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Managing Quality and Supply Chain Risks in Precast Spun Pile

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Abstract. *The precast spun pile manufacturing process involves complex operations with high quality requirements and integrated supply chain risks that may cause product defects and work-in-process accumulation. This study analyzes quality and supply chain risks in the precast spun pile industry by applying a Quality Risk Management framework at PT X. The method includes risk identification, risk analysis, risk evaluation, and risk reduction based on expert judgment, process observation, and internal production data. The results show that human factors, inadequate maintenance, process control errors, and material supply variability are dominant risk sources. Preventive maintenance, SOP evaluation, and operator training are identified as priority mitigation strategies to improve operational stability and production reliability.*

Keywords: *Supply Chain Risks; Quality Risk Management; Work-in-Process*

I. INTRODUCTION

The precast spun pile industry is a capital-intensive manufacturing sector in which product quality is critical because the piles function as structural foundation elements. The complexity of processes such as spiral welding, spinning, steam curing, storage, and distribution makes spun pile manufacturing vulnerable to operational disturbances and quality inconsistencies (Firdaus et al., 2019; Muka et al., 2023; Utomo Dwi Hatmoko et al., 2019). Previous studies have shown that material variability, equipment instability, and process deviations contribute to product defects, which in turn affect production cost and supply reliability (Li et al., 2016; Shih et al., 2008; Wang et al., 2023).

Quality problems in this industry often originate from disruptions within the supply chain, indicating that process risks and supply chain risks are inherently intertwined. Delays in spiral steel supply, fluctuations in aggregate quality, and inconsistencies in curing operations can trigger defects and reduce production yield (Liansari et al., 2020; Munawar Albana, 2023). Similar interrelated risks have been widely reported in construction, heavy manufacturing, automotive, and logistics sectors (Elseknidy et al., 2025; Hosny et al., 2018; Ngo et al., 2024; Oduoza, 2020; Tang & Xu, 2023; Yoga Irsyadillah & Dadang, 2020), highlighting the importance of viewing quality and supply chain risks through an integrated perspective.

A number of risk management methods have been applied to identify and prioritize risks in manufacturing and construction industries, including FMEA, Fuzzy AHP, fuzzy inference, ISM, and STAMP (Boon Sin et al., 2015; Meléndez & Goerlandt, 2025; Ouedraogo et al., 2026; Pellegrino, 2025; Ramadhan et al., 2025; Shakibaei et al., 2025). In the precast sector, the House of Risk (HOR) method is widely used to map risk agents and determine mitigation priorities (Andriyanto & Mustamin, 2020; Pujawan & Geraldin, 2009; Trenggonowati & Pertiwi, 2017). HOR has also been applied across various industries, including food processing, logistics, automotive, raw-material distribution, and construction (Alam et al., 2025; Alfa et al., 2024; Dvaipayana et al., 2024; Liansari et al., 2020), demonstrating its flexibility and adaptability.

Although numerous studies have explored risks in the precast and construction sectors, many of them tend to focus on a single risk domain rather than integrating multiple dimensions simultaneously. Prior works generally concentrated on procurement – related disruptions (Trenggonowati & Pertiwi, 2017), raw

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material distribution risks (Liansari et al., 2020), or risks emerging at the project execution stage. Other studies have examined broader supply chain risk perspectives in the precast industry (Dvaipayana et al., 2024; Muka et al., 2023), yet they typically emphasize high-level or interorganizational risks without conducting a detailed mapping of operational risk agents within daily factory processes such as welding, spinning, curing, handling, or internal logistics. Furthermore, research combining quality risks and supply chain risks within the specific operational context of spun pile manufacturing remains limited, despite evidence that defect generation and process variability can significantly affect supply chain continuity, production throughput, and cost structures (Firdaus et al., 2019; Hidayawanti et al., 2024; Shih et al., 2008).

Compared with these earlier studies, this research provides a more integrated view by analyzing both quality-related failures and supply chain disturbances simultaneously within a single manufacturing system. Moreover, while existing literature rarely links operational disruptions with direct financial implications, this study incorporates empirical evidence from PT X, where the proportion of defective spun piles recorded during 2020 – 2022 reached 0.63% of total production, affecting products from the manufacturing stage through delivery and pile-driving processes. Although the percentage appears relatively small, the defects generated within this period contributed significantly to the accumulation of items in WIP2, thereby increasing financial pressure due to ongoing depreciation and bank interest obligations that could not be absorbed as revenue-generating output (Mahardhika et al., 2024). This analytical approach aligns with the principles of Quality Risk Management (QRM), originally formalized by Sari et al., (2010), but here adapted to the precast spun pile environment, an application area that has not been extensively explored. Thus, although the methodological foundations are established in existing literature (Andriyanto & Mustamin, 2020; Pujawan & Geraldin, 2009; Ramadhan et al., 2025), the contextual integration offered in this study provides a grounded understanding of how intertwined quality and supply chain risks manifest in real manufacturing operations.

From an operational standpoint, elevated defect levels and WIP2 stagnation may indicate systemic issues in the production process or supply chain. This aligns with findings from earlier studies that material variability, process instability, and supply disturbances can lead to financial losses and reduced supply chain performance (Ba Awain et al., 2025; Hidayawanti et al., 2024; Utomo Dwi Hatmoko et al., 2019; Zhu & Liu, 2023). Thus, a structured risk analysis is needed to understand how quality issues and supply chain disruptions jointly contribute to operational inefficiencies within PT X.

Based on these conditions, this study adopts a Quality Risk Management (QRM) perspective to systematically identify, analyze, evaluate, and reduce risks affecting both quality and supply chain performance in PT X's precast spun pile manufacturing processes. The analysis focuses on mapping risk events and risk agents across daily operational activities, prioritizing critical risks, and formulating mitigation actions that are interrelated with operational and managerial strategies. This structured approach is intended to provide a practical understanding of how quality-related failures and supply chain disruptions jointly contribute to defect generation, WIP2 accumulation, and financial pressure, thereby supporting more effective risk reduction and operational stability.

The novelty and contribution of this study can be summarized in three points. First, it adapts the House of Risk (HOR) framework, originally developed for general supply chain risk management (Pujawan & Geraldin, 2009), to the precast spun pile manufacturing context, an integrated application of QRM and HOR that, to the authors' knowledge, has not been previously addressed in this industry. Second, the study links risk identification and prioritization directly to documented production data from PT X, including the recorded defect rate and its contribution to work-in-process (WIP2) accumulation, providing an empirically grounded illustration of how operational quality risks translate into financial consequences. Third, the

HOR Phase 2 prioritization is refined by weighting each risk agent-strategy correlation by the Aggregate Risk Potential $(ARP_j)$of each risk agent, so that the resulting Total Effectiveness (TE_k) ranking of mitigation strategies reflects both the strength of each risk agent-strategy relationship and the severity and frequency of the risk events associated with that agent, rather than raw correlation counts alone. Together, these elements provide a methodological refinement of the HOR Phase 2 prioritization procedure and a practical, data-grounded decision-support reference for quality and supply chain risk management in precast and other capital-intensive manufacturing industries.

II. Research Method

This research adopts a Quality Risk Management (QRM) framework to manage quality and supply chain risks in a precast spun pile manufacturing system. The study is conducted as a case study at PT X, focusing on identifying critical risk sources, evaluating their impacts, and formulating mitigation strategies. The methodological structure follows the QRM stages proposed by Sari et al., (2010) and is operationalized using the House of Risk (HOR) method to ensure systematic risk prioritization and mitigation planning.

Risk Identification

Risk identification was conducted by mapping all operational activities within PT X's spun pile supply chain and manufacturing processes, starting from material receiving and storage, reinforcement preparation, casting, prestressing and spinning, curing, finishing, stocking, until delivery handling. This process mapping serves as the basis for identifying potential failures that may affect product quality and operational performance.

Risk events (RE) were identified through direct observations, semi-structured interviews, and brainstorming sessions involving the Plant Manager, Site Engineer Manager, Quality Officer, Safety Officer, production supervisors, and logistics personnel. Supporting documents such as Standard Operating Procedures (SOPs), inspection records, maintenance logs, and historical defect reports were also examined. Identified risk events represent deviations, defects, or disruptions that may occur during daily operations, while risk agents (RA) represent the underlying causes of those risk events.

To support systematic risk identification, the entire operational flow of material handling and spun pile manufacturing at PT X was mapped, as illustrated in Figure 1.

Each activity depicted in Figure 1 represents a potential source of quality and supply chain risks and therefore serves as the basis for identifying risk events (RE) and corresponding risk agents (RA)

Figure 2. Process Flow of Spun Pile at PT X

Risk Analysis

In the risk analysis stage, each identified risk event was evaluated based on its severity (S), reflecting the potential impact on product quality, cost, delivery performance, and financial conditions. Meanwhile, each risk agent was assessed based on its occurrence (O), indicating the likelihood of the risk agent triggering risk events.

Following the QRM approach described by Sari et al., (2010), the severity and occurrence scores were assigned using expert judgment supported by historical production data from 2020 – 2022, including defect percentages and WIP2 accumulation. These values provide a quantitative basis for assessing the relative importance of identified risks.

Expert panel composition: the severity and occurrence scores above were elicited from a panel of three respondents at PT X, comprising (Plant Manager, Quality Control Supervisor, and Site Engineer Manager), each with a minimum of eight years of relevant experience in precast spun pile production. Scores were obtained through a focus group discussion and were cross-checked against the 2020–2022 production and defect records cited above to ensure consistency between expert judgment and historical data.

Risk Evaluation

The risk evaluation stage aims to compare and classify the analyzed risks against predefined risk criteria in order to determine their relative priority. At this stage, the results of the risk analysis namely the severity and occurrence scores, are further evaluated to identify which risks require immediate attention and control measures.

Risk evaluation in this study is conducted through risk mapping using a severity and occurrence matrix. Each identified risk event is positioned in the risk map based on its corresponding severity and occurrence values obtained in the previous stage. The risk map enables visual classification of risks into different risk levels, typically represented by color zones.

In this research, risk events located in the orange and red zones are selected as priority risks, as they represent combinations of high severity and/or high occurrence that may significantly affect product quality, operational continuity, and supply chain performance. Conversely, risks located in the green and yellow zones are considered acceptable or tolerable under current control measures.

Risk Reduction

The risk reduction stage was conducted to determine appropriate risk mitigation actions for controlling the prioritized risks. This stage corresponds to the risk control and treatment phase within the Quality Risk Management (QRM) framework proposed by Sari et al. (2010) and was implemented using the House of Risk (HOR) approach.

First, priority risk events were selected based on the results of the risk evaluation stage, specifically those located in the red and orange zones of the risk map. The associated risk agents were then identified as the primary targets for mitigation. The relationship between risk events and risk agents was assessed using an RE–RA correlation matrix, where correlation values of 2, 1, and 0 represent strong, moderate, and no relationship, respectively.

Using the RE–RA correlation matrix together with the Risk Priority Index obtained in the risk analysis stage, HOR Phase 1 was used to compute the Aggregate Risk Potential (ARP_j) of each risk agent j, defined as $ARP_j = \sum_{i=1}^{n} RPI_i \, R_{ij}$, where $RPI_i = S_i \times O_i$ is the Risk Priority Index of risk event i (its severity S_i multiplied by its occurrence O_i), and R_{ij} is the correlation between risk event i and risk agent j (2 = strong, 1 = moderate, 0 = none). The 33 risk agents with the highest ARP_j values were selected as the dominant risk agents carried forward to HOR Phase 2.

Next, a set of preventive mitigation actions (PA) was formulated through expert discussions and by considering PT X's operational constraints. Each mitigation action was subsequently linked to the identified risk agents using an RA – PA relationship matrix, applying interrelationship scores of 9 (strong), 3 (moderate), 1 (weak), and 0 (no relationship), in accordance with the HOR framework.

In HOR Phase 2, the Total Effectiveness (TE_k) of each mitigation strategy k was calculated as $TE_k = \sum_{j=1}^{m} (ARP_j \times R_{jk})$, where R_{jk} is the RA–PA interrelationship score described above. Mitigation strategies were then ranked in descending order of TE_k, with higher-ranked strategies considered more effective in addressing the dominant risk agents identified in HOR Phase 1. In the complete HOR framework, this effectiveness ranking is further divided by a

Degree of difficulty (D_k) to obtain an effectiveness-to-difficulty ratio ($ETD_k = \frac{TE_k}{D_k}$). Determining D_k requires a separate expert-elicitation exercise involving PT X's management team to assess the organizational, financial, and technical difficulty of implementing each strategy; this exercise was not conducted within the scope of the present study, and the prioritization presented here is therefore based on TE_k only. The computation of D_k and ETD_k is identified as a direction for future research (see Conclusion).

III. RESULT AND DISCUSSION

Risk Identification Results

Risk identification was carried out by mapping operational activities throughout the material handling and spun pile manufacturing process at PT X, from material receiving and storage to internal handling and final delivery. Using a Quality Risk Management (QRM) approach, each activity was reviewed against standard operating procedures to identify potential deviations that could lead to quality failures or operational disruptions. Based on observations, document review, and expert judgment, a total of 66 Risk Events (RE) and 67 Risk Agents (RA) were identified. Due to space limitations, only a representative subset of the identified risks is presented in Table 1. to illustrate the structure and linkage between activities, risk events, and risk agents.

The results indicate that risk events and risk agents are distributed across all stages of the production and internal logistics process. This confirms that quality risks in spun pile manufacturing are not isolated to a single operation but arise from interactions between materials, equipment, methods, and human factors throughout the production system.

Risk Analysis Results

At the risk analysis stage, each identified Risk Event (RE) was evaluated based on its severity (S), while each Risk Agent (RA) was assessed based on its occurrence likelihood (O). The assessment was conducted using expert judgment supported by historical production and quality records from 2020–2022. The resulting values were then combined to calculate the Risk Priority Index (RPI) as the product of severity and occurrence scores.

The analysis indicates that risk events related to product defects and equipment failure during critical manufacturing stages tend to have higher severity scores, as they directly affect product integrity, rework intensity, and delivery reliability. In contrast, risk agents associated with handling operations and equipment availability exhibit relatively high occurrence values due to their frequent exposure in daily operations. Table 2 summarizes selected risk events with the highest RPI values, representing the most critical risks requiring priority attention.

Risk Evaluation Results

To visualize the distribution of risk events according to their severity and occurrence levels, all identified risk events were subsequently mapped into a risk matrix. This mapping facilitates the classification of risks based on their relative criticality and supports the prioritization of mitigation actions. The resulting risk map is presented in Figure 2.

The risk map shows that several risk events are concentrated in the high-severity and high-occurrence zones, particularly those related to lifting equipment, stressing operations, and dimensional accuracy of critical components. These risks were therefore prioritized for further evaluation and mitigation planning in the subsequent stage of the Quality Risk Management analysis.

Risk evaluation was conducted by mapping all identified risk events into a severity–occurrence matrix, as illustrated in Figure X. Each risk event was positioned according to its evaluated severity and occurrence scores obtained from the risk analysis stage. The resulting risk map enables the classification of risks into different priority levels based on color zones, namely green (low risk), yellow (moderate risk), orange (high risk), and red (very high risk).

Based on the risk map, a significant number of risk events are located in the red zone, indicating a combination of high severity and high occurrence. These risks represent critical conditions that may directly impact product integrity, operational safety, and production continuity. Notable risk events in this zone include lifting equipment failure (E1), heading dimension deviation (E11), PC bar rupture during stressing (E42), and product damage during handling and delivery (E54). These risks are therefore classified as top-priority risks requiring immediate mitigation actions.

Several risk events are positioned in the orange zone, reflecting either high severity with moderate occurrence or moderate severity with high occurrence. Examples include material scattering during unloading (E24), overhead crane unavailability (E39), improper concrete slump conditions (E4, E5), and uneven concrete placement (E22). Although less critical than red-zone risks, these events still pose substantial threats to process stability and quality performance and should be addressed through preventive and corrective controls.

Risk events located in the yellow zone represent moderate risks that may affect

Table 1. Representative Risk Events and Risk Agents in Spun Pile Production at PT. X

Activity	Activity Sequence	Activity Performed According to Procedure	Risk Events	Code	Risk Agent	Code
Material Receiving & Storage	Material quality inspection process	Inspection of material samples from suppliers	Material does not meet specified quality	E27	Weather factors affecting material quality	A13
	Natural material storage process	Unloading and loading natural materials into stock	Natural materials scatter during unloading	E24	Stock area capacity exceeded	A60
	Cement material storage process	Transfer of cement from truck to cement silo	Cement partially dispersed into the air	E59	Cement pipeline leakage	A58
	Steel/rebar material storage process	Transfer of steel materials from truck using lifting equipment	Improper storage causing material defects	E64	Storage area overcrowded and narrow	A62
Pile Production	PC bar retrieval process	Retrieving steel materials from stock area	Material falls during lifting	E26	Incorrect lifting method	A20
	Cutting process	Installation of cutting blade & pen stopper according to PC bar diameter by supervisor and operator	Cutting results not as specified	E47	Incorrect work method	A21
	Button Heading Process	Machine readiness inspection	Heading machine unable to operate	E29	Maintenance team does not follow SOP	A65
	Caging Process	Inserting nail wire into drum guide	Nail wire does not enter drum guide	E36	Drum guide lack of maintenance	A12
	Spinning Process	Moving mould to spinning bed	OHC crane unavailable	E39	Poor machine maintenance	A45
	Steam Curing	Strength development	Temperature not achieved	E61	Low-quality coal	A47
	Mould Dismantling	Upper mould removal	Incorrect dismantling method	E32	Operator error	A32
	Product Finishing	Pile repair	Incorrect repair material	E2	Operator error	A32
	Product Stocking	Moving piles to stock area	Incorrect lifting causes product fall	E54	Webbing sling failure	A67
	Loading for Delivery	Loading piles onto trailer	Incorrect lifting causes product fall	E54	Webbing sling failure	A67

operational efficiency or quality consistency if left unmanaged. These risks, such as parameter setting errors (E28, E40, E41) and minor equipment or handling issues, are considered tolerable under current conditions but require routine monitoring and standard control measures.

Meanwhile, risk events in the green zone are classified as low-priority risks with relatively low severity and occurrence. These risks are deemed acceptable within the existing operational framework and can be managed through standard operating procedures and periodic supervision.

Overall, the risk evaluation results demonstrate that priority risks in the spun pile production process at PT X are predominantly associated with lifting operations, dimensional accuracy of critical components, stressing activities, and equipment reliability. The identification of red- and orange-zone risks from the risk map provides a clear basis for determining which risk agents should be prioritized in the subsequent risk mitigation and control planning stage.

Risk Reduction Results

The risk reduction stage aims to formulate and prioritize mitigation actions to control dominant risks affecting product quality and supply chain continuity in the spun pile manufacturing process at PT X. This stage

Table 2. Risk Priority Index (RPI) for Selected Risk Events

Risk Event Description	Code	Severity (S)	Occurrence (O)	RPI (S × O)
Natural materials scatter during unloading	E24	4	4	16
Overhead crane (OHC) unavailable	E39	4	4	16
Heading head dimension not as specified	E11	5	4	20
PC bar breaks during stressing process	E42	5	4	20
Lifting equipment failure	E1	5	5	25

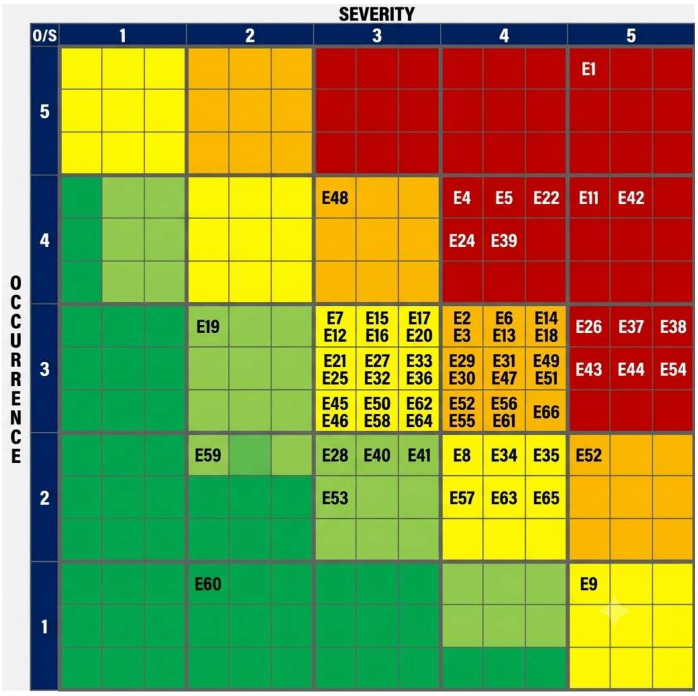

Figure 2. Risk Event Mapping

Table 3. Priority Risk Events and Associated Risk Agents

Code	Risk Event	RPI	Risk Agent	Code
E4	Concrete becomes too fluid during casting (high slump)	16	Operator error in inputting concrete mix design	A29
E5	Concrete sets prematurely during casting (low slump)	16	Operator error in inputting concrete mix design	A29
E22	Natural materials generate airborne dust pollution	16	Absence of protective covers on supplier transportation vehicles	A63
E24	Spillage of natural materials during unloading	16	Storage capacity is insufficient to accommodate incoming materials	A60
E39	Overhead crane (OHC) is not operational	16	Inadequate machine maintenance	A45
E26	Materials fall during lifting operations	15	Improper lifting method	A20
E37	Nail wire fails to attach to PC bar during cage assembly	15	Incorrect longitudinal bar input by the operator	A19
E38	Nail wire does not adhere properly to PC bar	15	Worn welding plate (excessive wear)	A55
E43	Locking nut installation does not meet standard requirements	15	Operator error in tightening locking nuts	A26
E44	Improper mold installation	15	Operator error in bolt installation	A25
E54	Improper lifting process causes product to fall	15	Webbing sling failure	A67
E54	Improper lifting process causes product to fall	15	Inaccurate calculation of lifting method	A64

corresponds to the risk control and treatment phase in the Quality Risk Management (QRM) framework, where identified and evaluated risks are systematically reduced through preventive and corrective actions.

Based on the risk evaluation results, priority risks were selected from the high- and medium-risk categories, as these risks exhibited the greatest potential impact on product defects, work-in-process (WIP2) accumulation, and operational disruptions. The associated risk agents were subsequently identified as the primary sources of risk propagation across multiple production stages, including material handling, fabrication, stressing, spinning, curing, and internal logistics.

Table 3 presents the priority risk events and their corresponding dominant risk agents, which were identified based on the Risk Priority Index (RPI). These risks represent critical operational vulnerabilities that directly affect process stability and quality consistency in spun pile manufacturing. Risk mitigation actions were developed through expert discussions involving plant manager, site engineer manager, quality control, and safety officer. These actions focused on eliminating root causes of risks rather than merely addressing their symptoms. Key mitigation strategies emphasized improvements in standard operating procedures, operator competence, preventive maintenance, material handling practices, and inspection mechanisms.

The proposed improvement strategies were formulated to enhance the control of the identified priority risks and to reduce their potential impact on product quality, production continuity, and supply chain performance. By implementing these strategies, the company is expected to achieve the targeted quality standards and production capacity more consistently. The proposed strategies focus on preventive actions, human resource development, process control, and coordination with external stakeholders. Table 4 presents the proposed improvement strategies and their corresponding codes, which serve as inputs for the risk reduction stage and mitigation prioritization.

The correlation between risk agents and proposed improvement strategies was re-evaluated using the House of Risk (HOR) framework. This step aims to determine how effectively each mitigation strategy addresses the dominant risk agents identified in the previous stages. The relationship between risk agents and mitigation strategies was assessed using an

Table 4. Priority Risk Events and Associated Risk Agents

Proposed Improvement Strategy	Code
Develop and implement a preventive maintenance program	S1
Evaluate and periodically monitor standard operating procedures (SOPs)	S2
Provide operator training every three months	S3
Conduct education programs on effective and efficient productivity	S4
Develop an optimal production scheduling system	S5
Establish cooperative agreements with customers regarding delivery coordination	S6
Identify and select suppliers that are optimal and understand the company's operational conditions	S7
Provide training for technical and engineering teams every six months	S8
Conduct machine readiness inspections before production activities	S9
Ensure the availability of backup critical materials and supporting equipment as needed	S10
Evaluate and improve workflow within the factory	S11
Monitor and evaluate production performance reporting	S12

interrelationship score, as commonly applied in HOR-based studies.

The interrelationship between risk agents and mitigation strategies was assessed using a qualitative scoring system adapted from the Quality Risk Management framework proposed by Sari et al., (2010). In this approach, the strength of the relationship is represented by discrete numerical scores to reflect the extent to which a mitigation strategy can control or reduce a specific risk agent. A score of 9 indicates a strong correlation, suggesting that the mitigation strategy has a significant and direct influence on reducing the impact or occurrence of the risk agent. A score of 3 represents a moderate correlation, implying that the strategy contributes partially to risk reduction. A score of 1 reflects a weak correlation, indicating a limited influence, while a score of 0 denotes no meaningful relationship between the risk agent and the mitigation strategy.

These scores were assigned through expert judgment involving personnel from production, quality, maintenance, and engineering functions at PT X. The resulting correlation matrix provides a structured representation of the relationships between dominant risk agents and the proposed improvement strategies and serves as the basis for prioritizing mitigation actions in the risk reduction stage. Table 5 presents the correlation between risk agents and improvement strategies, illustrating the relative strength of each relationship used in the House of Risk analysis. The full description corresponding to each of the 33 dominant risk agent codes used in Table 5 is provided in Table 6.

In the original House of Risk Phase 2 prioritization, improvement strategies were ranked using the raw sum of correlation scores ($\sum_{j=1}^{m} R_{jk}$)between each strategy and the dominant risk agents, without accounting for the relative severity and likelihood of the risk agents themselves. To address this limitation, the prioritization was revised by weighting each risk agent's correlation with a strategy by its Aggregate Risk Potential (ARP_j), computed in HOR Phase 1 as $ARP_j = \sum_{i=1}^{n} RPI_i \, R_{ij}$, where $RPI_i = S_i \times O_i$ is the Risk Priority Index of risk event i and R_{ij} is its correlation with risk agent j. The Total Effectiveness of strategy k is then $TE_k = \sum_{j=1}^{m} (ARP_j \times R_{jk})$. Ranking the twelve strategies by TE_k (Table 5) yields the order S2 (TE = 2,292) > S3 (TE = 2,286) > S1 (TE = 1,980) > S4 (TE = 1,914) > S9 (TE = 1,740) > S10 (TE = 1,332) > S8 (TE = 1,104) > S7 (TE = 648) > S11 (TE = 594) > S12 (TE = 366) > S5 (TE = 360) > S6 (TE = 150). Compared with the original raw-correlation ranking, in which preventive maintenance (S1) ranked first, the ARP-weighted ranking places periodic SOP evaluation and monitoring (S2) and regular operator training (S3) ahead of S1. This shift occurs because the dominant risk agents most strongly correlated with S2 and S3, including lack of operator focus while working (A40, ARP = 96), incorrect work method (A21 and A32, ARP = 48 each), and overloading (A16, ARP = 50), carry comparatively high Aggregate Risk

Table 5. Risk Agents Risk Agent–Improvement Strategy Correlation Matrix and ARP-Weighted Total Effectiveness Ranking (HOR Phase 2)

		Improvement Strategies											
		S1	S2	S3	S4	S5	S6	S7	S8	S9	10	S11	S12
	A2	9	3					3	3	9	9		
	A3				9	9						3	9
	A6	9									9		
	A7		3	3	3				3				
	A11	9	3										
	A14	9	9		3					9			
	A16		3	3	3		3					9	3
	A17		3	9	3				9				
	A19			3	3								
	A20		9	9					9				
	A21		9	3									
	A25			3	3					3			
	A26			3	3					3			
	A29			3	3					3			
	A32			3	3					3			
Risk Agent	A33			3	3					3			
	A34			3	3					3			
	A35			3	3					3			
	A37			3	3					3			
	A39		9						9				
	A40			3									
	A45												
	A47		3					9					
	A55	9								9	9		
	A56	9	3										
	A57		9	3									
	A60					9		9			9		
	A61	9	3	9									
	A63		3										
	A64				9					9			
	A65	9											
	A66				9						9	3	
	A67	3							9		9		
Correlation	75	72	69	66	18	3	21	42	60	54	15	12	
Rank	1	2	3	4	9	12	8	7	5	6	10	11	

Potential, reflecting their association with risk events of high severity and frequent occurrence across multiple production stages. By contrast, several risk agents most strongly addressed by preventive maintenance (S1), such as heading-dimension non-conformance (A11, ARP = 40) and welding-plate wear (A55, ARP = 30), have comparatively lower ARP values. The revised ranking therefore indicates that, although equipment-related failures remain an important contributor to risk (S1 still ranks third), procedural non-compliance and operator-related human factors are, in aggregate, associated with greater accumulated risk potential and should be prioritized first in the mitigation roadmap. This is consistent with the House of Risk framework of Pujawan and Geraldin (2009), in which mitigation priority is intended to reflect the cumulative risk that each agent contributes across all related risk events, rather than the number or strength of its correlations alone. Strategies oriented toward external coordination, such as customer delivery agreements (S6) and supplier selection improvement (S7), continue to rank lowest, indicating that internal process discipline and human-resource interventions offer the most immediate risk-reduction impact at PT X. It should be noted that the present ranking reflects effectiveness (TE_k) only; a complete HOR Phase 2 prioritization would additionally weight each strategy by its Degree of Difficulty (D_k) to obtain an Effectiveness-to-Difficulty ratio ($ETD_k = \frac{TE_k}{D_k}$), as proposed by Pujawan and Geraldin (2009). Because D_k requires a dedicated expert-elicitation exercise involving the company's management team, it was not conducted within the scope of the present revision and is identified as a direction for future research.

The implementation of the Quality Risk Management (QRM) framework, operationalized through the House of Risk approach, demonstrates its practical applicability in managing complex and interrelated risks within precast spun pile manufacturing. By systematically integrating risk identification, risk analysis, risk evaluation, and risk reduction, the framework enables the company to trace quality failures and supply chain disruptions back to their underlying risk agents. The results show that

Table 6. Risk Agent (RA) Codes Referenced in Table 5 (Dominant Risk Agents Used in HOR Phase 2)

Code	Risk Agent (RA) Description
A2	Impact wrench (bolt-tightening tool) pressure is weak
A3	Product stock area is full
A6	Sleeper bearing is damaged
A7	Eyebolt quantity is less than required
A11	Heading dimension does not meet specification
A14	Calibration is rarely performed
A16	Overloading
A17	Error in work method
A19	Operator error in inputting longitudinal bar data
A20	Incorrect lifting method
A21	Incorrect work method
A25	Operator error in installing bolts
A26	Operator error in installing nuts
A29	Operator error in inputting the mix design (concrete casting stage)
A32	Operator error in work method
A33	Operator error in installing the joint plate
A34	Operator error in machine parameter setting
A35	Operator error in equipment installation process
A37	Operator error when setting up the caging machine
A39	Technical team error in lifting calculation
A40	Lack of operator focus while working
A45	Insufficient machine maintenance
A47	Coal material is of insufficient quality (curing process)
A55	Welding plate is worn (thin)
A56	Wheel is obstructed by spilled concrete
A57	Incorrect placement of the vise and heading hammer
A60	Material stock capacity is exceeded
A61	Pulling force exceeds the specified capacity
A63	Supplier's transport vehicles lack protective covers
A64	Inaccurate lifting-method calculation
A65	Maintenance team does not perform maintenance according to SOP
A66	Volume of coal used is not proportional to the volume of product being cured
A67	Webbing sling breaks

many critical risks originate from recurring operational practices, such as improper lifting methods, inadequate machine maintenance, and operator-related errors, which propagate across multiple production stages. This finding reinforces earlier studies suggesting that quality risks in manufacturing systems are rarely isolated events but are instead the result of cumulative interactions between human, machine, material, and method-related factors (Firdaus et al., 2019; Pujawan & Geraldin, 2009; Sari et al., 2010).

From a managerial perspective, the framework provides a structured decision-support tool that allows PT X to prioritize mitigation strategies based on their relevance and potential effectiveness rather than relying on reactive corrective actions. The correlation analysis between risk agents and improvement strategies highlights that preventive maintenance, periodic training, SOP evaluation, and machine readiness inspections are consistently linked to multiple dominant risk agents. This indicates that risk reduction efforts should focus on strengthening systemic controls and organizational discipline rather than addressing individual defects in isolation. Moreover, the framework supports alignment between operational risk control and strategic initiatives, such as supplier coordination and production scheduling, thereby contributing to improved operational stability and reduced WIP2 accumulation. Overall, the application of this integrated QRM-based framework offers a replicable approach for similar precast and heavy manufacturing industries seeking to manage quality and supply chain risks in a structured and resource - efficient manner.

IV. CONCLUSION

This study demonstrates that the application of a Quality Risk Management (QRM) framework provides a systematic approach for identifying, evaluating, and mitigating quality and supply chain risks in precast spun pile manufacturing at PT X. The results indicate that dominant risks are mainly associated with human factors, equipment reliability, and process control, which collectively contribute to product defects and work-in-process (WIP2) accumulation despite relatively low defect rates. Mitigation strategies focusing on preventive maintenance, SOP evaluation, and regular training were identified as the most critical actions for improving operational stability. However, this study is limited by its single-case design and reliance on expert judgment for risk assessment, which may introduce subjectivity and constrain the generalizability of the findings. Future research is recommended to validate the proposed framework through multi-case studies, integrate quantitative performance indicators such as cost impact and lead-time reduction, and explore the use of data-driven or digital risk monitoring tools to enhance the robustness and scalability of quality and supply chain risk management in precast and other capital-intensive manufacturing industries.

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