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Robust Quality Control Implementation for Nickel Pig Iron Using Median Absolute Deviation Estimators

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ABSTRACT

Nickel Pig Iron (NPI) is one of the main products of Indonesia's nickel-based industry, which is still expanding. Reducing production costs and guaranteeing product quality depends on maintaining a constant nickel content. The Median Absolute Deviation (MAD) estimator, which is resistant to outliers and non-normal distributions, is used in this study's control charts and process capability analysis. After 15 days of production, data was gathered and examined using capability indices and control charts based on MAD. According to the results, the process mean is not statistically in control since many points exceed the control borders, even while process variation stays within the control limits. Acceptable process precision was indicated by the process capability index CpMAD being above 1. However, the CpkMAD value below 1 suggests that the mean process output does not consistently meet the target specifications. These findings highlight the need for further investigation and process improvement to enhance quality consistency in NPI production.

INTRODUCTION

In recent years, Indonesia's nickel-based industry has grown significantly, with Nickel Pig Iron (NPI) emerging as a key product due to its application in stainless steel manufacturing. Ensuring consistent nickel content in NPI is critical, as deviations may lead to product nonconformance, rework, and increased production costs. Traditional quality control methods, such as control charts and process capability indices, typically rely on assumptions of normal data distribution and the absence of outliers. However, industrial data often violate these assumptions, rendering conventional estimators like the mean and standard deviation less effective. This condition necessitates robust statistical approaches that remain reliable in the presence of outliers and non-normality.

Controlling the nickel content in NPI products is certainly one of the key concerns for companies in order to maintain the quality of NPI and minimize production losses resulting from non-conforming

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products. One of the methods for quality control is the use of Statistical Quality Control (SQC). A widely used tool in SQC is the control chart. A control chart is a graphical tool used to monitor variations in the production process and to identify potential deviations that may cause product non-conformance [1], [2]. Control charts also reveal shifts in the mean and variation over time and provide insights into whether the production process is under control [3]. The implementation of control charts in production processes aims to help companies determine whether the process is operating within predefined control limits or experiencing undesirable variation due to certain causes [4], thereby enabling timely corrective actions once the cause of variation is identified [5]. In addition to control charts, process capability analysis is also an important quality control tool that plays a key role in evaluating the ability of a process to produce products that meet specified requirements [6] as well as in identifying process variation [7]. Process capability measures the extent to which a process can consistently meet quality requirements in terms of both accuracy and precision [8].

Control charts and process capability analysis typically require the assumption of normal data distribution and the absence of outliers [2], [9], [10], However, production process data often deviate from normality. Under such conditions, using the mean as an estimator may introduce bias, highlighting the need for robust estimators that can handle non-normal data and outliers. Selecting an appropriate method to estimate variability is crucial for accurately assessing product quality characteristics. The Median Absolute Deviation (MAD) is a robust statistical measure suitable for evaluating process variability, especially when data contain outliers or are not normally distributed [11]. Compared to standard deviation-based methods, MAD demonstrates greater resistance to outliers [12], [13], leading to more reliable estimates of process capability. The MAD control chart is a modified Shewhart chart that uses the median for central tendency and MAD for variability, offering greater robustness to outliers [14].

Previous studies have explored control charts and process capability analysis using MAD estimators. Research by [14], [15] indicates that control charts based on the median and MAD outperform traditional mean and standard deviation-based charts in terms of robustness. Similarly, [9] shows that process capability analysis using MAD is more effective in detecting out-of-specification conditions in non-normally distributed data. This study aims to analyze the quality control of NPI products based on nickel content using a robust estimator suited for non-normal data with outliers. The application of this method is expected to improve production efficiency and enhance the competitiveness of Indonesia's nickel-based industry.

RESEARCH METHODS

This study uses data on nickel content in NPI products collected over a 15-day production period, with each day representing a subgroup (m). Each subgroup consists of 8 randomly selected NPI samples (n), which were then subjected to laboratory testing to determine their nickel content. The resulting data represent continuous variables, which in terms of quality control are referred to as variable quality characteristics, and were analyzed using a descriptive statistical approach.

The laboratory test results for nickel content over the 15-day production period were then tested for normality—one of the assumptions required for conducting quality control using control charts and process capability analysis. The normality test was performed using the Shapiro-Wilk test with a significance level (α) of 5%. The Shapiro-Wilk test was selected because it effectively assesses non-normality across various data distributions (symmetric, skewed, short-tailed, and long-tailed) and is applicable to a wide range of sample sizes. [16].

After the normality assumption test was conducted, quality analysis was performed using control charts. A control chart is a graphical tool used to continuously monitor process variability in order to assess the stability of process variations [17]. Process stability for quality characteristics that vary must be monitored by examining both the process average and its variability. In this study, process variability is tracked using the MAD control chart, while the process average is monitored using a median control chart with the standard deviation estimated via MAD. The MAD calculation is given by the following equation [14]:

$$MD_i = \begin{cases} x_{\frac{j+1}{2}} & \text{if n is an odd number} \\ x_{\frac{j}{2}} + x_{\frac{j}{2}+1} & \text{if n is an even number} \end{cases} ; j = 1,2,3,\cdots,n \quad (1)$$

$$MAD_i = 1,4826 \times Median\left\{\left|x_{ij} - MD_i\right|\right\}; i = 1,2,3,\cdots,m \quad (2)$$

Notes:
MD_i = Median i-th subgroup
MAD_i = Median Absolut Deviation i-th subgroup

The control limits of the MAD control chart can be calculated using the following equation [14]:

$$UCL = B_6^* \overline{MAD} \quad (3)$$

$$CL = c_4^* \overline{MAD} \quad (4)$$

$$LCL = B_5^* \overline{MAD} \quad (5)$$

with,

$$\overline{MAD} = \frac{1}{m}\sum_{i=1}^{m} MAD_i \quad (6)$$

After monitoring process variability, the process average is then tracked using a median control chart with the standard deviation estimated via MAD. The control limits for this chart are calculated using the following equation [15]:

$$UCL = \overline{MD} + R_1 \overline{MAD} \quad (7)$$

$$CL = \overline{MD} \quad (8)$$

$$LCL = \overline{MD} - R_1 \overline{MAD} \quad (9)$$

with,

$$\overline{MD} = \frac{1}{m}\sum_{i=1}^{m} MD_i \quad (10)$$

The values of constants c_4^*, B_5^*, B_6^* and R_1 can be found in **Table 1** [14], [18].

Table 1. Constants for Control Limit Calculation

n	c^*_4	B^*_5	B^*_6	R_1
2	0,954	0,000	3,117	3,17899
3	1,325	0,000	3,403	3,24454
4	1,256	0,000	2,846	2,56176
5	1,134	0,000	2,369	2,02738
6	1,142	0,035	2,249	1,84153
7	1,094	0,129	2,059	1,61968
8	1,089	0,202	1,977	1,50045
⋮	⋮	⋮	⋮	⋮
25	1,022	0,577	1,467	0,77661

The final step in this study is to calculate the process capability index. The specified nickel content ranges from 8% to 14%. The process capability index measures the process's ability to maintain precision in variability and accuracy of the process average relative to the target [19]. Using the MAD estimator, the capability indices are C_{Pmad} for measuring precision and C_{pkMAD} for measuring the accuracy of the process average against the target. Both indices can be calculated using the equations [9], [18]:

$$C_{pMAD} = \frac{USL - LSL}{6\overline{MAD}} \tag{11}$$

$$C_{pkMAD=} \min\left\{ \frac{USL - \overline{MD}}{4,45 \times \overline{MAD}}; \frac{\overline{MD} - LSL}{4,45 \times \overline{MAD}} \right\} \tag{12}$$

The precision level indicated by the C_{pMAD} index is used to determine whether a process can maintain its average within specification limits, while the accuracy level shown by the C_{pkMAD} index indicates how close the process average is to the target value [20]. Descriptions of the values for each process capability index can be found in Table 2 [21].

Table 2. Capability Process Index Description

Index	Value	Description
C_{pMAD}	<1	Variasi proses lebih besar daripada batas spesifikasi
	1	Variasi proses sama dengan batas spesifikasi
	>1	Variasi proses lebih kecil daripada batas spesifikasi
C_{pkMAD}	0	Rata-rata proses tepat berada disalah satu batas spesifikasi
	<1	Ada rata-rata proses yang berada diluar batas spesifikasi
	1	Rata-rata proses tepat berada di tengah batas spesifikasi
	>1	Semua rata-rata proses berada dalam batas spesifikasi

RESULTS AND DISCUSSION

The laboratory test data for nickel content in NPI products, grouped into subgroups with a sample size of 8 per subgroup, were analyzed to calculate measures of central tendency and dispersion (descriptive statistics) as an initial overview or general description of the data. The descriptive statistics for the nickel content in each NPI product subgroup can be seen in Table 3.

Table 3. Descriptive Statistics of Nickel Content in NPI Products

Date	Subgroup	Sample	Average (%)	Standard Deviation (%)	Median (%)	MAD (%)
1 January	1	8	9,0449	0,2695	8,9795	0,2825
2 January	2	8	8,7902	0,3147	8,7816	0,4385
3 January	3	8	8,6419	0,5121	8,6402	0,7188
4 January	4	8	8,5666	0,5986	8,5721	0,8214
5 January	5	8	8,5508	0,7181	8,6145	0,9142
6 January	6	8	8,4648	0,8275	8,6019	0,9053
7 January	7	8	8,5986	0,7347	8,6186	1,0582
8 January	8	8	8,8734	0,4686	8,9324	0,6347
9 January	9	8	9,7224	0,3333	9,7572	0,3293
10 January	10	8	10,6625	0,6119	10,6758	0,9413
11 January	11	8	11,6430	1,1079	12,2855	0,4998
12 January	12	8	11,5872	0,7029	11,5599	0,7135
13 January	13	8	11,1802	0,4105	11,1252	0,4862

Date	Subgroup	Sample	Average (%)	Standard Deviation (%)	Median (%)	MAD (%)
14 January	14	8	11,4092	0,3986	11,3926	0,4463
15 January	15	8	11,5830	0,4487	11,5665	0,6624

Based on Table 3, the nickel content in NPI products produced from January 1 to 15 shows variation. The average nickel content ranges from 8.4648% to 11.6430%, with an initial downward trend from 9.0449% on January 1 to 8.4648% on January 6, followed by a gradual increase after January 7, peaking at 11.6430% on January 11. Data variability, measured by standard deviation and median absolute deviation (MAD), indicates the largest fluctuations occurred on January 11, with a standard deviation of 1.1079, while the highest MAD was recorded on January 7 at 1.0582, suggesting considerable spread around the median. Overall, the data indicate changes in the nickel content pattern in NPI products, likely due to production factors or raw materials causing variability during the observed period.

After characterizing the nickel content data, a normality test was performed using the Shapiro-Wilk test in R software version 4.4.1 with the following hypothesis:

H_0	: The data follow a normal distribution
H_1	: The data do not follow a normal distribution
α	: 5%
Rejection Region	: Reject H_0 if *p-value* < α

The results of the hypothesis test can be seen in Table 4.

Table 4. Results of the Data Normality Test

Parameter	Value
W	0,9459
p-value	0,0001

Based on Table 4 p-value for the nickel content data is 0.0001, which is smaller than the significance level (α) used in the test. Therefore, it can be concluded that the data do not follow a normal distribution. When the data are not normally distributed, the MAD control chart and the median control chart with standard deviation estimated by MAD perform better than the classical mean and standard deviation control charts ($\bar{x} - R$ atau $\bar{x} - s$).

Quality control of nickel content in NPI products is carried out by monitoring process variation using the MAD control chart. The MAD control chart resulting from the quality control analysis of nickel content in NPI products is shown in Figure 1.

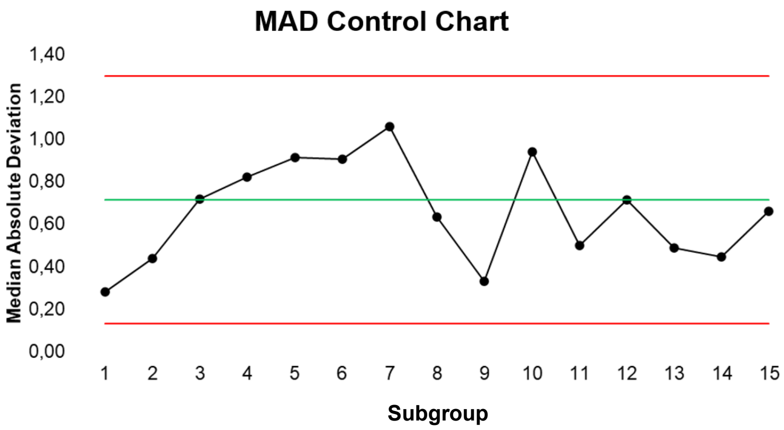

Figure 1. MAD Control Chart

Based on Figure 1, all MAD values fall within the control limits, with the lower control limit (LCL) at 0.1327, the upper control limit (UCL) at 1.2985, and a center line value of 0.7153. This indicates that the process remains in statistical control with no signs of significant deviation. However, some MAD values near the upper limit, such as in subgroups 7 and 10, suggest an increase in process variability. Nevertheless, no MAD values exceed the control limits, so there is no strong evidence that the nickel content in NPI products is out of control. Additionally, the fluctuation pattern of MAD shows a more stable trend after an initially more variable period. Continued monitoring is necessary to ensure that variability does not increase in the future. After analyzing process variability using the MAD control chart, the next step is to monitor the nickel content in NPI products using the median control chart with standard deviation estimated by MAD (MDMAD control chart). The MDMAD control chart is shown in Figure 2.

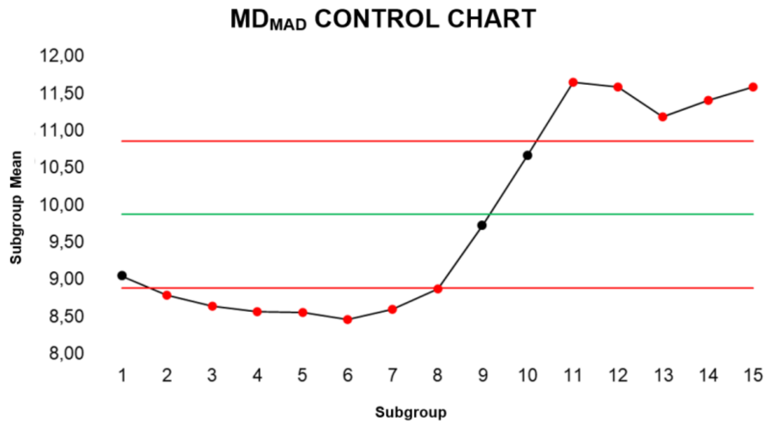

Figure 2. MD_{MAD} control chart

Based on Figure 2, the results of the median control chart with standard deviation estimated using the median absolute deviation (MAD) indicate that several data points lie outside the control limits. The lower control limit is 8.8880, the upper control limit is 10.8591, and the center line is 9.8735. At the beginning of the period, the average nickel content tends to be below the lower control limit, as seen in subgroups 2 through 8, where all values fall below 8.8880. This suggests a possible shift in the nickel content during the NPI production process. Conversely, from subgroups 10 to 15, the average values consistently exceed the upper control limit, peaking at subgroup 11, indicating increased variability in the average nickel content during production. Based on this, the process is statistically out of control, as there are several points beyond the control limits.

After assessing the variability of both the process variation and average, a process capability analysis was conducted to measure the precision and accuracy of the NPI production process regarding the nickel content, which has a specification range of 8–12%. The results of the process capability indices calculated with the MAD-based standard deviation estimator are shown in Table 5.

Table 1. Process Capability Index

Index	Value
C_{pMAD}	1,015
C_{pkMAD}	0,641

Based on Table 5, the C_{pMAD} index is 1.015, indicating that the process variation is smaller than the specification limits. This aligns with the MAD control chart results, which show that the process variability remains within control limits. Conversely, the C_{pkMAD} index is 0.641, a value less than 1, indicating that the process means producing products outside the specification limits. This is consistent with the control chart that shows high variability in the process average.

CONCLUSION

Based on the control chart analysis using the standard deviation estimator with the median absolute deviation (MAD), it was found that the variation in nickel content in Nickel Pig Iron (NPI) products is statistically under control. However, the average nickel content shows statistical instability, indicating deviations in the production process that require further attention.

The C_{pMAD} index value of 1.015 indicates that the process has the potential to meet the specified nickel content limits of 8–12%. However, the C_{pkMAD} index value of 0,641 suggests that the distribution of nickel content in the product has not fully remained within the expected specification range.

This study is limited by its reliance on subgroup sampling and the assumption of process stability throughout the sampling period. External factors such as raw material heterogeneity, equipment wear, and environmental influences were not explicitly accounted for, potentially impacting the accuracy of process control assessments.

Findings underscore the necessity for enhanced process control strategies aimed at stabilizing the average nickel content. The integration of real-time monitoring systems and tighter quality control protocols could mitigate deviations and improve overall product consistency, thereby aligning production outputs more closely with industry standards.

Future studies should prioritize comprehensive root cause analysis to identify factors contributing to the instability in average nickel content. Methodologies such as Failure Mode and Effects Analysis (FMEA) or Design of Experiments (DoE) are recommended to systematically investigate process parameters. Additionally, examining the influence of raw material variability and process conditions on nickel content may yield valuable insights for further process optimization.

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