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Risk Mitigation Analysis for Tofu Production Process to Minimize Product Defects Using House of Risk Approach †

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Abstract: Enhancing the sustainability of manufacturing systems requires reducing product defects through effective management of risks that impact product quality. A crucial component in minimizing defects is the adoption of robust risk management strategy. This study examines risk mitigation in the tofu production process to reduce product defects, by employing the House of Risk (HOR) framework to prioritize mitigation efforts. Data were collected through observations, in depth interviews, and focus group discussions, following the two-step HOR methodology. The analysis identified 12 risk events and seven risk agents, along with six prioritized mitigation strategies, based on the Aggregate Risk Potential (ARP) ranking of the identified risk agents. The highest-priority strategy involves developing standardized work instructions for the tofu production process. This study offers practical insights for companies seeking to lower defect rates, thereby supporting the sustainability of their manufacturing systems.

Keywords: risk mitigation; product defects; HOR method; sustainable manufacturing

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1. Introduction

In the era of Industry 4.0, company management is tasked with achieving sustainable production, which emphasizes reducing waste, minimizing pollution, and mitigating other adverse environmental impacts [1,2]. Sustainable production not only aligns with global environmental objectives but also significantly enhances the operational efficiency and long-term viability of manufacturing companies [3]. Improving sustainability in manufacturing systems can be effectively realized by minimizing product defects and reducing production disruptions, both of which contribute to reducing the environmental footprint associated with manufacturing activities [4].

The MD Tofu Factory, located in West Bandung and specializing in the production of yellow tofu, faces a persistent challenge of high defect rates in its production process. Data collected from 1 April to 20 April 2024, revealed a total of 6404 defective pieces, far exceeding the factory's tolerance limits. As despicted in Figure 1, the defect rate surpasses the company's acceptable thresholds, resulting in non-compliance with established product standards [5,6]. Such non-conformance indicates that products are not consistently meeting customer expectations, thereby impacting customer satisfaction and potentially leading to financial losses. In light of these challenges, it is essential to identify and address the root risk factors contributing to quality defects within the production process [7].

Several risks have been identified as directly impacting product quality. Previous research has highlighted that various risk factors in production processes can lead to defects in the final product [8,9]. A significant challenge for MD Tofu Factory lies in the absence of a comprehensive risk management strategy designed specifically for the tofu production process. Without an effective risk mitigation framework, the factory continues to encounter quality-related issues, further undermining its operational efficiency and product reliability.

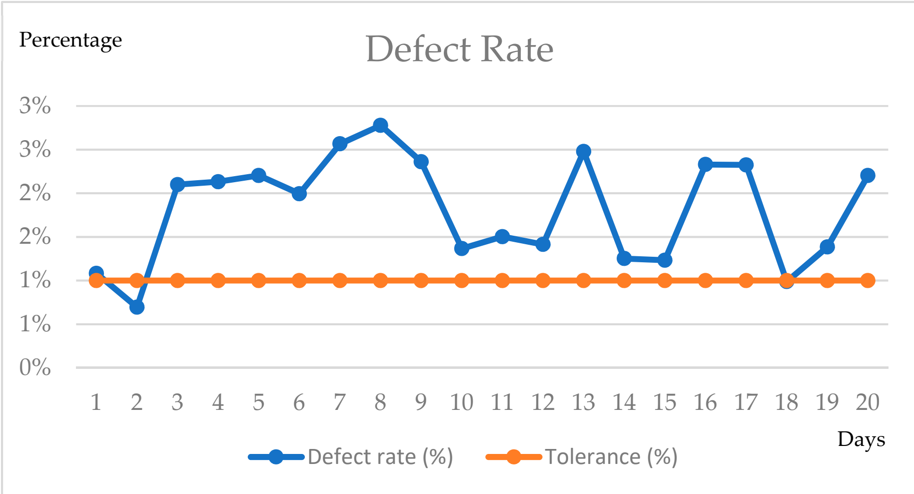

Figure 1. Defect rate.

The high defect rate at MD Tofu Factory poses a significant threat to production efficiency, customer satisfaction, and overall competitiveness. Continued production inefficiencies stemming from defects and quality inconsistencies can lead to financial losses and reputational damage [10]. In line with the factory's objectives to achieve operational sustainability and adopt Industry 4.0 practices, there is an urgent need to implement a strategic approach to risk mitigation in the tofu production process. Promptly addressing this issue is crucial to ensuring product quality, reducing production costs, and enhancing customer satisfaction.

Based on ISO 31000:2018, risk management aims to increase the likelihood of success in managing projects and developing products [11]. Effective risk management involves identifying, analyzing, and controlling risks to protect workers, the environment, and the community. Additionally, it implements risk mitigation strategies aimed at minimizing both the likelihood and impact of the identified risks [12,13]. Risk mitigation, as a critical component of this process, involves making decisions based on comprehensive risk and exposure assessments to minimize the probability of risk occurrence and/or mitigate their negative impacts [13].

To prioritize risk mitigation actions, this research utilizes the house of risk (HOR) approach. The HOR method has been chosen for this study due to its structured framework for identifying and prioritizing risk mitigation actions. The HOR method integrates aspects of failure mode and effect analysis (FMEA) with elements of the house of quality (HOQ), making it particularly well-suited for comprehensive risk analysis and the strategic prioritization of preventive measures [14]. Its systematic approach to identifying and ranking risk agents based on their impact ensures a focused strategy for addressing risks that contribute to product defects [15]. Previous applications of the HOR method in contexts such as risk mitigation for hijab production [16] and reducing rework in the furniture industry [14] further demonstrate its versatility and effectiveness.

This study aims to provide essential insights and practical solutions reduce defect rates at the MD Tofu Factory. By identifying critical risk factors and developing targeted mitigation strategies, this research offers actionable recommendations to enhance product quality, reduce waste, and improve operational consistency. These advancements support the factory's sustainability objectives and align with the broader goals of Industry 4.0, fostering efficient and environmentally friendly production practices.

The primary goal of this study is to analyze and implement risk mitigation strategies for the tofu production process, with the aim of minimizing product defects and supporting sustainable manufacturing practices. The HOR framework will be utilized to prioritize risk mitigation actions according to their potential impact. Expert input from company stakeholders with in-depth knowledge of tofu production will be incorporated into the analysis, ensuring that the proposed strategies are practical, effective, and aligned with the operational goals of MD Tofu Factory.

The findings of this study highlight key risk agents contributing to defects and present prioritized mitigation strategies, including the development of standardized work instructions and process improvements. The paper is organized as follows: Section 2 provides a comprehensive literature review and theoretical background, Section 3 outlines the research methodology, Section 4 presents the results and discusses the key findings, and Section 5 concludes the study.

2. Literature Review

The concept of sustainable production is increasingly important in the context of Industry 4.0, which emphasizes digital transformation, automation, and interconnected systems [17]. Sustainable production seeks to minimize environmental impact through resource optimization, waste reduction, and energy efficiency while maintaining profitability and operational effectiveness [18,19]. Research shows that minimizing product defects and enhancing process stability are key to achieving sustainability goals in manufacturing [20]. For instance, reducing production waste directly reduces costs and resource consumption, improving both ecological and economic outcomes [21]. This study applies sustainable production principles to reduce defects in tofu manufacturing, aligning with broader environmental and economic objectives.

Tofu production is a delicate process that can be significantly affected by various factors such as raw material variability, processing conditions, and human error [22]. Quality defects in tofu, such as inconsistencies in texture, color, and taste, can adversely affect consumer satisfaction and product marketability [22]. Previous studies have highlighted that effective quality control and robust risk management strategies are essential for maintaining product consistency [23]. The high defect rate at the MD Tofu Factory highlights deficienciesin its current quality management practices, necessitating a focused risk mitigation approach to improve production outcomes [24].

Risk management, as outlined in ISO 31000:2018, involves systematically identifying, assessing, and mitigating risks to enhance project success and operational efficiency [25]. Key components of this framework include risk identification, risk analysis, and the development of mitigation strategies to minimize both the likelihood and impact of risks [26]. Effective risk management protects workers, the environment, and stakeholders by proactively addressing potential threats [27]. This study leverages ISO 31000:2018 principles to guide the identification and prioritization of risks in tofu production.

The HOR methodology combines components of FMEA and the HOQ, offering a systematic framework for effective risk management [14,15]. The HOR approach comprises two main phases: (1) identifying risk events and their corresponding risk agents and (2) formulating prioritized mitigation strategies based on the aggregated risk priority (ARP) scores [28]. By combining risk analysis with strategic prioritization, HOR enables decision-makers to allocate resources effectively and focus on the most critical risk agents [28].

Previous studies have demonstrated the effectiveness of the HOR approach in managing risks across various sectors, including the food industry [29], textile production [30], and manufacturing operations [15]. This study applies HOR to identify and mitigate risks in tofu production, thereby improving quality consistency and reducing defect rates.

Research on HOR applications highlights its versatility in addressing complex production risks. Armala et al. (2024) used HOR to develop risk mitigation strategies for hijab production, resulting in significant reductions in production defects [16]. Winarso and Jufriyanto (2020) employed HOR to minimize rework and quality costs in the furniture manufacturing process [14]. These cases demonstrate the potential of HOR to systematically prioritize and mitigate risks in diverse manufacturing contexts, reinforcing its suitability for this study's objectives.

Despite the demonstrated effectiveness of the HOR methodology, there is limited research applying this framework specifically to tofu production. This study fills this gap by analyzing risk factors and developing mitigation strategies tailored to the unique challenges of tofu manufacturing. By improving product quality and reducing defects, the study offers practical recommendations that contribute to the operational sustainability of tofu producers and align with the broader goals of Industry 4.0.

3. Research Methodology

This study employed a combination of observational data collection, in-depth interviews, and focus group discussions to identify and analyze the risks and processes involved in tofu production at MD Tofu Factory. Data were collected from three expert respondents—the director, head of production, and a production operator—who were selected due to their comprehensive knowledge of the tofu production process. The study utilized the HOR framework as a risk assessment tool to determine and prioritize actions for risk mitigation. The HOR framework is comprised of two main stages, HOR 1 and HOR 2, as shown in Figure 2 [31].

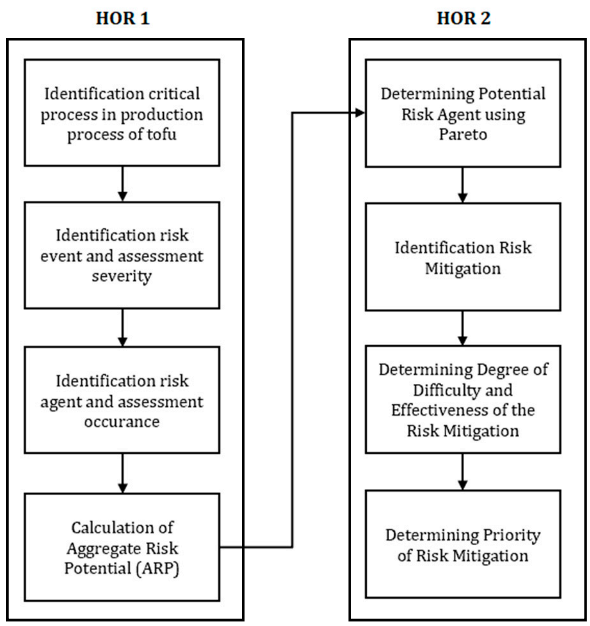

Figure 2. Methodology of research.

The HOR 1 stage focuses on identifying and assessing risks within the production process. Expert began by identifying critical production processes that significantly impact the quality of tofu. They then identified potential risk events, assigning each a severity rating (S_i) to reflect the impact on production quality. Subsequently, they identified risk agents—the underlying causes or triggers of these risk events—and rated their occurrence levels (O_j) to indicate how frequently they arise. This step aimed to determine the frequency of risk agent occurrences. To assess the influence of risk agents on risk events, the correlation (R_{ij}) between the two was assessed using a scoring system: 0 for no correlation, 1 for low correlation, 3 for medium correlation, and 9 for high correlation [32]. Table 1 presents the criteria used to rate the severity of risk events and the occurrence frequency of risk agents. The aggregate risk priority (ARP) score was then calculated using the equation:

$$ARP_j = O_j \sum S_i R_{ij} \quad (1)$$

Table 1. Description of activities [33].

Rating	Severity Criteria	Occurrence Criteria
1	No	Almost Never
2	Very Slight	Remote
3	Slight	Very Slight
4	Minor	Slight
5	Moderate	Low
6	Significant	Medium
7	Major	Moderately High
8	Extreme	High
9	Serious	Very High
10	Hazardous	Almost Certain

In the HOR 2 stage, the focus shifts to developing and prioritizing risk mitigation strategies. Experts utilized Pareto analysis to identify and rank significant risk agents based on their contribution to the overall ARP score. Potential mitigation actions were then proposed to address each prioritized risk agent. The degree of difficulty (D_k) associated with implementing each mitigation action was assessed on a scale of 3 (easy to apply), 4 (somewhat easy to apply), or 5 (difficult to apply) [33]. The correlation between risk mitigation actions and corresponding risk agents (E_{jk}) was then scored using the same system as in HOR 1 [33]. To measure the overall impact of each proposed action, the total effectiveness (TE_k) was calculated using:

$$TE_k = \sum ARP_j E_{jk} \quad (2)$$

Finally, the effectiveness-to-difficulty (ETD_k) ratio was calculated to prioritize risk mitigation actions based on their relative effectiveness and ease of implementation, using the formula:

$$ETD_k = \frac{TE_k}{D_k} \quad (3)$$

This methodological approach ensures a systematic and practical way to identify, prioritize, and implement risk mitigation strategies, leveraging expert insights and the structured HOR framework to improve production processes and reduce defects.

4. Result and Discussion

The findings of the study are presented in this section, focusing on the identification of critical processes, risk events, and agents, as well as the formulation of effective risk mitigation strategies for MD Tofu Factory using the HOR methodology.

Based on observational data, Figure 3 depicts the operation chart of the tofu production process, while Table 2 outlines the key activities. A critical process is defined as any process that significantly impacts product quality and determines whether the product meets established standards. Through in-depth interviews with expert respondents, this study identified 14 operation processes, of which 11 were deemed critical. The O-13 activity represents a process in which operations and inspections are conducted simultaneously.

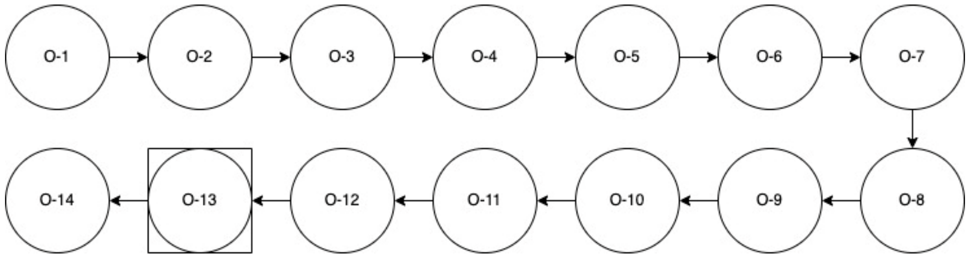

Figure 3. Operation chart.

Table 2. Detail of activities (based on operation chart).

Code	Description	Critical Process (Yes/No)
O-1	Measuring the weight of soybean raw materials	Yes
O-2	Soaking soybean seeds	Yes
O-3	Grinding soybeans using a machine	Yes
O-4	Adding water to the milling machine	No
O-5	Transferring the grinding results to the boiling place	Yes
O-6	Boiling soybean seeds with firewood	No
O-7	Filtering the boiled product to another place (barrel)	No
O-8	Adding soybean juice with vinegar	Yes
O-9	Shaping the tofu	Yes
O-10	Compacting/pressing tofu	Yes
O-11	Cutting tofu into small pieces	Yes
O-12	Boiling tofu with natural coloring or turmeric water	Yes
O-13	Draining, cooling and inspecting yellow tofu	Yes
O-14	Packaging	Yes

Table 3 presents the identified risk events for each critical process, along with their severity ratings based on established criteria. Meanwhile, Table 4 lists the risk agents, along with their occurrence levels. The HOR method allows one risk agent to contribute to multiple risk events, reflecting its complex impact within the production process.

Table 3. Risk event identification.

Activity	Risk Event	Code	Severity (S_i)
Measuring the weight of soybean raw materials	Measurement error	E1	6
Soaking soybean seeds	Soybeans soaked for too long, potentially causing unpleasant scent	E2	8
	Soaking water contaminated with rainwater	E3	8
Grinding soybeans using a machine	The milling machine is broken, which causing a pile-up of previous workstations	E4	10
Transferring the grinding results to the boiling place	Products contaminated with foreign objects	E5	6
Adding soybean juice with vinegar	Incorrect dosage of vinegar	E6	9
Shaping the tofu	Products contaminated with saliva and sweat	E7	10
Compacting/pressing tofu	When the coagulation process is not perfect, and the tofu is destroyed when pressed	E8	10

Table 3. *Cont.*

Activity	Risk Event	Code	Severity (S_i)
Cutting tofu into small pieces	Errors in cutting tofu so that it becomes waste	E9	8
Boiling tofu with natural coloring or turmeric water	Errors in the dosage of coloring in the boiling water so that the color of the tofu is too pale	E10	6
Draining, cooling, and inspecting yellow tofu	Tofu is destroyed in the process of being transferred to the shelf	E11	9
Packaging	Packaging leaks or does not meet standards	E12	9

Table 4. Risk agent identification.

Risk Agent	Code	Occurence (S_i)
Operators are not careful	A1	10
Rainwater enters the soybean seed soaking place	A2	6
Operators do not perform maintenance on the machine properly	A3	10
Operators do not maintain the cleanliness of raw materials	A4	6
Operators do not measure properly	A5	6
Operators do not use mouth guards	A6	8
Inspection process is not carried out before the pressing process is carried out	A7	10

Table 5 illustrates the calculation of the ARP. The correlation between risk events and risk agents (R_{ij}) was assessed by the experts, using a scale to indicate the strength of their relationship (0 for no correlation, 1 for low, 3 for medium, and 9 for high correlation). For example, the relationship between the risk agent "operator error" (A1) and the risk event "measurement error" (E1) was deemed highly correlated. Risk agents were ranked based on their ARP scores, with "operator error" (A1) emerging as a top priority.

Table 5. Calculation of ARP scores.

Risk Agent	Risk Event												Occurrence Rating	ARP	Ranking
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12			
A1	9	9	0	0	3	3	3	0	9	9	9	9	10	4890	1
A2	0	0	9	0	0	0	0	0	0	0	0	0	6	432	6
A3	0	0	0	9	0	0	0	0	0	0	0	0	10	900	2
A4	0	0	0	0	9	0	0	0	0	0	0	0	6	324	7
A5	9	0	0	0	0	9	0	0	0	0	0	0	6	810	4
A6	0	0	0	0	0	0	9	0	0	0	0	0	8	720	5
A7	0	0	0	0	0	0	0	9	0	0	0	0	10	900	3
Severity Rating	6	8	8	10	6	9	10	10	8	6	9	9			

The Pareto diagram, shown in Figure 4, was employed as a statistical tool to prioritize the most impactful risk agents. The results indicate that risk agents A1 (operator error), A3, and A7 are the most critical and should be prioritized for mitigation efforts.

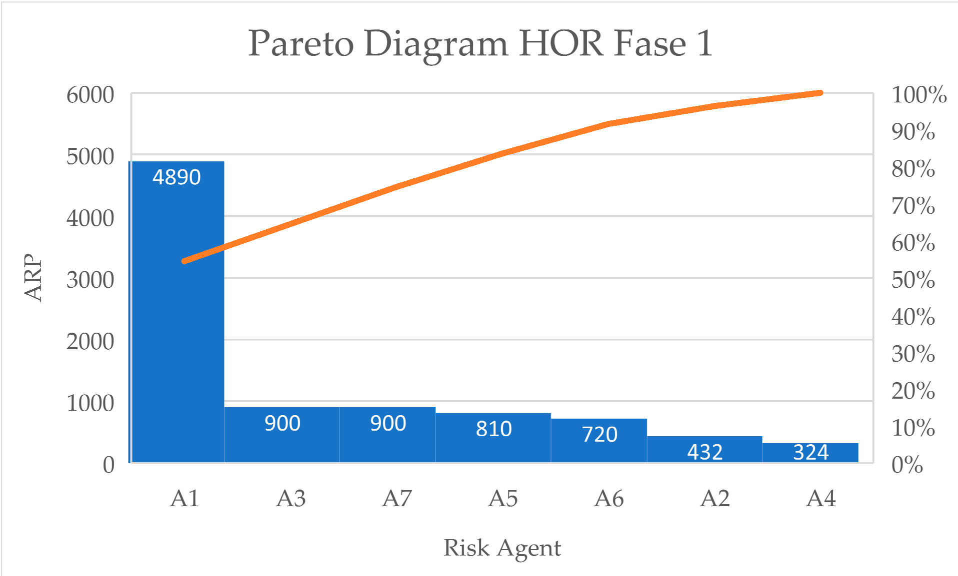

Figure 4. Pareto diagram.

Table 6 outlines the top three risks and their corresponding mitigation strategies (preventive action/PA_k), derived through discussions with expert respondents. Each risk agent may necessitate one or more preventive measures to effectively mitigate associated risks.

Table 6. Risk mitigation.

Risk Agent	Code	Risk Mitigation	Code
Operators are not careful (operator error)	A1	Create work instructions for each process Provide training	PA1 PA2
Operators do not perform maintenance on the machine properly	A3	Create SOP for machine maintenance	PA3
		Create routine machine maintenance schedules	PA4
Inspection process is not carried out before the pressing process is carried out	A7	Create tools to help in the pressing process	PA5
		Create inspection work instructions	PA6

The degree of difficulty for implementing each preventive action and the calculation of the effectiveness-to-difficulty (ETD) ratio are presented in Table 7. First, experts evaluated the correlation between risk mitigation measures and risk agents (E_{jk}). For instance, there was a strong correlation between "operator error" (A1) and the development of work instructions. The total effectiveness (TE_k) was calculated for each mitigation strategy. Experts then evaluated the degree of difficulty (D_k) for each action based on company conditions, using a scale where 3 represented "easy to apply", 4 indicated "somewhat easy", and 5 denoted "difficult". For instance, creating a new tool (PA5) was rated as difficult due to budgetary constraints. Risk mitigation measures were then ranked based on their ETD scores.

Table 7. Calculation of ETD.

Risk Agent	Preventive Action (Risk Mitigation)						ARP
	PA1	PA2	PA3	PA4	PA5	PA6	
A1	9	9	1	0	9	9	4890
A3	1	3	9	9	0	0	900
A7	9	3	0	0	9	9	900

Table 7. *Cont.*

Risk Agent	Preventive Action (Risk Mitigation)						ARP
	PA1	PA2	PA3	PA4	PA5	PA6	
Total Effectiveness	53,010	49,410	12,990	8100	52,110	52,110	
Degree of Difficulty	3	4	3	3	5	3	
ETD	17,670	12,352.5	4330	2700	10,422	17,370	
Ranking	1	3	5	6	4	2	

The results indicate that creating work instructions for each process, including inspection procedures, is the most effective risk mitigation strategy. Work instructions serve as detailed, step-by-step guides, enabling operators to perform their tasks correctly and safely. Previous studies have demonstrated that well designed work instructions significantly reduce defects and enhance operational consistency [34]. Thus, developing and implementing detailed work instructions was selected as a primary mitigation measure for minimizing defects.

In comparing the existing and proposed solutions, four key defects were identified as critical to quality (CTQ) for the MD Tofu Factory's production process: excessively thin product width, stained products, fragile texture, and unpleasant odor. The most common production failures led to defects related to product width and texture. During data collection from 1 April to 20 April 2024, a total of 6404 defective products were recorded. Given an estimated loss of IDR 500 per defective unit, this equates to a total financial impact of IDR 3,202,000 over 20 days.

To mitigate these issues, this study proposed the development of a standard operating procedure (SOP) focused on equipment maintenance and process improvement. By addressing two out of the four CTQs, the proposed SOP is expected to reduce defect occurrences by up to 50%, translating to cost savings of approximately IDR 1,601,000. This reflects a notable reduction in defect-related costs and an improvement in operational efficiency.

The economic viability of the proposed solution was assessed through a benefit–cost ratio (BCR) analysis. Implementation costs include a fee of IDR 300,000 for outsourced technician services and IDR 1,100,000 for part maintenance and repairs, resulting in a total cost of IDR 1,400,000. The BCR calculation yields a ratio of 1.143 (1,400,000/1,601,000), indicating that the anticipated benefits surpass the associated costs, confirming the economic value of the proposed SOP as a cost-effective measure to reduce defects and enhance product quality.

This study employed the HOR framework to prioritize risk mitigation efforts. HOR combines the methodologies of FMEA and the HOQ, making it a systematic and adaptable tool for risk management across various types of organizations. Although the types of risks, agents, and mitigation measures may vary, the procedure remains consistent, allowing for broad applicability [35]. However, HOR has limitations such as its reliance on accurate data for identifying and analyzing risks, as well as the time-consuming nature of expert consultations during data collection and risk evaluation.

Risk management is an ongoing, dynamic process that must adapt to new risk events as they arise [36]. Organizations should periodically review and update their risk management strategies to ensure alignment with current operational objectives [37]. The integration of HOR with technological tools can further enhance the risk management process, as demonstrated by studies such as those by Salma et al. [38]. Consequently, this study recommends that MD Tofu Factory regularly reassess and update its risk mitigation strategies, leveraging technological advancements to enhance the process.

5. Conclusions

This study analyzed risk mitigation strategies in the tofu production process minimize product defects. The HOR framework was employed to prioritize mitigation actions, identifying 12 risk events and seven risk agents. The findings revealed that the most effective strategy is the creation of detailed work instructions for each process, including inspection procedures. These instructions aim to guide operators in performing their tasks accurately and safely, a practice supported by previous research as a means to significantly reduce defects and improve operational consistency.

In comparison to the existing processes, the study identified four CTQ defects—excessively thin product width, stained products, fragile texture, and unpleasant odor. These defects were primarily linked to product width and texture. To address these issues, the study proposes a SOP focused on equipment maintenance and process improvements, expected to reduce defects by up to 50%. A BCR analysis confirmed the economic viability of the SOP, showing that the benefits outweigh the implementation costs, demonstrating its effectiveness and economic feasibility.

While the HOR framework provided valuable insights, it has some limitations, such as its reliance on accurate data and the time-consuming nature of expert consultations during risk evaluation. Nonetheless, HOR remains a useful tool for systematic risk management, and this study recommends that MD Tofu Factory periodically review and update its risk mitigation strategies. Incorporating technological innovations into the risk management process could further enhance its effectiveness.

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