QUALITY CONTROL ANALYSIS OF SUGAR PRODUCTION PROCESS WITH FTA AND FMEA METHODS IN PT XYZ

Mardila Nur Imamah[1]
Universitas Pembangunan Nasional "Veteran" Jawa Timur, Indonesia
mardilanurr@gmail.com

Rr. Rochmoeljati[2]
Universitas Pembangunan Nasional "Veteran" Jawa Timur, Indonesia
rochmoeljati@gmail.com

Abstract

One of the sugar factories built by the Indonesian state as an effort to revitalize the national sugar industry through the use of modern technology is PT XYZ. However, this sugar factory is experiencing problems with the results of testing the production of white crystal sugar which has defects that are not in accordance with the quality requirements of white crystal sugar with SNI number 3140-3: 2020. Defects that occur include defects in sugar moisture content, sugar solution color, grain size, and sugar crystal uniformity. This study was conducted to determine the factors that can affect the occurrence of defects in the white crystal sugar production process at PT XYZ and how the proposed improvements can be implemented to control the quality of white crystal sugar products at PT XYZ. The methods used in this research are the Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA) methods. Based on calculations using the Fault Tree Analysis method, the calculated probability results for each type of defect, namely large grain defects, moisture content, color, and sugar crystal uniformity, are 0.000657%, 0.000889%, 0.001597%, and 0.000662%, respectively. The FMEA method obtained a large grain type defect with the highest RPN value of 120 (High). Large grain type defects cause white crystal sugar to not conform to market specifications and dissolve more slowly. In the second rank, there is a defect in water content with an RPN value of 112 (medium). Quality control should be carried out regularly and continuously so that it can be a reference for continuous improvement in the future.

Keywords: FMEA, FTA, Quality Control, White Crystal Sugar

INTRODUCTION

The sugar industry in Indonesia is deeply intertwined with the history of colonialism and economic growth. The establishment of sugar factories in Indonesia was primarily driven by the Dutch colonialists' economic interests, aiming to monopolize the country's natural resources, particularly sugar cane, for European sugar production. As time progressed, the integration of advanced modern technology was anticipated to considerably enhance sugar production quality and operational efficiency beyond what the best available equipment could achieve. High-quality production serves as a strategic asset in boosting the industry's competitive edge (Nurfauzi et al., 2023).

PT XYZ stands as one of the sugar factories established to revitalize the national sugar industry through modern technology in producing white crystal sugar. Nevertheless, during production, the factory faces issues related to the quality of white crystal sugar produced in the milling process, frequently resulting in defects that fail to meet the National Standardization Agency's standards for white crystal sugar, marked by SNI 3140-3: 2020. These defects include issues like sugar moisture content exceeding the limit of ≤ 0.1%, sugar solution color beyond the 76-300 IU range, grain size outside the 0.8-1.2 mm parameters, and sugar crystal uniformity surpassing the 35% threshold. Such production defects have persisted for a prolonged period and have been growing yearly, prompting this study to aid companies in analyzing the factors that impact sugar product quality.

The study's objective is to identify the factors contributing to defects and offer improvement recommendations to enhance PT XYZ's white crystal sugar products using Fault Tree Analysis (FTA) and Failure Mode and Effect Analysis (FMEA) methods. FTA is employed to dissect product defects and the factors contributing to these issues (Nuruddin and Dharma, 2023). Within the company, defects appear as issues in moisture content, color, grain size, and crystal uniformity. The purpose of employing FTA is to pinpoint the fundamental causes of failure in systems or processes, evaluate the interplay of various failure-inducing factors comprehensively, estimate the likelihood of failure based on involved factors, aid in system design by mitigating risks, and enhance system safety and efficiency with risk reduction recommendations. Conversely, the FMEA method, utilizing the RPN value, aims to curb failure by ranking failure modes and zeroing in on the most critical issues for rectification (Firmansyah and Nuruddin, 2022). Additionally, FMEA assesses the impact of the defects and proposes remedial actions to help the company improve sugar quality during production. Utilizing FTA and FMEA together provides a holistic approach to quality control, pinpointing defect causes while offering tailored improvement suggestions (Ridwan, 2023). Hence, it is crucial to tackle it utilizing the FTA and FMEA techniques, which offer companies alternative strategies for enhancing product quality, as highlighted by research from Desmafianti and Fauzzia in 2021.

REVIEW OF LITERATURE

Product quality refers to how well a good or service performs its function to deliver results that meet or surpass customer expectations (Pasaribu, 2022). When a product exhibits high quality, it encourages customers to repurchase, demonstrating both their loyalty and satisfaction with the product offered. Maintaining product quality is crucial for companies to uphold product standards and aim for consumer satisfaction (Desmafianti & Fauzzia, 2021).

Beyond the product's physical appearance, companies must also ensure the quality of taste and presentation. If these aspects are satisfactory, then the product is well-suited for the market.

Setting quality standards aims to reduce accidents, defects, and customer complaints (Walujo et al., 2021). For white crystal sugar products, these standards are dictated by the BSNI institution under the SNI 3140.3: 2020 category, with parameters such as sugar color quality being <3000 IU, grain size being <1.2 mm, and moisture content being <0.1%. Quality control involves activities that confirm a process is performed according to standards and results in products that meet desired quality levels (Lestari & Purwatmini, 2021). Granulated sugar is derived from sugar cane liquid that undergoes crystallization, transforming into pure white or slightly brownish sugar granules (Erwanto & Martiyanti, 2024). Companies need to adhere to these standards to ensure customer satisfaction with the sugar products they produce.

Fault Tree Analysis (FTA) is a technique that illustrates the causal relationships between various events, allowing for the identification of root causes through a tree diagram. It serves as a failure analysis method used to systematically pinpoint and evaluate potential causes of system failures using a top-down approach, starting from a primary failure event (Nurfatha & Herwanto, 2023). In FTA, a fault tree analysis is created using Boolean symbols to identify the output of a minimum cut set (Duyo, 2020). A cut set includes system components that, if they fail, can lead to system failure, representing a minimal combination of base events leading to a top event in the system. If all events in a cut set occur simultaneously, the top event will also occur (Hariadi et al., 2023). Failure Mode and Effect Analysis (FMEA) helps determine, recognize, and reduce potential problems or failures in designs, systems, processes, or services before they reach consumers (Nuruddin et al., 2023). FMEA is used to assess the impact of failure at each stage and prioritize actions through prevention and improvement to ensure products meet standards in subsequent productions (Suseno and Kalid, 2022). Three criteria—severity, occurrence, and detection—are used to determine issues and calculate the Risk Priority Number (RPN), with the highest RPN indicating potential causes for production failure, which is further examined (Fitriana, 2023). This research employs the FTA and FMEA methods to assist companies in enhancing sugar quality, aligning with Ridwan's (2023) findings that highlight positive outcomes and improvement strategies such as choosing high-quality raw materials, regular operator training, and ongoing production process monitoring. These considerations can guide companies in boosting product quality.

RESEARCH METHOD

This investigation took place at PT XYZ, beginning in June 2024 and continued until enough data samples were obtained. The study's dependent variable is the quality of sugar products, specifically whether they meet the established standards. The independent variables encompass the production volume of sugar, the frequency of defects in sugar products, and the kinds of defects impacting the production quality, including sugar's moisture content, color, granule size, and uniformity of sugar crystals. Secondary research data were sourced from company information gathered through interviews concerning production and defect data. Data collection involved using primary data through interviews and observations, alongside secondary data related to production and sugar defect information. The data analysis utilizes the Fault Tree Analysis (FTA) and Failure Mode and Effects Analysis (FMEA) methods. FTA is applied to scrutinize the factors contributing to poor sugar quality, whereas FMEA is used to determine the RPN values and suggest improvements to enhance sugar quality in future production endeavors.

RESULTS AND DISCUSSION

Table 1
Data on the number of defects and types of product defects from June to October 2024

Month	Number of Defects per Ton				Total Defect
	Moisture content Defect	Color Defect	Large Grain Type Defect	Crystal Uniformity Defect	
June	603.23	1431.35	651.35	701.56	3387.50
July	1355.60	1146.23	3399.48	570.94	6472.25
August	472.85	941.60	1104.48	295.55	2814.48
September	1797.05	750.69	1599.02	608.99	4755.74
October	773.68	532.55	1645.44	293.15	3244.81
Total	5002.41	4802.41	8399.77	2470.19	20674.78

Source: PT XYZ Quality Control Data

Based on the table above, it appears that the most significant total of defects occurred in June, July, and September. This can be attributed to the increased production levels during these months, coupled with operators being less focused on the production process, resulting in a relatively higher rate of defects compared to the subsequent months. This situation should be addressed by the company to enhance sugar quality.

Figure 1
Cause and Effect Diagram of Large Grain Type Defect

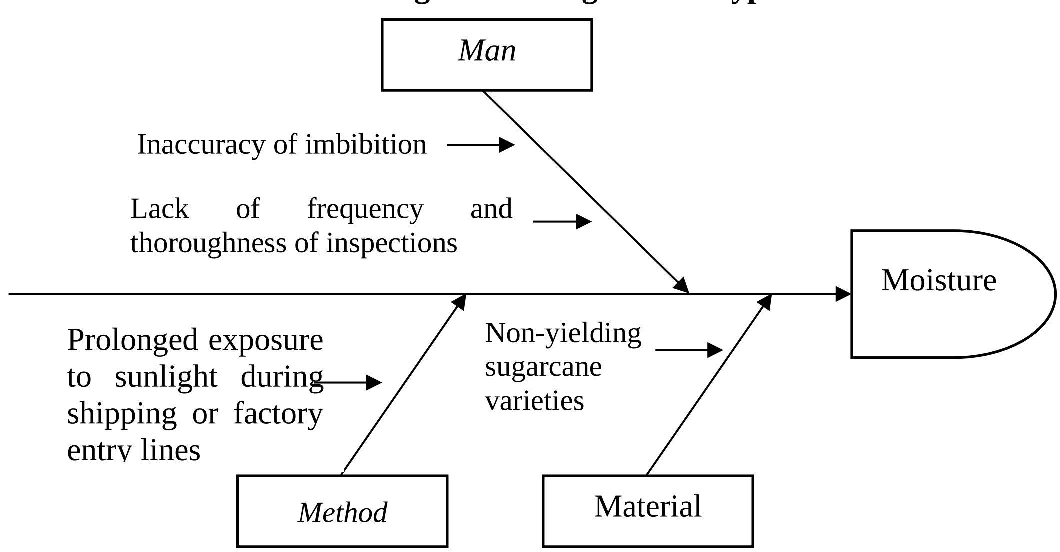


Figure 2
Cause and Effect of Moisture content Defect

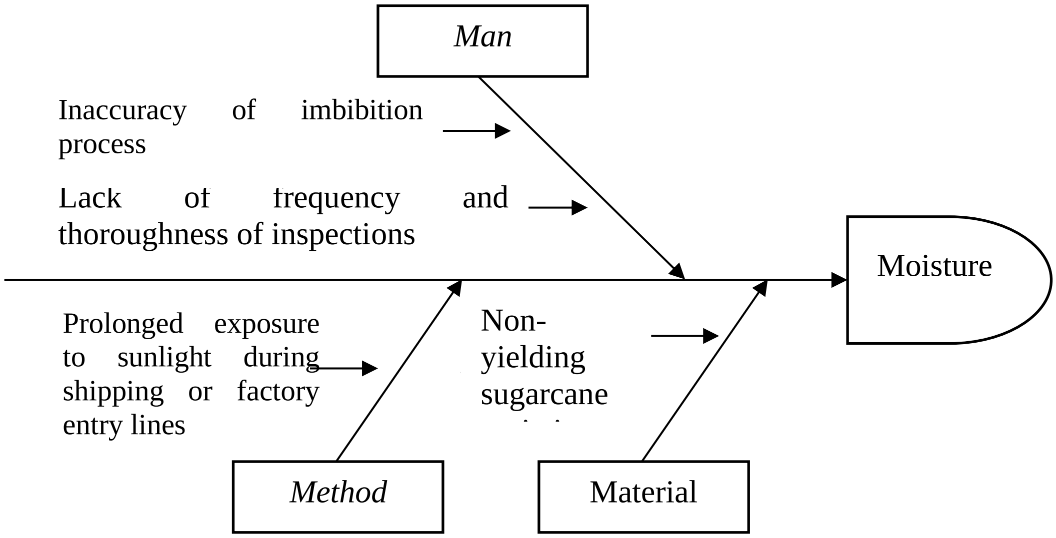


Figure 3
Cause and Effect of Color Defect

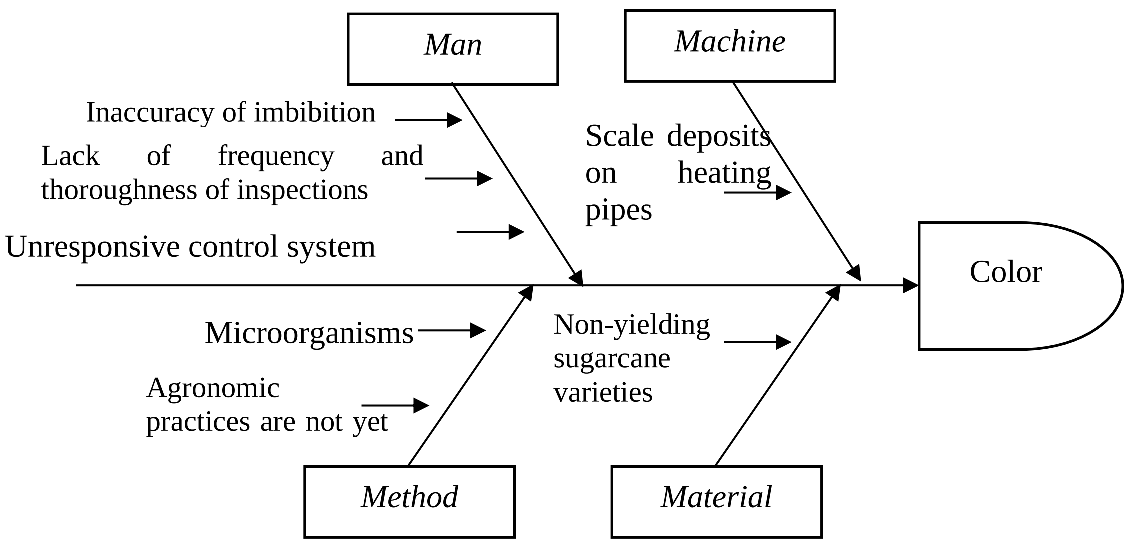
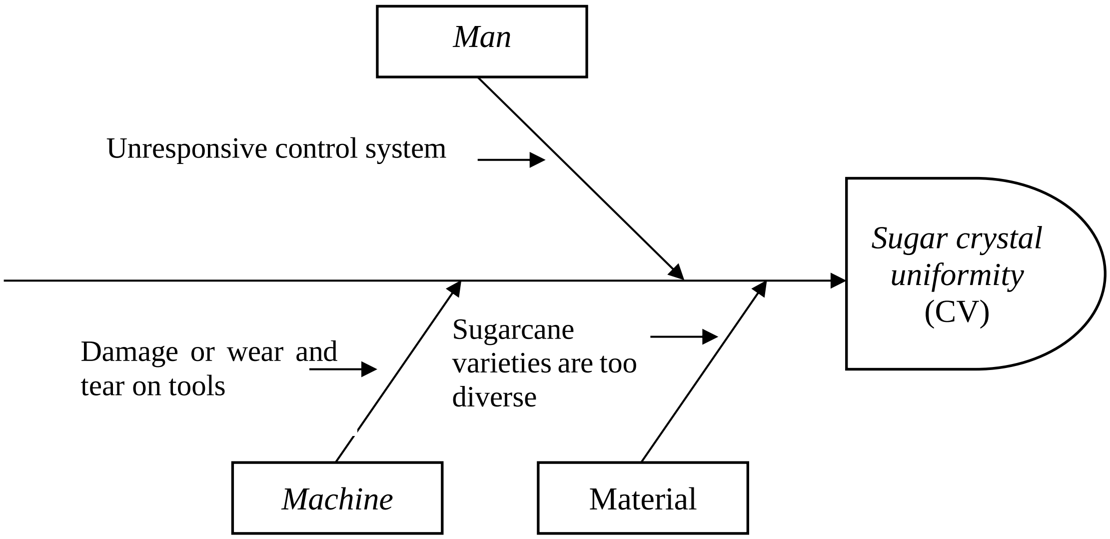


Figure 4
Cause and Effect Sugar Crystal Uniformity



The explanation of the root causes that cause the defect event is as follows:

1. Inaccurate estimation of time and cooking pattern
   Inaccurate estimation or determination of time in the process of cooking sap until the formation of sugar crystals will affect the size and quality of the desired sugar. Inaccurate cooking patterns result in decreased process efficiency because too long or too short a time can disrupt the balance of production.
2. Inaccurate water injection
   The inaccuracy of water addition or injection into the production system will affect the control of the viscosity of the sugar solution in the crystallization process which affects the final white crystal sugar grain size, affect the temperature stability in the cooking process to be uneven which risks causing problems such as non-uniform sugar, and cause clumping and/or refined sugar because the water content in the cooking is less than or exceeds the standard.
3. Leakage in the vacuum maker line
   Leaks in the vacuum cause a decrease in pressure in the vacuum, so that the cooking temperature rises, and the instability of the vacuum causes the evaporation of water from the sugar solution to be incomplete, which affects the formation of sugar crystals to be too small or even dissolve again.
4. Inaccuracy of the imbibition process
   Inaccurate imbibition or addition of water or liquid to bagasse to obtain maximum sugar extract during the milling stage greatly affects the water content of white crystal sugar. If the imbibition is excessive, the juice produced becomes thinner and tends to contain higher water when it enters the crystallization stage. As a result, the sugar crystals that are formed have higher moisture defecture and thus the moisture content of the sugar increases. Sugar with high water content in storage will be more prone to clumping, mold, or deterioration.
5. Lack of frequency and thoroughness of inspections

Periodic inspections are essential to ensure a process is running optimally. If inspection frequency is lacking and implementation is not thorough, various technical problems can occur and impact the quality of white crystal sugar. For example, inaccuracies in the evaporation process that are not detected early will result in the final sugar having a higher moisture content than the standard, and insufficient inspection of the cooking equipment will result in uneven cooking, resulting in sugar containing more or less water.

6. Sugarcane is exposed to sunlight for too long during shipping or queuing to enter the factory

   The occurrence of sucrose inversion due to prolonged exposure to direct sunlight on sugar cane that has been cut down. Causes sucrose to be hydroscopic and affects the evaporation process and cooking because hydroscopic properties will make sugar crystals absorb higher humidity.

7. Low-yielding sugarcane varieties

   Low-yielding sugarcane varieties tend to have lower sucrose content. The lower the sucrose content, the darker or yellowish the color of the white crystal sugar produced.

8. Operator fatigue resulting in an unresponsive control system

   Operator fatigue causes slow response in the control system, which ultimately impacts the quality of white crystal sugar.

9. Scaling deposits on the heating pipe

   Scaling will slow down the thickening process; as a result, the nira is too long exposed to high temperatures and or overheating, which causes the formation of a darker white crystal sugar color.

10. Microorganisms

    The uncontrolled presence of microorganisms can cause various problems ranging from discoloration, decreased sugar yield, to contamination of the final product. These types of microorganisms can be found in the sugar production process, especially at the sap extraction, refining, and crystallization stages. Microorganisms that produce organic acids and pigments cause the color of the juice to become browner, which is difficult to remove in the refining stage, and the resulting white crystal sugar becomes darker or yellowish in color.

11. Agronomic practices are not optimal

    Inappropriate agronomic practices, such as the use of unbalanced fertilizers, cause problems such as excess nitrogen, which causes sugarcane growth to have many leaves but low sucrose levels, where the sap produced from sugarcane with low sucrose levels will be more prone to browning during the refining and evaporation process.

12. Equipment damage or wear and tear

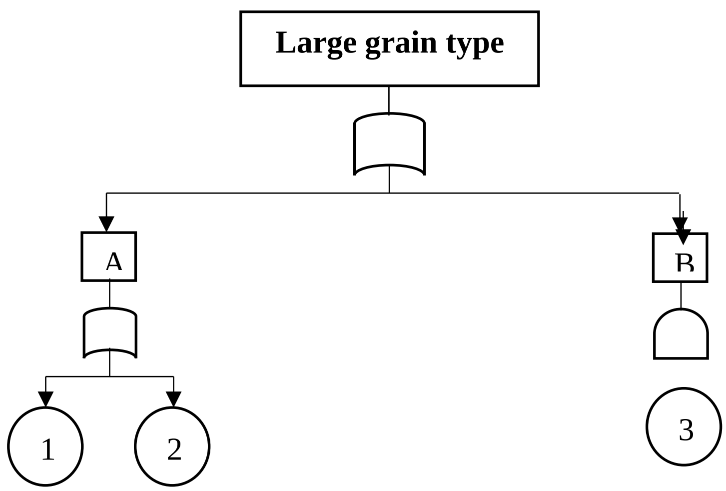
    Causes interruptions in production as well as variations in machine capacity and performance that increase the sugar crystal uniformity (CV) value or sugar quality uniformity. Wear and tear, such as on the mill roll, results in uneven extraction of sap, leading to variations in sucrose content and crystal size. Damage that occurs includes imbalances in the evaporator which makes the heating of the juice non-uniform, affecting the consistency of evaporation and crystallization, damage to the centrifuge resulting in non-optimal separation of molasses which causes variations in purity levels and impacts variations in the color of white crystal sugar, and interference with the dryer system affects the moisture content in the sugar resulting in variations in the color and texture of white crystal sugar.

13. Sugarcane varieties are too diverse
Too much variety in a production batch can lead to non-uniformity in the quality of white crystal sugar, which results in high sugar crystal uniformity. Some of the factors causing excessive sugarcane variation include differences in sugarcane varieties, uneven harvesting time, transportation, and storage. Each variety has different levels of sucrose, fiber, and non-sugar compounds, so that sap processing becomes inconsistent. Different harvest times have varying sucrose content and moisture content, causing differences in extraction and crystallization. Sugarcane that is stored too long before milling will undergo non-uniform fermentation that changes the chemical composition of the juice, affecting the quality of white crystal sugar.

Fault Tree Analysis (FTA)

After identifying the causes of the defects, the next step is to create the Fault Tree Analysis (FTA) diagram for each type of defect.

Figure 5
Fault Tree Analysis of Large Grain Type Defect



Description:
A : *Man*
B : *Machine*
1 : Inaccurate estimation of cooking time and pattern
2 : Inaccurate water injection
3 : Leakage in hollow maker channel

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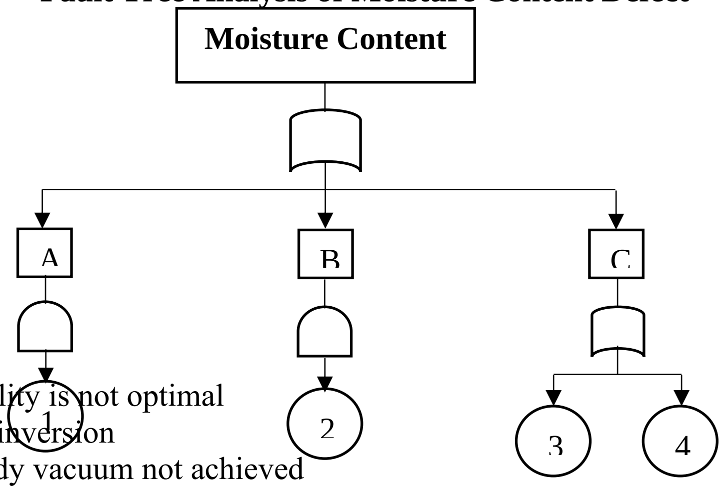
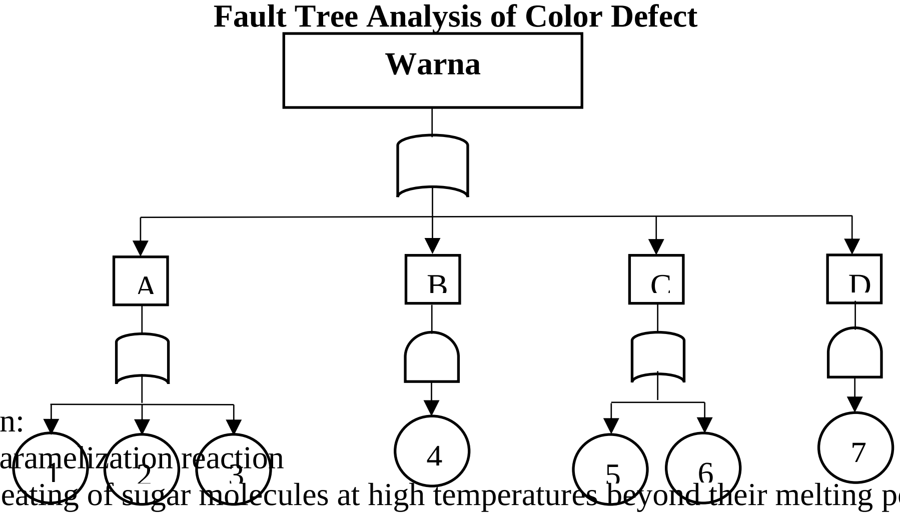
Figure 6
Fault Tree Analysis of Moisture Content Defect



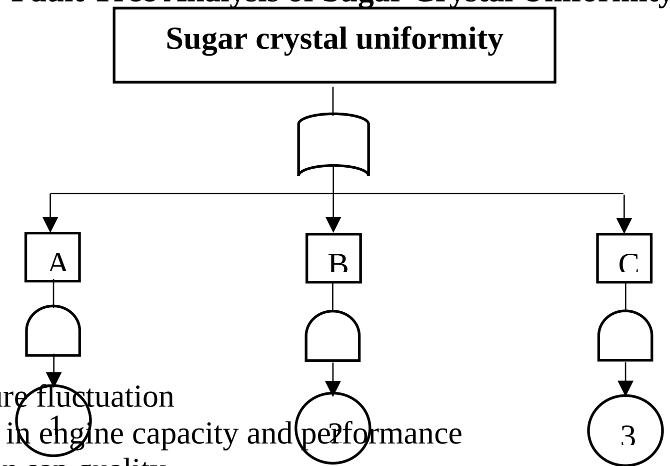
Description:
A : Nira quality is not optimal
B : Sucrose inversion
C : Final body vacuum not achieved
1 : Sugarcane variety is not superior
2 : Sugarcane is exposed to sunlight for too long during shipping or queuing to enter the mill
3 : Lack of frequency and thoroughness of inspection
4 : Inaccuracy of imbibing process

Figure 7
Fault Tree Analysis of Color Defect



Description:
A : Caramelization reaction
B : Heating of sugar molecules at high temperatures beyond their melting point.
C : Post-harvest damage
D : Non-optimal sap quality
1 : Lack of frequency and thoroughness of inspection
2 : Inaccuracy of imbibition process
3 : Operator fatigue resulting in unresponsive control system
4 : Scale deposits on the heating pipe
5 : Microorganisms
6 : Not optimal agronomic practices
7 : Sugarcane varieties are not superior

Figure 8
Fault Tree Analysis of Sugar Crystal Uniformity



Description:
A : Temperature fluctuation
B : Variations in engine capacity and performance
C : Variation in sap quality
1 : Operator fatigue resulting in an unresponsive control system
2 : Damage or obsolescence of the equipment
3 : Sugarcane varieties are too diverse

After doing the Fault Tree Analysis, proceed to calculate the probability for each type of white crystal sugar defect. Probability calculation for a large grain type defect

P_1: 0,000221
P_2: 0,000227
P_3: 0,000209

$P_A = P_1 + P_2 – (P_1 \times P_2)$
$= 0{,}000221 + 0{,}000227 – (0{,}000221 \times 0{,}000227)$
$= 0{,}000448 – 0{,}000000$
$= 0{,}000448$

$P_B = P_3$
$= 0{,}000209$

$P_{\text{Large grain type}} = P_A + P_B - (P_A \times P_B)$
$= (0{,}000448 + 0{,}000209) – (0{,}000448 \times 0{,}000209)$
$= (0{,}000657 – 0{,}000000)$
$= 0{,}000657 = 0{,}000657\%$

Probability calculation for moisture defecture defect

P_1: 0,000245
P_2: 0,000198
P_3: 0,000214
P_4: 0,000232

$P_A = P_1$
$= 0{,}000245$

$P_B = P_2$
$= 0{,}000198$

$P_C = P_3 + P_4 – (P_3 \times P_4)$
$= 0{,}000214 + 0{,}000232 – (0{,}000214 \times 0{,}000232)$
$= 0{,}000446 – (0{,}00000000)$

$= 0{,}000446$

$P_{\text{moisture content}} = P_A + P_B + P_C - (P_A \times P_B \times P_C)$

$= 0{,}000245 + 0{,}000198 + 0{,}000446 – (0{,}000245 \times 0{,}000198 \times 0{,}000446)$

$= 0{,}000889 – 0{,}000000$

$= 0{,}000889\%$

Probability calculation for color defect

P_1: 0,000214

P_2: 0,000232

P_3: 0,000232

P_4: 0,000222

P_5: 0,000226

P_6: 0,000226

P_7: 0,000245

$P_A = P_1 + P_2 + P_3 – (P_1 \times P_2 \times P_3)$

$= 0{,}000214 + 0{,}000232 + 0{,}000232 – (0{,}000214 \times 0{,}000232 \times 0{,}000232)$

$= 0{,}000678 – 0{,}000000$

$= 0{,}000678$

$P_B = P_4$

$= 0{,}000222$

$P_C = P_5 + P_6 – (P_5 \times P_6)$

$= 0{,}000226 + 0{,}000226 – (0{,}000226 \times 0{,}000226)$

$= 0{,}000452 – 0{,}000000$

$= 0{,}000452$

$P_D = P_7$

$= 0{,}000245$

$P_{\text{Warna}} = P_A + P_B + P_C + P_D - (P_A \times P_B \times P_C \times P_D)$

$= (0{,}000678 + 0{,}000222 + 0{,}000452 + 0{,}000245) – (0{,}000678 \times 0{,}000222 \times 0{,}000452 \times 0{,}000245)$

$= (0{,}001597 – 0{,}000000)$

$= 0{,}001597 = 0{,}001597\%$

Probability calculation for sugar crystal uniformity

P_1: 0,000232

P_2: 0,000206

P_3: 0,000224

$P_A = P_1$

$= 0{,}000232$

$P_B = P_2$

$= 0{,}000206$

$P_C = P_3$

$= 0{,}000224$

$P_{\text{Sugar crystal uniformity}} = P_A + P_B + P_C – (P_A \times P_B \times P_C)$

$= 0{,}000232 + 0{,}000206 + 0{,}000224 – (0{,}000232 \times 0{,}000206 \times 0{,}000224)$

$= (0{,}000662 – 0{,}000000)$

$= 0{,}000662 = 0{,}000662\%$

Failure Mode and Effect Analysis (FMEA)

After knowing the types of failure components using Fault Tree Analysis (FTA), the next step is to determine priorities and recommendations for improvements to improve the quality of white crystal sugar production using Failure Mode and Effects Analysis (FMEA). Input failure modes use failure components that have been determined using Fault Tree Analysis (FTA). The identification of potential failures is conducted by assigning a value or score to each failure mode based on its severity level (S), occurrence level (O), and detection level (D). Subsequently, the Risk Priority Number (RPN) value is determined, which helps prioritize improvements that need to be addressed first.

Table 2
Failure Mode and Effect Analysis (FMEA)

Priority	Potential Failure Mode	Potential Cause	RPN	Recommendation
1	Large grain type (BJB)	1. Inaccurate estimation of cooking time and pattern	120	1. Determine the ideal cooking time after testing the characteristics of the juice and periodically evaluating the standard operating procedures.
		2. Inaccurate water injection		2. Conduct sugar content test in the pulp to determine imbibition and adjustment of imbibition water ratio & monitoring of imbibition ratio according to SOP
		3. Leakage in hollow maker channel		3. Regular inspection and maintenance
2	Moisture content	Inaccuracy of the imbibition process	112	1. Conduct sugar content test in pulp to determine imbibition and adjustment of imbibition water ratio & monitoring of imbibition ratio as per SOP

Priority	Potential Failure Mode	Potential Cause	RPN	Recommendation
		2. Lack of inspection frequency		2. Technical training for operators and technicians to make the inspection more effective, to help with faster defect detection
		3. Sugarcane is exposed to sunlight for too long		3. Supply chain optimization, such as the implementation of a scheduled queuing system to reduce waiting time in the field, as well as the use of UV protection canopies or tarpaulins to protect sugarcane from direct sunlight.
		4. Sugarcane varieties are not superior		4. Equitable development of certified seedlings to ensure crop quality and select varieties that have high yields and are resistant to pests/diseases such as PS 862, PSJT 941, Bululawang (BL), and Kidang Kencana.
3	Warna	1. Lack of inspection frequency and thoroughness	84	1. Technical training for operators and technicians to make inspections more effective to help detect defects faster.

Priority	Potential Failure Mode	Potential Cause	RPN	Recommendation
		2. Inaccuracy of imbibition process		2. Conduct sugar content test in pulp to determine imbibition and imbibition water ratio adjustment & monitoring of imbibition ratio according to SOPs
		3. Unresponsive control system		3. Evaluation of workload and HR adjustments and implementation of a balanced shift system
		4. Scale deposits on the heating pipe		4. Routine cleaning and maintenance
		5. Microorganisms		5. Controls at the harvest and transportation stages such as a maximum milling time of 24 hours after the sugarcane is cut down, reducing excessive sun exposure, and reducing mechanical injuries to the sugarcane
		6. Not optimal agronomic practices		6. Conducting training for cultivators to achieve tillage, fertilizer management, irrigation and water management, and pest control 6.
		7. Non-yielding sugarcane varieties		7. Equitable development of certified seedlings

Priority	Potential Failure Mode	Potential Cause	RPN	Recommendation
				to ensure crop quality and select varieties that have high yields and are resistant to pests/diseases such as PS 862, PSJT 941, Bululawang (BL), and Kidang Kencana.
4	Sugar crystal uniformity (CV)		48	1. Evaluation of workload and human resource adjustments, as well as implementation of a balanced shift system
		1. The control system is not responsive		2. Create and adhere to routine maintenance and periodic inspection schedules
		2. Damage or wear and tear on tools		3. Standardize the use of superior varieties

Based on analysis using the FTA and FMEA methods, the results indicate several factors impacting the inadequate quality of sugar production. These include human elements, machinery, methods, and the environment, all of which inevitably influence production quality. High production volumes lead to more frequent machine breakdowns, and from the human aspect, there is increased fatigue due to high target demands. Thus, these factors contribute to the suboptimal quality of sugar. This issue is also a focal point for the company as it aims to enhance the quality in future production processes.

CONCLUSION

Based on calculations using the Fault Tree Analysis method, the probability results calculated each type of defect, namely large defects in grain type, moisture content, color, and sugar crystal uniformity, are 0.000657%, 0.000889%, 0.001597%, and 0.000662%, respectively. The FMEA method obtained a large grain type defect with the highest RPN value of 120 (High). Large grain type defects cause white crystal sugar to have a mismatch with market specifications and is slower to dissolve. Sugar with fine grains increases the possibility of sugar melting faster during storage. Meanwhile, sugar with large grains is more susceptible to re-crystallization or changes in moisture content that can cause clumping. In the second rank, there is a moisture content defect with an RPN value of 112 (medium). Moisture content defects will clearly affect the physical quality of white crystal sugar products and product shelf life. Too high moisture content can cause sugar to clump and or increase the risk of microorganism growth that can degrade the quality of sugar. Based on the research results, the company is advised to implement the proposed improvements from the FMEA analysis to improve the quality control of white crystal sugar. In addition, quality control should be carried out periodically and continuously so that it can be a reference for continuous improvement in the future. For future research, it is recommended to add additional criteria if the company wants to expand the scope of quality control and consider other methods in quality control analysis.

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