufacturing systems, and dependence on specialized materials and components. Shipbuilding operations require the coordination of multiple supply chain actors, including raw material suppliers, subcontractors, logistics providers, internal production units, and customers. Such complexity increases the possibility of disruption at various stages of the supply chain. Delays in material procurement, mismatches in technical specifications, warehouse inaccuracies, rework processes, and disruptions in customer handover may all interfere with operational performance. Moreover, disruptions in shipbuilding supply chains may affect economic performance while also generate environmental-social consequences, including increased transportation emissions, material waste, additional energy consumption, and elevated labor workload. This indicates that risks in the shipbuilding supply chain are multidimensional and closely related to sustainability aspects.

PT XYZ is a shipbuilding manufacturing company operating in Indonesia and engaged in ship design, construction, and repair activities. In conducting its operations, the company manages supply chain processes involving procurement, receiving and quality inspection, warehousing, internal distribution, production support, and customer delivery activities. Each stage of the supply chain contains distinct characteristics and disruption potentials that require specific managerial attention. Variability in supplier lead times and delivery frequencies may affect material availability and disrupt production schedules. In procurement and warehousing activities, stock discrepancies and material returns may result in inefficiencies, rework, and increased operational costs. Furthermore, downstream activities such as documentation transfer and product handover may experience scheduling constraints that affect service quality. These issues indicate that PT XYZ faces sustainability-related risks throughout multiple supply chain stages, which may weaken operational performance and threaten long-term resilience if not systematically managed.

To systematically identify and mitigate supply chain risks, organizations require structured analytical frameworks capable of mapping supply chain processes and prioritizing risk sources. One of the commonly used frameworks in supply chain analysis is the Supply Chain Operations Reference (SCOR) model, which categorizes supply chain activities into five major processes: plan, source, make, deliver, and return [7]. SCOR enables organizations to comprehensively analyze supply chain activities and identify critical areas where disruptions may occur. Through systematic process mapping, companies can better evaluate the performance and vulnerability of each operational stage while aligning risk management strategies with business processes.

House of Risk (HoR) has been widely applied as a proactive tool for identifying, assessing, and prioritizing risks. HoR was developed by adapting principles from Failure Mode and Effect Analysis and Quality Function Deployment to provide a structured mechanism for determining mitigation priorities based on the relationships between risk events and risk agents [8]. The method enables organizations to identify the most critical sources of risk and ascertain the most appropriate mitigation strategies by considering both severity and occurrence factors [9]. Moreover, Pareto analysis can be incorporated to determine dominant priorities among identified risk agents by highlighting the most influential factors contributing to overall supply chain disruption [10].

Beyond risk prioritization, understanding the structural relationships among resilience-related factors is equally important in developing strategic mitigation plans. Interpretive Structural Modeling (ISM) is a decision-making and structural analysis technique used to identify contextual relationships among variables and construct hierarchical models within complex systems [11]. ISM assists researchers and practitioners in understanding the interdependencies among resilience-related elements and identifying the driving variables that influence overall system performance. Furthermore, the Matrix of Crossed Impact Multiplications Applied to a Classification (MICMAC) is frequently applied in conjunction with ISM to categorize variables according to their driving and dependence power, thereby supporting strategic decision-making [12].

Previous studies have demonstrated the effectiveness of House of Risk in assessing sustainability-related risks in supply chain systems, while Interpretive Structural Modeling has been used to map the relationships among resilience elements in organizational contexts. House of Risk has been applied to evaluate sustainability risks in supply chain operations [13], while ISM has been used to hierarchically structure resilience-related elements [14]. Furthermore, the integration of HoR and ISM has been used to identify disruption sources and formulate strategies for improving supply chain resilience [15]. Although these studies provide valuable insights, most prior research has focused on general manufacturing sectors and has not specifically examined the shipbuilding industry, which has unique supply chain characteristics involving project-based production, specialized procurement, long lead times, and high operational uncertainty.

Based on the aforementioned discussion, a research gap exists in the limited application of integrated sustainability risk and resilience assessment frameworks within the shipbuilding industry. Previous studies have generally analyzed sustainability risk and resilience separately or have not comprehensively addressed the structural relationships between risk mitigation strategies and resilience drivers in highly complex industrial environments. In addition, several methods such as Failure Mode and Effect Analysis (FMEA), Analytic Hierarchy Process (AHP), and other ranking-based approaches have been widely used in risk analysis and decision-making. FMEA generally focuses on evaluating failure modes, while AHP emphasizes criteria weighting and alternative prioritization [16]. However, the characteristics of the shipbuilding industry, which involve project-based production, long lead times, specialized procurement, and interrelated risks, require an approach capable of simultaneously prioritizing risk sources and structuring resilience improvement strategies. Therefore, this study proposes the integration of HoR and ISM to assess sustainability-related supply chain risks and analyze the structural relationships among resilience elements in the shipbuilding sector. HoR was selected because it can identify risk events, prioritize dominant risk agents, and determine proactive mitigation actions. Meanwhile, ISM was employed because it can map interrelationships among strategies, identify key driving factors, and determine implementation priorities. The integration of these methods provides a more comprehensive analytical approach by combining proactive risk prioritization with structured resilience analysis.

Accordingly, this study aims to identify and prioritize sustainability risks in the supply chain of PT XYZ using HoR and to analyze the relationships among supply chain resilience elements through ISM. Based on the synthesis of both methods, this study seeks to formulate mitigation strategies that support supply chain resilience improvement in the company. The findings of this research are expected to contribute theoretically to the development of integrated sustainability risk and resilience frameworks and practically to provide managerial recommendations for improving operational efficiency, resource management, and resilience performance in shipbuilding supply chain operations.

2. Method

2.1. Research location and time

This research was conducted at PT XYZ, a shipbuilding manufacturing company located in Surabaya, East Java. The research was carried out starting from September 2025 until all required data for the study were obtained.

2.2. Data collection technique

Data collection in this study was conducted through a literature review and field data collection. The literature review was used to obtain theoretical foundations related to supply chain management, sustainability risk, supply chain resilience, House of Risk (HoR), and Interpretive Structural Modeling (ISM). Meanwhile, field data were obtained through observation, interviews, brainstorming, and questionnaire distribution to five expert respondents with more than five years of work experience who were directly involved in the company's supply chain activities. Based on their experience and responsibilities, the respondents were considered to adequately represent key supply chain functions and possess a comprehensive understanding of operational issues, risks, material flow, information flow, and decision-making processes. The selection of five expert respondents was considered adequate because HoR and ISM are expert judgment-based methods, in which respondent adequacy depends on the expertise, relevance, and representativeness of the selected experts. Previous studies indicate that there is no universally fixed number of experts required, while five to nine experts are commonly recommended for face-to-face expert assessments [17]. The collected data included identification of supply chain activities, risk events, risk agents, mitigation strategies, and relationships among supply chain resilience elements.

2.3. Data analysis method

The initial stage of analysis was carried out by mapping the company's end-to-end supply chain operations using the SCOR framework, which consists of plan, source, make, and deliver processes [7]. This framework was used to systematically identify supply chain activities so that potential risks at each process stage could be comprehensively recognized. The results of this mapping then served as the basis for identifying risk events and risk agents. Risk analysis in this study was conducted using HoR. In HoR Phase 1, risk events, risk agents, severity, occurrence, and the correlation of risk events–risk agents were identified and assessed. Severity and occurrence were rated on a scale from 1 to 10, while correlation was assessed using a scale of 0, 1, 3, and 9. The severity and occurrence values were obtained from the average respondent assessments using the following equations:

$$S_i = \frac{\sum S_{ij}}{n} \tag{1}$$

$$O_j = \frac{\sum O_{jk}}{n} \tag{2}$$

where,
S_i = average severity value of risk event i
S_{ij} = severity value from respondent j
O_j = average severity value of risk agent j
O_{jk} = severity value from respondent k
n = number of respondents

Afterward, Aggregate Risk Potential (ARP) was calculated to prioritaze risk agents using the following equation:

$$ARP = O_j \sum (S_i \times R_{ij}) \tag{3}$$

where,
O_j = occurrence value of risk agent *j*
S_i = severity value of risk event *i*
R_{ij} = correlation value between risk event *i* and risk agent *j*

Furthermore, Pareto analysis was used based on the 80/20 principle by selecting risk agents that contributed the most to the total risk value. The selected priority risk agents were then analyzed in HoR Phase 2 to determine the most effective mitigation strategies. This stage involved identifying mitigation strategies, assessing the relationship between mitigation strategies and risk agents, and calculating the Total Effectiveness (TE_k) and Effectiveness to Difficulty Ratio (ETD_k). Total Effectiveness was calculated using the following equation:

$$TE_k=\sum\left(ARP_j\times E_{jk}\right) \quad (4)$$

Meanwhile, ETDk was calculated using the following equation:

$$ETD_k=\frac{TE_k}{D_k} \quad (5)$$

where,
ARP_j = aggregate risk potential value of risk agent j
E_{jk} = correlation value between risk agent j and mitigation strategy k
D_k = implementation difficulty level of mitigation strategy k

Mitigation strategies with the highest ETD_k values were prioritized as the primary strategies for risk treatment. Subsequently, the mitigation strategies were analyzed using ISM to model the structural relationships among supply chain resilience elements. ISM is a structural modeling method used to analyze relationships among elements in a complex system and organize them into hierarchical structures [11]. The ISM process began with the identification of supply chain resilience elements, followed by the preparation of the Structural Self-Interaction Matrix (SSIM), conversion into the Reachability Matrix, level partitioning, and digraph construction to establish a hierarchical structural model of the elements.

To strengthen the structural analysis, MICMAC was employed to classify elements based on driving power and dependence power in order to identify the key driving elements within the system [12].

The final stage of the research involved synthesizing the results of HoR and ISM to formulate mitigation strategies toward supply chain resilience. This synthesis was conducted by mapping the prioritized mitigation strategies to the key driving elements of supply chain resilience in order to produce more integrated recommendations aligned with the company's conditions.

3. Results and Discussion

3.1. Business process mapping using SCOR

The company's supply chain activities were systematically identified and classified through business process mapping using SCOR. Based on the mapping results, PT XYZ's supply chain activities were classified into four major processes, namely plan, source, make, and deliver, while the return process was not identified because the company does not implement a final product return mechanism in its operational activities. The results of the company's business process mapping using SCOR are shown in Table 1.

Table 1. Business process mapping using SCOR

Major Process	Sub Process	Detail Activity
Plan	Contract Document Preparation	Preparation of equipment technical specifications
		Preparation of material list
	Project Requirement Planning	Coordination of work plan preparation
		Preparation of implementation schedule
Source	Supplier Selection and Contracting	Supplier evaluation and selection
		Purchase Order (PO) issuance
	Material Procurement and Receiving	Monitoring of material delivery
		Incoming material inspection
		Material storage in warehouse
		Supplier claim process
Make	Structure Fabrication and Erection	Structural cutting and welding process
		Structural erection in workshop
		Steel material utilization
		Management of steel scrap leftovers
	Outfitting and System Installation	Piping and equipment installation
		Inter-team work coordination
		Completion of system works
		Assignment of critical tasks
	Blasting and Painting	Blasting process in dock area
		Epoxy coating process
Deliver	Inspection and Sea Acceptance Test	Electrical system operation
		Final inspection execution
		Sea trial execution
	Delivery	Project handover process

Based on Table 1, each main process consists of several sub-processes and detailed activities that describe the company's overall supply chain operational flow. These mapping results were subsequently used as the starting for identifying risk events in the following stage.

3.2. Risk assessment using house of risk phase 1

Risk assessment using House of Risk (HoR) Phase 1 was conducted to identify and prioritize risk sources that potentially disrupt the company's supply chain activities. A total of 24 risk events and 30 risk agents were identified within various supply chain activities based on the identification results. Furthermore, each risk event was assessed based on its severity to determine the magnitude of impact if the risk occurs. The severity assessment results are shown in Table 2.

Table 2. Severity assessment of supply chain sustainability risk events

REi	Risk Event	Severity
RE1	Technical specifications in planning and contract documents are not clearly defined	8
RE2	Mismatch between material list and actual project requirements	5
RE3	Lack of cross-functional coordination in project execution	5
RE4	Project scheduling exceeds production capacity	8
RE5	Dependence on specific suppliers for main material procurement	8
RE6	Changes in material specifications or quantities during procurement process	5
RE7	Delays in the delivery of materials or main components	7
RE8	Received materials do not meet specifications	6
RE9	Material quality degradation during storage	6
RE10	Lengthy claim process for non-conforming materials	7
RE11	Rework occurs during production process	9
RE12	Misalignment between structural components	7
RE13	Material usage exceeds planned allocation	6
RE14	Ineffective management of leftover materials	6
RE15	Workplace accidents occur during production process	7
RE16	Work overlap within the same working area	6
RE17	Installation does not comply with established standards	7
RE18	Limited availability of certified workforce	7
RE19	Impact of production activities on other work areas	4
RE20	Improper hazardous waste management	5
RE21	Unstable energy usage during production process	5
RE22	Electrical parameters do not comply with standards	10
RE23	Machine operational performance does not meet parameters	7
RE24	Delay in project completion and handover	9

Based on Table 2, the highest severity value was identified in RE22 with a score of 10, indicating that the risk has the most critical impact on the company's operations. Meanwhile, the lowest severity value was identified in RE19 with a score of 4, indicating that the risk has a relatively lower impact compared to other identified risks.

Furthermore, the probability of each risk source occurring within supply chain activities was assessed through an occurrence evaluation conducted for each risk agent. The occurrence assessment results are shown in Table 3.

Table 3. Occurance assessment of supply chain sustainability risk agents

RAj	Risk Agent	Occurrence
RA1	No cross-functional technical review is conducted before finalizing project documents	3
RA2	Technical design documents are incomplete during project planning stage	4
RA3	Changes in work scope occur after initial planning approval	7
RA4	No integrated schedule reference exists across functions	4
RA5	Changes in project priorities without production capacity adjustment	3
RA6	Production capacity planning does not consider facility utilization duration	4
RA7	Limited suppliers meet technical specifications	6
RA8	Lack of verification between design and procurement before purchasing process	5
RA9	Uncertainty in logistics and material delivery process	7
RA10	No time limit in procurement approval process	6
RA11	Material inspection procedures are not comprehensive	2
RA12	Material storage management is not consistently implemented	3
RA13	Material claim process is not integrated into monitoring system	5
RA14	Quality control in production process is not conducted progressively	3
RA15	Technical revision information is not communicated comprehensively	2
RA16	Limited production facilities hinder process flexibility	5
RA17	Material distortion during production process	2
RA18	Material recording and identification system is not optimal	8
RA19	Occupational safety supervision is not optimal	7
RA20	Work planning does not consider detailed work area allocation	4
RA21	Project completion pressure reduces compliance with technical procedures	4
RA22	Uneven distribution of certified workforce	3
RA23	Production supporting facility capacity is inadequate	8
RA24	Waste management does not comply with procedures	7
RA25	Energy usage is not optimally scheduled	2
RA26	System testing does not represent operational conditions	1
RA27	Machine operational parameters are not adjusted to actual conditions	2
RA28	Testing execution does not comply with established standards	2
RA29	Increased rework during final project stage	3
RA30	Final inspection planning is not conducted in a timely manner	4

Based on Table 3, the highest occurrence values were identified in RA18 and RA23 with scores of 8, indicating that both risk agents have the highest probability of occurrence. Meanwhile, the lowest occurrence value was identified in RA26 with a score of 1, indicating that the risk agent rarely occurs in the company's activities.

After obtaining the severity and occurrence values, House of Risk Phase 1 calculation was performed by considering the correlation of risk events–risk agents to obtain the ARP value. It was used to determine the priority level of each risk agent based on its contribution to the total potential risk in the supply chain. The results of House of Risk Phase 1 calculation are shown in Table 4.

Table 4. House of risk phase 1 analysis results

Risk Event (RE)	Risk Agent (RA)																														Sev
	RA 1	RA 2	RA 3	RA 4	RA 5	RA 6	RA 7	RA 8	RA 9	RA 10	RA 11	RA 12	RA 13	RA 14	RA 15	RA 16	RA 17	RA 18	RA 19	RA 20	RA 21	RA 22	RA 23	RA 24	RA 25	RA 26	RA 27	RA 28	RA 29	RA 30	
RE1	3	9	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8
RE2	3	0	9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
RE3	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	5
RE4	0	0	3	1	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8
RE5	0	0	0	0	0	0	9	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8
RE6	0	0	0	1	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
RE7	0	0	0	0	0	0	0	0	9	9	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	7
RE8	0	0	0	0	0	0	0	9	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
RE9	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
RE10	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
RE11	0	0	1	0	0	0	0	0	0	0	0	0	0	9	9	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	9
RE12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	3	0	0	0	0	0	0	0	0	0	7
RE13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	1	0	0	0	0	0	0	0	0	0	6
RE14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	6
RE15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	3	0	0	0	0	0	0	0	0	0	7
RE16	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	6
RE17	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	7
RE18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	9	0	0	0	0	0	0	0	0	7
RE19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	4
RE20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	5
RE21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	9	0	0	0	0	0	5
RE22	0	0	3	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	1	0	0	0	0	9	0	0	0	0	10
RE23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	3	0	0	7
RE24	0	0	3	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	9	9	9
Occurrence	3	4	7	4	3	4	6	5	7	6	2	3	5	3	2	5	2	8	7	4	4	3	8	7	2	1	2	2	3	4	
ARP	117	288	945	392	216	288	432	495	609	378	108	162	315	423	204	315	108	432	441	276	860	189	288	315	90	90	126	42	243	324	
Rank	25	15	1	9	20	15	6	4	3	10	26	23	12	8	21	12	26	6	5	18	2	22	15	12	28	28	24	30	19	11	

Based on Table 4, risk agents with higher ARP values indicate greater contributions to potential supply chain disruptions and higher mitigation priority. Pareto chart analysis was then used to identify priority risk agents using 80/20 principle. The results are shown in Fig. 1.

Based on Fig. 1, risk agents with a cumulative percentage of ≤ 80% were designated as priority risk agents to be further analyzed in HoR Phase 2. These results indicate that most potential risks in the company's supply chain are influenced by a small number of dominant risk agents; therefore, risk control efforts are focused on these priority risk agents to improve mitigation effectiveness.

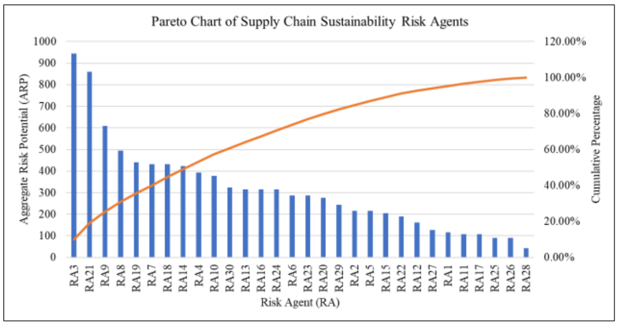

Figure 1. Pareto chart of supply chain sustainability risk agents

3.3. Risk assessment using house of risk phase 1

Risk treatment using House of Risk (HoR) Phase 2 was the most effective mitigation strategies for priority risk agents identified in HoR Phase 1 were determined through risk treatment using House of Risk (HoR) Phase 2. Based on the results, mitigation strategy recommendations were formulated to control dominant risk agents within the supply chain. The recommended strategies are shown in Table 5.

Based on Table 5, a total of 14 mitigation strategies were formulated based on the priority risk agents identified in HoR Phase 1. The proposed strategies include strengthening coordination, improving planning control, optimizing supervision, and enhancing operational control to support effective management of supply chain sustainability risks.

Table 5. Recommended supply chain sustainability risk mitigation strategies

PA	Risk Mitigation Strategy
PA1	Implementation of cross-functional technical review prior to material requirement finalization with scope control mechanism
PA2	Monitoring project progress against baseline schedule accompanied by periodic evaluation and corrective actions
PA3	Establishment of approval lead time in procurement process supported by notification and escalation system
PA4	Verification and approval of technical documents prior to procurement execution
PA5	Supplier performance evaluation and implementation of penalties for delays and non-conformities
PA6	Planning of critical material requirements with buffer time and early procurement strategy for long lead items
PA7	Implementation of quality control checkpoints at each stage of production process
PA8	Implementation of digital-based material recording system to support traceability and optimize material utilization
PA9	Strengthening occupational health and safety supervision through routine inspections and compliance enforcement mechanisms
PA10	Implementation of cross-functional project coordination meetings based on integrated scheduling
PA11	Optimization of resource allocation and utilization through integrated scheduling system
PA12	Production capacity planning based on facility utilization and multi-project analysis
PA13	Early scheduling of final inspection and coordination with relevant parties prior to project completion
PA14	Implementation of hazardous waste management and environmental control in accordance with standards

Table 6. House of risk phase 2 analysis results

		Preventive Action (PA)														ARP
		PA1	PA2	PA3	PA4	PA5	PA6	PA7	PA8	PA9	PA10	PA11	PA12	PA13	PA14	
Risk Agent (RA)	RA3	9	1	0	0	0	0	0	0	0	3	0	0	0	0	945
	RA21	0	3	0	0	0	0	0	0	0	1	0	9	0	0	860
	RA9	0	0	9	3	0	0	0	0	0	1	0	0	0	0	609
	RA8	3	0	1	9	0	0	0	0	0	0	0	0	0	0	495
	RA19	0	0	0	0	0	0	0	0	9	3	0	0	0	0	441
	RA7	0	0	0	0	9	1	0	0	0	0	0	0	0	0	432
	RA18	0	0	0	0	0	0	0	9	0	0	0	0	0	1	432
	RA14	3	1	0	0	0	0	9	0	0	0	0	0	0	0	423
	RA4	0	1	0	0	0	0	0	0	0	9	0	0	0	0	392
	RA10	0	0	0	0	9	3	0	0	0	0	0	0	0	0	378
	RA30	0	0	0	0	0	0	0	0	0	1	0	0	9	0	324
	RA13	0	0	9	3	0	0	0	0	0	0	0	0	0	0	315
	RA16	0	0	0	0	0	0	0	0	0	3	9	0	0	0	315
	RA24	0	0	0	0	0	0	0	1	0	0	0	0	0	9	315
	RA6	0	0	0	0	0	0	0	0	0	1	0	9	0	0	288
	RA23	0	0	0	0	0	0	0	1	0	0	0	0	0	9	288
	RA20	9	0	0	0	0	0	0	0	0	3	0	0	0	0	276
TEk		13743	4340	8811	7227	7290	1566	3807	4491	3969	11540	2835	10332	2916	5859	
Dk		4	3	4	3	4	3	4	4	3	3	5	5	3	5	
ETDk		3435.75	1446.67	2202.75	2409	1822.5	522	951.75	1122.75	1323	3846.67	567	2066.4	972	1171.8	
Rank		2	7	4	3	6	14	12	10	8	1	13	5	11	9	

Furthermore, the implementation priority of mitigation strategies was established through HoR Phase 2 analysis using the Effectiveness to Difficulty Ratio (ETD_k), by considering the balance between the effectiveness of each strategy in reducing risk and its implementation difficulty. The results of House of Risk Phase 2 analysis are shown in Table 6.

Based on Table 6, mitigation strategies with the highest ETD_k values are the top priorities, as they are more effective and relatively easier to implement. The prioritized strategies are dominated by coordination strengthening, document control, and operational supervision improvement. Furthermore, Pareto chart analysis was conducted to clarify implementation priorities, with the results shown in Fig. 2.

Based on Fig. 2, mitigation strategies with a cumulative percentage of ≤ 80% were designated as priority strategies recommended for initial implementation. These results indicate that most risk reduction effectiveness is generated by a small number of dominant mitigation strategies; therefore, focused implementation on priority strategies is expected to improve the effectiveness of sustainability risk control within the company's supply chain.

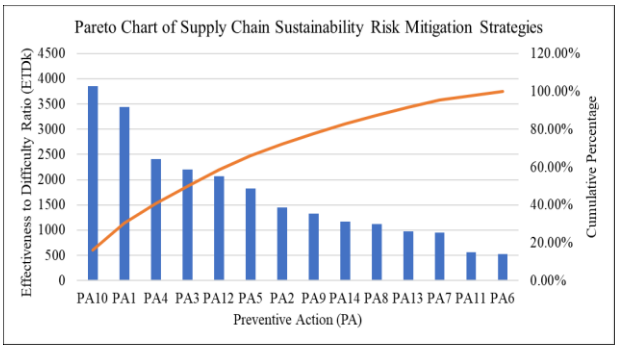

Figure 2. Pareto chart of supply chain sustainability risk mitigation strategies

3.4. Supply chain resilience modeling using interpretive structrual modeling (ISM)

Supply chain resilience modeling using Interpretive Structural Modeling (ISM) was conducted to analyze the relationships among resilience elements and identify the elements acting as key drivers within the company's supply chain resilience system. The results of this analysis were used to understand the hierarchical structure of relationships among elements as a basis for supporting the formulation of supply chain resilience improvement strategies. The Structural Self-Interaction Matrix (SSIM), which illustrates the contextual relationships among supply chain resilience elements, is shown in Table 7.

Table 7. Structural self-interaction matrix (SSIM)

i/j	Resilience Elements	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15
E1	Visibility	X	V	V	V	A	V	V	V	V	V	V	V	V	A	A
E2	Situation awareness		X	O	V	A	V	O	O	O	V	O	V	A	A	A
E3	Security			X	V	A	O	O	O	V	O	O	O	O	O	O
E4	Sustainability				X	A	A	A	A	A	A	A	A	A	A	A
E5	Risk management culture					X	V	O	V	O	V	O	V	V	X	V
E6	Flexibility						X	V	A	V	V	V	V	A	A	A
E7	Redundancy							X	V	V	O	O	V	A	A	A
E8	Collaboration								X	V	V	V	V	V	A	X
E9	Robustness									X	V	O	V	A	A	A
E10	Agility										X	V	V	A	A	A
E11	Velocity											X	V	A	A	A
E12	Adaptability												X	A	A	A
E13	Information sharing													X	V	A
E14	Knowledge														X	V
E15	Trust															X

Based on Table 7, the relationships among supply chain resilience elements indicate diverse cause-and-effect interactions within the company's supply chain resilience system. These relationships show that several elements have direct influence on other elements, while some others mutually influence one another or depend on specific elements within the system.

The next step involved constructing the reachability matrix to convert the inter-element relationships into binary form in order to analyze direct and indirect influences among supply chain resilience elements. The reachability matrix resulting from the ISM analysis is shown in Table 8.

Table 8. Reachability matrix

i/j	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15
E1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	0
E2	0	1	0	1	0	1	0	0	0	1	0	1	0	0	0
E3	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0
E4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
E5	1	1	1	1	1	1	0	1	0	1	0	1	1	1	1
E6	0	0	0	1	0	1	1	0	1	1	1	1	0	0	0
E7	0	0	0	1	0	0	1	1	1	0	0	1	0	0	0
E8	0	0	0	1	0	1	0	1	1	1	1	1	1	0	1
E9	0	0	0	1	0	0	0	0	1	1	0	1	0	0	0
E10	0	0	0	1	0	0	0	0	0	1	1	1	0	0	0
E11	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0
E12	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
E13	0	1	0	1	0	1	1	0	1	1	1	1	1	1	0
E14	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1
E15	1	1	0	1	0	1	1	1	1	1	1	1	1	0	1

Based on Table 8, the reachability matrix results indicate that several elements possess broader influence ranges than others, suggesting their important roles in shaping the supply chain resilience structure. Conversely, some elements exhibit higher dependency levels and therefore function more as outcomes of strengthening other elements within the system.

Furthermore, a conical matrix was developed to determine the driving power and dependence values of each supply chain resilience element. These values were used as the basis for determining the hierarchical position of each element within the system structure. The conical matrix results are shown in Table 9.

Table 9. Conical matrix

i/j	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	Driving Power	R
E1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	0	12	2
E2	0	1	0	1	0	1	0	0	0	1	0	1	0	0	0	5	8
E3	0	0	1	1	0	0	0	0	1	0	0	0	0	0	0	3	12
E4	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	3	12
E5	1	1	1	1	1	1	0	1	0	1	0	1	1	1	1	12	2
E6	0	0	0	1	0	1	1	0	1	1	1	1	0	0	0	7	7
E7	0	0	0	1	0	0	1	1	1	0	0	1	0	0	0	5	8
E8	0	0	0	1	0	1	0	1	1	1	1	1	1	1	1	10	5
E9	0	0	0	1	0	0	0	0	1	1	0	1	0	0	0	4	10
E10	0	0	0	1	0	0	0	0	0	1	1	1	0	0	0	4	10
E11	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	3	12
E12	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	3	12
E13	0	1	0	1	0	1	1	0	1	1	1	1	1	1	0	10	5
E14	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	13	1
E15	1	1	0	1	0	1	1	1	1	1	1	1	1	0	1	12	2
Dependence	4	6	3	15	2	8	7	6	10	10	8	13	5	4	5		
L	12	8	14	1	15	5	7	8	3	3	5	2	10	12	10		

Based on Table 9, elements with the highest driving power values indicate dominant roles as key drivers in the supply chain resilience system, whereas elements with high dependence values indicate that they are strongly influenced by other elements. These results indicate that strengthening the company's supply chain resilience depends on optimizing fundamental elements that exert broad influence across the system. The level partitioning results were subsequently visualized in the form of a hierarchical structure and digraph model to illustrate the layered relationships among supply chain resilience elements based on their level of influence within the system. The hierarchical structure and digraph model of supply chain resilience are shown in Fig. 3.

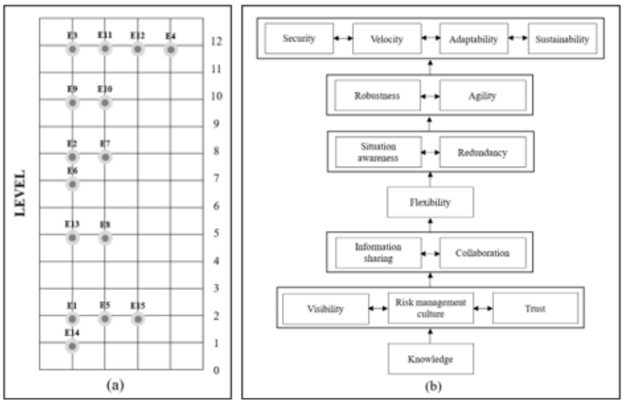

Figure 3. (a) Hierarchical structure; (b) Diagraph model of supply chain resilience

Based on Fig. 3, the hierarchical structure indicates that supply chain resilience elements are arranged hierarchically from foundational elements at the lowest level to outcome elements at the highest level. Elements at the lower levels serve as the primary foundation influencing the formation of operational and strategic elements at higher levels, indicating that resilience enhancement should begin with strengthening the foundational elements within the system.

To further classify the role of each element within the system, MICMAC analysis was conducted based on the driving power and dependence values. The results are shown in Fig. 4.

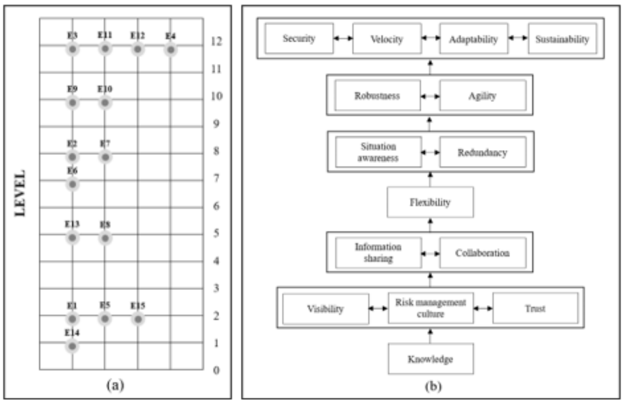

Figure 4. MICMAC mapping results

Based on Fig. 4, the MICMAC analysis classifies supply chain resilience elements into independent, dependent, and autonomous groups. Independent elements serve as the main drivers with high influence and low dependence, while dependent elements are outcomes of strengthening these drivers. The identified driver elements were then used to develop resilience improvement strategies along with the prioritized mitigation strategies from House of Risk Phase 2.

3.5. Synthesis of supply chain resilience improvement strategies

Supply chain resilience improvement strategies were formulated by integrating prioritized mitigation strategies from HoR Phase 2 with key driving elements from Interpretive Structural Modeling (ISM). This integration supports risk mitigation and systematic resilience strengthening. The strategies were then grouped into pre-disruption, during disruption, and post-disruption phases, as shown in Table 10.

Table 10. Mapping of supply chain resilience improvement strategies

Phase	Strategy	Mitigation	Resilience Element	Supply Chain Resilience Strategy
Phase 1 (Pre-Disruption)	Proactive	PA1, PA4, PA3	E5 (Risk Management Culture)	Establishment of baseline schedules and change control through cross-functional review and scope control to maintain project planning stability
			E1 (Visibility)	Identification of critical activities and materials along with integrated monitoring of their status within project planning
			E13 (Information Sharing)	Documentation and dissemination of technical information as references to improve planning consistency in future projects
Phase 2 (During Disruption)	Resistant	PA10, PA12, PA2	E8 (Collaboration)	Cross-functional coordination based on integrated scheduling to adjust activities and resource allocation during deviations
			E15 (Trust)	Responsive operational decision-making based on performance evaluation to maintain project continuity
Phase 3 (Post-Disruption)	Recovery & Growth	PA5	E14 (Knowledge)	Performance evaluation and documentation of lessons learned as a basis for improving future supply chain performance

Based on Table 10, the supply chain resilience improvement strategies are structured into three main phases according to the resilience stages. In the pre-disruption phase, the strategies focus on strengthening risk management culture, visibility, and information sharing through enhanced planning, design change control, and improved technical information accuracy. In the during disruption phase, the strategies are directed toward strengthening collaboration and trust through cross-functional coordination and optimization of resource allocation during operational disruptions. Meanwhile, in the post-disruption phase, the strategies focus on strengthening knowledge through supplier performance evaluation and project learning documentation as a basis for continuous improvement. These findings indicate that improving supply chain resilience does not solely depend on partial risk mitigation implementation, but also requires strengthening the key driving elements that contribute to building overall supply chain system resilience.

Overall, the findings indicate that enhancing supply chain resilience requires not only operational risk mitigation but also strengthening the key organizational drivers that support long-term resilience capabilities. The integration of HoR and ISM provides a comprehensive approach for linking sustainability risk mitigation with resilience development, enabling organizations to address operational disruptions while improving adaptive capacity and continuous learning within the supply chain system. The importance of implementing a systemic and proactive approach to resilience enhancement, particularly in complex and uncertainty-driven project-based industries, is emphasized by these findings.

4. Conclusion

This study identified 24 risk events and 30 risk agents within the supply chain activities of PT XYZ. The House of Risk analysis showed that the highest Aggregate Risk Potential (ARP) value was associated with additional works after material list approval (945), followed by project completion pressure in the final phase (860) and delays in critical material procurement (609). The prioritized mitigation strategies based on Effectiveness to Difficulty Ratio (ETD_k) were cross-functional project coordination meetings (3,846.67), mandatory technical review before material list finalization (3,435.75), and document verification prior to procurement processes (2,409.00). Furthermore, the Interpretive Structural Modeling analysis identified knowledge, visibility, risk management culture, information sharing, collaboration, and trust as the key driving elements of supply chain resilience. Based on the synthesis of HoR and ISM, supply chain resilience improvement strategies were formulated across pre-disruption, during disruption, and post-disruption phases, focusing on strengthening planning, operational coordination, and organizational learning. These findings provide a structured framework to support sustainability risk mitigation and enhance supply chain resilience at PT XYZ. Therefore, PT XYZ is recommended to strengthen cross-functional planning, technical verification, and project knowledge documentation to support continuous improvement, while future research may consider incorporating financial evaluation of the proposed mitigation strategies to assess their economic feasibility and implementation impact more comprehensively.

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