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Identification of Determinants of Quality Variability in Upstream Nickel Industry Production Systems Based on a Quality Engineering Approach

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Abstract
The upstream nickel industry is a strategic sector playing a vital role in supporting the national industrial supply chain and Indonesia's natural resource downstreaming program. However, high raw material heterogeneity, fluctuating process parameters, and limitations in quality control systems lead to product quality variability, which impacts production efficiency, energy consumption, and process stability. This study aims to identify the key determinants influencing quality variability in upstream nickel production systems, analyze the relationships between these determinants using a Quality Engineering approach, and formulate a conceptual framework of quality variability to serve as a basis for developing a prevention-based quality control system. The study employs a descriptive-analytic approach using mixed methods, integrating quantitative and qualitative data gathered through observations, interviews, document reviews, and questionnaires. Analysis was conducted based on the 5M+1E framework, encompassing the factors of Man, Machine, Material, Method, Measurement, and Environment. The results indicate that the Material factor is the most dominant determinant influencing quality variability, with a mean score of 4.70 (94%), followed by Machine (4.20 or 84%), Man (4.00 or 80%), Method (3.90 or 78%), Measurement (3.50 or 70%), and Environment (3.30 or 66%). The findings reveal that quality variability is systemic in nature, with all determinants interacting and influencing the quality of the final product. This research produces a conceptual framework of quality variability determinants that can serve as a foundation for developing adaptive quality systems and prevention-based quality control within the upstream nickel industry.

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Keywords: Upstream nickel industry, Quality variability, Quality Engineering, Quality determinants, Prevention-based quality control

1. Introduction

The upstream nickel industry is a strategic sector that plays a vital role in supporting national industrial development, particularly regarding natural resource down streaming programs and the development of renewable energy-based industries. As one of the world's largest nickel producers, Indonesia possesses significant potential to enhance the value-added of nickel commodities by strengthening efficient and sustainable production systems. However, in practice, the upstream nickel industry continues to face various challenges, one of which is the high variability in the quality of the products generated. Such quality variability can compromise production process stability, increase operational costs, and reduce resource utilization efficiency [16].

The heterogeneous nature of nickel laterite raw materials results in variations in nickel content, moisture levels, and particle sizes, all of which directly impact the stability of the processing operations. Furthermore, fluctuations in operating parameters, equipment conditions, operator competence, and suboptimal quality control systems exacerbate the potential for quality variations in intermediate products [17]. Failure to effectively manage these conditions can lead to energy waste, increased process waste, and reduced corporate productivity [5]. In general, quality control in the upstream nickel industry remains dominated by

end-product inspection and Statistical Quality Control (SQC) methods that focus on detecting quality deviations after the production process has taken place. This approach is considered inadequate for explaining the causal relationships between the factors driving quality variation, which are complex and dynamic [7]. Therefore, an approach is needed that is not merely oriented toward identifying product defects but is also capable of identifying sources of variation from the initial stages of the production process. The Quality Engineering (QE) approach offers a more comprehensive quality control paradigm by focusing on variation as the primary object of control. Taguchi's concept emphasizes that quality must be built through efforts to prevent sources of variation, rather than merely inspecting the final product [12].
Quality Engineering has been widely applied in the manufacturing industry to enhance process stability, reduce quality-related costs, and improve production system performance. However, studies regarding the application of this approach in natural resource-based upstream industries—specifically the nickel processing industry in Indonesia—remain very limited [13].
Previous research indicates that the factors of man, machine, material, method, measurement, and environment (5M+1E) contribute differently to quality variability within a production system [6]. Yet, there is a lack of research systematically identifying and mapping the relationships among these determinants within the context of the upstream nickel industry. This research gap highlights the need for a deeper study of quality variability determinants to serve as a foundation for developing future prevention-based quality control systems and adaptive quality systems. Based on the foregoing, this study focuses on identifying the determinants of quality variability in the upstream nickel industry's production system using a Quality Engineering approach. The findings are expected to contribute theoretically to the advancement of quality control science and serve as a foundation for designing more effective, adaptive, and sustainable quality systems for the upstream nickel industry in Indonesia.

2. Literatur Review

2.1. Quality Variability in Production Systems

Quality variability refers to differences in product characteristics or process performance resulting from variations in factors affecting the production system. In manufacturing and process industries, quality variability is considered one of the primary causes of inefficiency because it can lead to unstable processes, increased operational costs, and reduced product consistency [7].
In the nickel upstream industry, quality variability is primarily influenced by the heterogeneous characteristics of lateritic nickel ore, including variations in nickel content, moisture levels, and particle size distribution. These differences directly affect process stability and the quality of intermediate products generated during production [17]. Therefore, understanding the sources of variability is essential to improving process performance and maintaining product quality.

2.2. Quality Engineering

Quality Engineering (QE) is a systematic approach that focuses on preventing process variations by designing products and production systems capable of consistently meeting quality requirements. The concept was introduced by Genichi Taguchi, who argued that quality should be built into the product and process design rather than achieved solely through final inspection [12].
According to Taguchi, quality is measured by the loss imposed on society due to deviations from the target value. Consequently, Quality Engineering emphasizes the identification and control of sources of variation and the reduction of quality losses through robust design and process optimization [14]. The application of Quality Engineering has been widely adopted in manufacturing industries to improve process stability, reduce quality costs, and enhance production performance. In process-based industries, Quality Engineering provides a comprehensive framework for understanding the relationship between process parameters and product quality, enabling organizations to implement proactive quality control systems [3].

2.3. Determinants of Quality Variability Based on the 5M+1E Approach

The causes of quality variability are generally analyzed using the 5M+1E framework, which consists of Man, Machine, Material, Method, Measurement, and Environment.[6] This approach provides a systematic basis for identifying and evaluating the factors contributing to process and product variations.

2.3.1. Material Factors

Material is considered one of the most significant determinants of quality variability in the nickel industry because differences in raw material characteristics directly influence process parameters and product quality. Variations in nickel grade, moisture content, and ore composition can significantly affect production stability and operational efficiency [16].

2.3.2. Machine Factors

Machines and production equipment play a crucial role in maintaining process stability. Equipment deterioration, unplanned downtime, and inappropriate operating parameters can increase process variability and lead to quality deviations [6]. Therefore, effective maintenance and monitoring systems are essential to ensure production consistency.

2.3.3. Human Factors

Human factors refer to the competence, experience, and performance of operators involved in the production process. Skilled and knowledgeable operators are more capable of identifying potential process deviations and implementing corrective actions, thereby minimizing quality variability [8].

2.3.4. Method Factors

Methods include the procedures, work instructions, and standard operating procedures (SOPs) used during production activities. Inconsistent implementation of operational procedures may result in significant variations in process outcomes and product quality [7].

2.3.5. Measurement Factors

Measurement systems provide the basis for decision-making in quality control activities. The reliability of measuring instruments, testing procedures, and calibration practices significantly affects the accuracy of quality data and the effectiveness of process control [4].

2.3.6. Environmental Factors

Environmental conditions such as temperature, humidity, workplace cleanliness, and operational surroundings can influence material properties, machine performance, and employee productivity. Consequently, environmental factors contribute substantially to the variability observed in industrial processes [1].

2.4. Previous Studies

Several previous studies have investigated factors influencing quality variability in process industries. Zhang and Liu (2023) found that raw material heterogeneity is the primary cause of process instability in nickel processing industries [16]. Similarly, Li and Chen (2022) demonstrated that adaptive control-based quality management significantly improves process stability and product consistency in metal production systems [6].

Furthermore, Xu and Wang (2022) developed a digital twin-based quality prediction system and concluded that digital technologies could enhance the ability of companies to predict and control process variations in real time [15]. However, most previous studies have focused on operational aspects and have not comprehensively developed a conceptual framework for identifying the determinants of quality variability in the upstream nickel industry.

Therefore, there remains a research gap regarding the systematic identification and mapping of relationships among determinants of quality variability in upstream nickel production systems using the Quality Engineering approach. This study aims to address this gap by developing a conceptual framework that can support preventive and adaptive quality management systems in the nickel industry.

3. Methods

3.1. Research Location and Period

The research was conducted in an upstream nickel processing company in Indonesia. The study was carried out from January to December 2026, covering the stages of preparation, data collection, data analysis, and report preparation.

3.2. Research Design

This study employed a descriptive-analytical research design using a mixed-method approach, integrating both quantitative and qualitative data. The mixed-method approach was selected to provide a comprehensive understanding of the determinants of quality variability in upstream nickel production systems and to examine the relationships among these determinants from the perspective of Quality Engineering.

3.3. Research Variabels

The study investigated six determinants of quality variability based on the 5M+1E framework:

1. Man – operator competence, experience, and compliance with standard operating procedures.
2. Machine – equipment condition, maintenance, and process stability.
3. Material – raw material characteristics, including nickel grade, moisture content, and particle size.
4. Method – production procedures and consistency of process implementation.
5. Measurement – reliability of measuring instruments and calibration systems.
6. Environment – workplace conditions, including temperature, humidity, and operational surroundings.

The dependent variable of this study is quality variability in the upstream nickel production system.

3.4. Population and Sample

The population consisted of employees directly involved in the nickel production process, including production supervisors, operators, quality control personnel, and maintenance staff.

A purposive sampling technique was employed to select respondents who possessed adequate knowledge and experience regarding the production process and quality management system.

3.5. Variable Consequence of Failure (CoF)

The CoF is determined based on the following impact parameters:

- Impact on population
- Impact on the environment
- Economic impact
- Reputational impact

3.6. Data Collection Methods

The data were collected through the following techniques:

3.6.1. Observation

Direct observation was conducted to identify production activities and quality control practices within the company.

3.6.2. Interviews

Semi-structured interviews were carried out with managers, supervisors, and operators to obtain in-depth information regarding factors influencing quality variability.

3.6.3. Questionnaires

Structured questionnaires were distributed to respondents using a five-point Likert scale to evaluate the significance of each determinan.

3.6.4. Documentation Study

Company reports, production records, quality reports, and standard operating procedures were reviewed to support the analysis.

3.7. Research Instruments

The primary instrument used in this study was a questionnaire developed based on the 5M+1E dimensions and Quality Engineering concepts. The questionnaire consisted of statements representing each determinant of quality variability.

Prior to data collection, the instrument was subjected to:

- **Validity Test** using Pearson Product Moment correlation.
- **Reliability Test** using Cronbach's Alpha coefficien

3.8. Data Analysis Techniques

The collected data were analyzed through the following stages:

- **Descriptive Analysis**

Descriptive statistics were used to describe respondents' characteristics and evaluate the importance of each determinant of quality variability.

- **Identification of Quality Variability Determinants**

The determinants affecting quality variability were identified based on the average scores and rankings obtained from the questionnaire results.

- **Quality Engineering Analysis**

The Quality Engineering approach was employed to analyze the relationships among determinants and identify the dominant factors contributing to quality variability.

- **Development of a Conceptual Framework**

The findings were synthesized to develop a conceptual framework of quality variability determinants that can support preventive and adaptive quality management systems in the upstream nickel industry.

4. Result and Discussion

4.1. General Description of the Research Object

The study was conducted in an upstream nickel processing company in Indonesia. The company processes lateritic nickel ore into intermediate products through several production stages, including ore preparation, drying, reduction, smelting, and refining processes. The production system involves complex interactions among raw materials, equipment, human resources, and environmental conditions, which contribute to variations in product quality.

The company has implemented a quality management system to control production performance. However, fluctuations in product quality still occur due to differences in raw material characteristics and variations in operational parameters.

4.2. Characteristics of Respondents

The respondents consisted of employees directly involved in production and quality management activities. The respondents included production supervisors, operators, maintenance personnel, and quality control staff.

Table 1 : Characteristics of Respondents

Position	Number of Respondents	Percentage (%)
Production Operators	20	40
Supervisors	10	20
Quality Control Staff	12	24
Maintenance Staff	8	16
Total	50	100

The respondents were selected because they possessed sufficient knowledge and experience regarding production processes and quality control systems.

4.3. Identification of Quality Variability Determinants

Based on questionnaire analysis, six determinants were identified as factors affecting quality variability in the upstream nickel production system.

Table 2: Average Scores of Quality Variability Determinants

Determinant	Mean Score	Percentage (%)	Category
Material	4.70	94	Very High
Machine	4.20	84	High
Man	4.00	80	High
Method	3.90	78	High
Measurement	3.50	70	Moderate
Environment	3.30	66	Moderate

The results indicate that material factors are the most influential determinants of quality variability, followed by machine and human factors.

4.4. Relationship Among Quality Variability Determinants

The findings indicate that quality variability in the upstream nickel production system is systemic in nature. The determinants do not operate independently but interact with one another.

The interaction among determinants can be illustrated as follows:

Material → Machine → Method → Product Quality Human → Process Control → Product Quality Environment → Machine and Material → Product Quality

Therefore, quality improvement efforts should adopt an integrated approach rather than focusing on individual factors.

4.5. Implications of the study

The results provide several implications: Practical Implications

1. Improving raw material classification systems.
2. Strengthening preventive maintenance programs.
3. Enhancing operator competency through training.
4. Standardizing operational procedures.
5. Improving measurement system reliability. Theoretical Implications

This study contributes to the development of Quality Engineering applications in process industries, particularly in identifying determinants of quality variability in upstream nickel production systems.

5. Conclusion

Based on the results and discussion, several conclusions can be drawn regarding the determinants of quality variability in the upstream nickel production system based on the Quality Engineering approach.

1. Quality variability in the upstream nickel production system is influenced by six main determinants, namely Man, Machine, Material, Method, Measurement, and Environment (5M+1E). These determinants collectively contribute to variations in process performance and product quality.
2. Material is identified as the most dominant determinant of quality variability. Variations in nickel ore characteristics, including nickel grade, moisture content, and particle size distribution, significantly affect process stability and the consistency of product quality.
3. Machine and human factors also have a substantial influence on quality variability. Equipment reliability, maintenance effectiveness, operator competence, and compliance with standard operating procedures are critical factors in maintaining stable production

performance.
4. Method, measurement, and environmental factors contribute to quality variability indirectly by affecting process control and operational consistency. Standardized procedures, reliable measurement systems, and controlled environmental conditions are necessary to minimize production deviations.
5. The determinants of quality variability are interconnected and operate as an integrated system rather than as independent factors. Changes in one determinant may influence the performance of other determinants and ultimately affect product quality.
6. The Quality Engineering approach provides a comprehensive framework for identifying and controlling sources of variation through preventive actions rather than relying solely on final product inspection. Therefore, the implementation of Quality Engineering can improve process stability, reduce quality losses, and enhance operational efficiency in the upstream nickel industry.
7. This study proposes a conceptual framework of quality variability determinants that can serve as a foundation for developing preventive and adaptive quality management systems in the upstream nickel industry.

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