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Optimizing Dry Bulk Port Performance: Development of Adaptive DMAIC 4.0 Framework Integrated with Lean Six Sigma for Indonesian Ports

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Abstract: Continuous improvement in service quality assurance, based on customer satisfaction, is critical for loading and unloading activities at dry bulk ports. Many ports are now adopting and refining various methods in response to the advancements of Industry 4.0. This research aims to develop and implement Adaptive DMAIC 4.0. Key advantages of this method include IoT based real-time monitoring systems, predictive data analytics, and process automation capabilities. Current Six Sigma measurements show level 3 (DPMO 11,800). While the Cp value of 1.19 indicates stable process stability, the Cpk value of $0.76 < 1$ reveals remaining issues requiring systematic, continuous improvement. To enhance process performance, the average loading/unloading time should be maintained closer to the target midpoint of 1.5 minutes/bulk, creating a more balanced distribution. This adjustment would help increase the Cpk value to meet the minimum standard $\geq$ of 1.33, ensuring consistently efficient operations. In theory, implementing the DMAIC 4.0 framework will establish a system that is more resilient to internal and external disruptions, enables sustained performance improvement, and drives toward zero defects and Six Sigma capability. In practice, this approach significantly enhances loading and unloading performance for boosting capacity, operational capability, and TKBM professionalism while eliminating human error.

Keywords: Dry bulk port performance; Industri 4.0 in ports; Smart port; Lean Six Sigma; Adaptive DMAIC 4.0

1 Introduction

International dry bulk ports face increasingly complex challenges due to the imbalance between global trade volume growth and limited infrastructure capacity [1]. This situation is further exacerbated by geopolitical dynamics such as the tariff war between the United States and China, fluctuations in global market demand, and pressure to improve logistics efficiency [2]. As a result, there is uncertainty in the flow of goods between countries, which directly impacts port performance, especially in developing countries [3].

Dry bulk ports experience various structural and operational constraints that can affect the quality of service [4]. Users of loading and unloading services at the port frequently face several challenges, including long waiting times, excessive dust generation during operation, reliance on manual equipment, limited operational flexibility due to the diverse cargo types, and minimal adoption of automation technology [5]. This problem stems from multiple interconnected factors, including technological limitations, fragmented regulations, and evolving global economic pressures [6, 7]. This situation requires a systematic and standardized approach to enhance the quality of port services, particularly in the dry bulk sector, which is highly susceptible to inefficiency. Improvement is not enough to be done just by updating the physical infrastructure.

However, it also requires business process reform, the adoption of suitable digital technologies, and the implementation of performance-based operational standards [8, 9]. The Strategy to improve the quality of port services must also consider the complexity of the overall logistics system, as well as local needs, to respond effectively and sustainably to global challenges [8, 9].

As the demand for efficiency and sustainability increases, global ports have adopted various quality management approaches, including Total Quality Management (TQM), the ISO 9000 series, Six Sigma, and Lean Six Sigma [10]. These fourth approaches have proven effective in improving the quality of service and products in various sectors. Furthermore, both Lean and Sigma methods are integrated into Lean Six Sigma. Lean Six Sigma is a method for identifying waste in industries that utilizes a measurement model based on the Six Sigma concept.

Lean Six Sigma is a strategy commonly used to improve operations in the manufacturing, healthcare, automotive, and electronics industries. The Six Sigma method emphasizes measuring process capabilities and calculating sigma levels to achieve zero waste conditions, while Lean principles focus on identifying and reducing waste [11, 12]. However, the application of Lean Six Sigma in the port services sector has distinct characteristics compared to its application in the manufacturing industry [13–15]. In the manufacturing sector, product quality is measured based on the tolerance of deviations from a particular standard. Products that exceed tolerance limits are considered defective and must be rejected [10, 13, 16, 17].

In the port sector, service quality is primarily measured by speed and punctuality. Exporter and importers perceive faster services as higher quality. In the international port service industry, the critical quality standard for loading and unloading is 3 minutes [18]. The application of Six Sigma in the dry bulk loading and unloading process is crucial because time and efficiency are primary factors in determining service quality. The readiness of equipment significantly influences the speed and efficiency of the operational system, the competence of the loading and unloading workforce, and the condition of the port infrastructure [10, 12, 18].

Furthermore, in the era of Industry 4.0, Lean Six Sigma theory has evolved into Lean Six Sigma 4.0, indicating that the application of Industry 4.0 technology can enhance the implementation of Lean Six Sigma. The integration of LSS and Industry 4.0 concepts is inadequate in conceptualizing gradual improvements. To identify the impact of integrating Industry 4.0 and Lean Six Sigma, it is necessary to employ structured and systematic methods, and the entire desired improvement process must be thoroughly documented. The technique that is often used is DMAIC (Define, Measure, Analyze, Improve, Control).

According to Wang et al. [19], many industries have successfully integrated DMAIC, Lean Six Sigma, and Industry 4.0 methods to enhance their production activities. Most of the focus on material and information flow in the manufacturing industry remains limited, particularly in case studies of the port service industry, especially for dry bulk ports. Therefore, this research was designed to implement an Adaptive DMAIC 4.0 concept. Adaptive DMAIC 4.0 is a problem-solving approach driven by Lean Six Sigma, supported by the concepts of quality improvement through fishbone diagrams and the 5W + 1H method, as well as the principles of Industry 4.0. It consists of five stages of procedures for improving existing process problems based on the scientific method [19–24].

The Adaptive DMAIC 4.0 concept was developed to improve the shortcomings of the conventional DMAIC concept, which has been previously applied to the port industry. The conventional DMAIC method still uses a manual measurement method. Hence, several factors cannot be identified in real-time. According to Skalli et al. [25], There are several weaknesses of conventional DMAIC such as lack of support management and third-party commitment, lack of motivation, lack of skills and Training in loading and unloading work, resistance to changes in work behavior, technological limitations, all of which are sources of inefficiency and wasted costs. In this context, the background for designing new measurement methods is to achieve greater precision and control.

To address these challenges, this study introduces the Adaptive DMAIC 4.0 framework, an innovative integration of Six Sigma, DMAIC methodology, Industry 4.0 technologies, and Lean Principles, specially adapted for developing country port operations [16, 19]. The novelty of this model lies in the flexibility of the DMAIC phase, which can accommodate fluctuations in ship arrivals, the complexity of local customs regulations, and the utilization of mid-level digital technologies such as simple IoT and cloud-based analytics [20, 21].

Theoretically, this study contributes to the development of a Six Sigma framework relevant to the context of port development. In practical terms, the DMAIC and Lean Process based approach offered is expected to be an operational blueprint for port managers, especially in: (1) reducing logistics costs through the elimination of waste, (2) increasing service speed with process automation, and (3) creating operational standards that can be developed in various types of ports [6, 22, 23]. Through this approach, the loading and unloading process is expected to run faster, more efficiently, and more consistently, increasing the port's competitiveness, attracting more logistics service users, and supporting more modern and competitive port management.

Therefore, this research has two objectives: First, to develop an Adaptive DMAIC 4.0 framework that integrates Lean Six Sigma and Industry 4.0 technologies for dry bulk ports. This innovative approach is designed to be flexible and responsive in addressing real-time loading/unloading challenges. Second, to implement and evaluate the framework by measuring Six Sigma performance and process capability for loading/unloading operations at Indonesian dry bulk ports. This research consists of six stages, namely: 1. Introduction; 2. Literature Review; 3.

Research Methods; 4. Results; 5. Analysis and Discussion; and 6. Conclusion.

2 Literature Review

The development of industry in the digital era is driving the evolution of traditional Lean Six Sigma (LSS) methodologies into more Adaptive DMAIC 4.0 frameworks [24, 25]. The Lean Six Sigma, integrated with the DMAIC Adaptive 4.0 framework, emerged as an integrated approach that combines conventional LSS principles with Industry 4.0 technology, utilizing the DMAIC concept [26]. This integration enables organizations to achieve more precise, efficient, adaptive, flexible, and sustainable process improvements in the face of the complexities of the modern business environment. The application of this methodological approach aligns with the overall research objective of investigating how quality management instruments, which were initially designed for the manufacturing sector, can be adapted to the typical attributes of port [24, 27].

The development and implementation of this approach are carried out in stages, according to the capabilities and policies of each industry. In the initial stage of implementing this concept, the industry first unifies a vision for the sustainable implementation of quality management throughout the production chain. Then, slowly, all employees understand the importance of applying the Adaptive DMAIC 4.0 concept, and it becomes a necessity in the industry. The gradual application of Adaptive DMAIC 4.0 can be seen in various industrial sectors. One of the applications of this framework can reduce packaging overweight by up to 46% in manufacturing sectors, such as biscuit production, increasing the process sigma level [25].

Meanwhile, boiler efficiency increased from sigma level 2 to 3 in the pulp and paper industry, resulting in a 76% reduction in defects [25]. The cosmetics industry also leverages DMAIC to expedite the product filling process, resulting in a 14.86% reduction in cycle time [28]. The manufacturing industry is showing better results with a significant increase in sigma levels in the production of brushless motors, from 5.11σ to 5.44σ, through the implementation of artificial intelligence-based inspections and data-driven supplier selection systems. In the manufacturing sector, Integrated LSS and Advanced DMAIC 4.0 support the creation of a more sustainable and responsive production system. Intelligent equipment coordination through IoT helps reduce energy and material waste, while digital twin technology enables mass customization without sacrificing efficiency [25].

The application of the Adaptive DMAIC 4.0 framework in the port service industry differs from that in the manufacturing industry [25]. In the manufacturing sector, the production quality is judged by the suitability of the product's technical specifications. If the size of a product exceeds the tolerance, the product produced is declared defective and unfit for market [10, 13, 16, 17]. On the other hand, in the loading and unloading service sector at the port, the quality of service is more determined by the speed of response and punctuality, which directly affect the service level satisfaction [10, 12, 18].

Therefore, in this study, to improve the inefficiency of loading and unloading port services, the concept of Adaptive DMAIC 4.0 is applied, which is an integrated model combining the principles of Lean Six Sigma and the Industry 4.0 concept. Research on integrating Lean Six Sigma with Industry 4.0 using the DMAIC methodology is a novel approach [29]. Contextually, this model has been modified from the operational concept of a conventional port to accommodate the operational realities encountered in ports [12]. There is a difference between traditional DMAIC versus Adaptive DMAIC 4.0 frames as shown in Table 1. Traditional models rely on infrastructure, manual operations, and labor-intensive operational workflow.

Table 1. DMAIC Conventional vs. Adaptive DMAIC 4.0

Aspects	Conventional DMAIC	Adaptive DMAIC 4.0
Supporting technology	Manual, basic statistical tools	IoT, AI, big data, cloud computing
Data collection	Manual sampling is prone to human error	Automatic via sensor & real-time monitoring
Data analysis	Traditional statistics (Regression)	Predictive analytics, machine learning
Speed	Slow (Depending on the team)	Fast (Automated & real-time computing)
Problem detection	Reactive (After occurring)	Proactive (Predict anomaly early)
Solution implementation	Physical trial and error	Digital Simulation before execution (Digitalization)
Process control	Periodic monitoring (SPC manual)	Control automatically with AI & adaptive
Implementation costs	Relatively low (Simple tool)	High (IT infrastructure & specialized Training)
Conformity	Simple problems	Complex industries (Manufacturing 4.0, logistics)

Meanwhile, the Adaptive DMAIC 4.0 framework is specifically designed to operate effectively in delivering services through advanced process digitalization and more efficient processes, with minimal integration of Internet of Things (IoT) technology and cloud-based data analysis [26]. Digital technology is necessary at each stage of the DMAIC process to enhance the accuracy of repairs, as it facilitates time savings in each loading and unloading activity. Digitalization, including data mining, machine learning, big data analytics, and intelligent sensors, can enable real-time data collection, reduce reliance on manual inputs, and enhance the reliability and validity of measurements [25].

The conceptual framework of Adaptive DMAIC 4.0 is divided into three main pillars, namely people, processes, and technology. The people aspect emphasizes the importance of developing digital competencies in loading and unloading work, while the processes pillar focuses on automation and data-driven optimization [29]. Technology is a key driver of the success of the Adaptive DMAIC 4.0 framework. The loading and unloading workforce must fully comprehend digital transformation in port operations. Particularly, its role is in enhancing process efficiency, improving energy utilization, and eliminating time waste. This understanding also encompasses how to enhance customer satisfaction by leveraging digital devices such as AI, IoT, and digital predictive analytics through Lean Six Sigma [13].

The synergy between Lean and Six Sigma, known as Lean Six Sigma, is a process quality measurement concept that identifies various wastes in the production process within an industry. This concept can also be utilized to enhance the quality of the loading and unloading process at international ports, particularly when combined with the DMAIC and Industry 4.0 frameworks. The advantage of this integrated approach lies in its exceptional flexibility and rapid adaptability to changes. Each stage in the Adaptive DMAIC 4.0 cycle is designed to adapt to the dynamics of dry bulk port operations, including fluctuations in ship arrivals and document validation, as well as the diverse types of cargo vessels. Furthermore, incorporating lean principles enables systematic identification and elimination of non-value-added activities and time waste. This dual approach enhances service speed while minimizing logistics costs [29].

This research process includes several main stages:

1. Define Phase. In this Phase, a thorough analysis of port operations was conducted through interviews with relevant parties, the collection of primary and secondary data, and direct reporting. Define Phase finds service bottlenecks and issues that customers often complain about [10].

2. Basic Measurement (Measurement Phase). Operational data, including ship waiting time, loading and unloading duration, tool usage, and worker performance, are collected and analyzed. Data measurement is carried out using statistical calculations to calculate the achievement of operational DPMO [30].

3. Root Cause Analysis (Analysis Phase). Various methods, such as the Fishbone Diagram, Pareto Chart, and FMEA (Failure Mode and Effects Analysis), are used to identify the primary cause of inefficiency [16].

4. Intervention Design (Upgrade/Analyze Phase). At this stage, a process capability analysis is conducted in collaboration with stakeholders. Furthermore, the Adaptive DMAIC 4.0 team designed alternative solutions to improve service processes through automation, workflow simplification, and digitization [26].

5. Sustainability Assurance (Control Phase). At this stage, a performance monitoring system is designed using KPIs (Key Performance Indicators) that are displayed on the dashboard and regularly audited. The goal is to keep repairs effective for a long time [11].

Implementing Adaptive DMAIC 4.0 in port operations can significantly enhance efficiency, minimize time wastage, and boost overall productivity. Lean Six Sigma, which combines lean manufacturing principles with Six Sigma tools, aims to optimize processes by reducing variability and eliminating waste [26]. The Adaptive DMAIC 4.0 (Define, Measure, Analyze, Improve, Control) framework is a structured approach in Lean Six Sigma that drives process improvement. Integrating Industry 4.0 technology into DMAIC, also known as Adaptive DMAIC 4.0, can increase its effectiveness through advanced data analysis and automation. This approach is particularly beneficial for complex and dynamic port operations [11].

The integration of Industry 4.0 technologies, such as Big Data Analytics and the Internet of Things (IoT), strengthens the Adaptive DMAIC 4.0 framework by enabling data-driven decision-making and real-time monitoring. Automation also enhances the efficiency of port operations, for example, in logistics management and cargo handling, thereby reducing reliance on manual labor [31]. Additionally, predictive maintenance based on Industry 4.0 technology helps minimize equipment downtime and extend asset life, thereby enhancing operational reliability [26].

The success of Adaptive DMAIC 4.0 is supported by statistical and quality management tools, such as process capability analysis, factorial design experiments (DOE), fishbone diagrams, and the 5W + 1H method [29]. These tools help integrate and determine the right solution. As a result, various case studies show increased productivity, reduced costs, and process stability. For example, in the automotive industry, the rejection rate of brushless motor products decreased after implementing this framework, resulting in an increase in the sigma level from 5.11 to 5.44 [13].

Although effective, implementing Lean Six Sigma in the Adaptive DMAIC 4.0 framework for port operations poses challenges. Integrating advanced technology requires a significant investment and a skilled workforce to manage the system [26, 29]. The complexity of port operations also demands solutions tailored to specific needs. Stakeholder resistance to change must also be overcome through effective management strategies. However, the potential for increased efficiency and productivity makes this approach very valuable for modernizing port operations [11].

In the future, the development of the Adaptive DMAIC 4.0 framework is likely to continue evolving in response to technological advancements. Integration with this concept and generative artificial intelligence is a potential area for further exploration [30]. Researchers who wish to implement this framework are advised to start with a pilot project before committing to full-scale implementation, while ensuring a firm commitment from top management. With the right approach, Adaptive DMAIC 4.0 will be the key framework for achieving operational excellence in the digital era and a crucial contributor to meeting the Sustainable Development Goals [26].

3 Research Methods

This research integrates DMAIC, Six Sigma, Industry 4.0, and Lean principles into the Adaptive DMAIC 4.0 framework. This approach enables real-time monitoring of operational conditions, facilitating the planning and execution of continuous improvement. The framework's implementation provides superior accuracy through real-time data processing, allowing for the rapid identification of failures and waste during loading and unloading activities.

3.1 Research Question, Objective, and Hypothesis

The questions of this research are divided into two research questions, as described in chapter I of the introduction, namely:

RQ1: What is the current state of research integration between Lean Six Sigma, Industri 4.0 technologies, and the DMAIC methodology in the dry bulk port industry?

RQ2: Can the Adaptive DMAIC 4.0 framework significantly enhance operational performance in dry bulk port operations, as evidenced by case study findings?

From the research question, the following research objectives were formulated:

1. Develop an Adaptive DMAIC 4.0 framework that integrates Lean Six Sigma and Industry 4.0 technologies for dry bulk ports.

2. Demonstrate and calculate the effect of the application of the Adaptive DMAIC 4.0 framework to increase operational performance significantly through a case study of the dry bulk port industry.

From the Objective Research, the following research hypotheses were formulated:

H_0: The application of the Adaptive DMAIC 4.0 framework has no significant effect on increasing operational performance through a case study of the dry bulk port industry

H_1: The application of the Adaptive DMAIC 4.0 framework has a significant effect on increasing operational performance through a case study of the dry bulk port industry.

3.2 Research Framework

As illustrated in Figure 1, the Adaptive DMAIC 4.0 Framework, specifically designed for dry bulk ports in Indonesia, lies at the core of this research. This framework facilitates systematic process improvement by integrating Six Sigma's defect-reduction capabilities with Lean's emphasis on waste elimination. It is contextually adapted to accommodate the infrastructural and digital constraints commonly encountered in developing country ports. The Adaptive DMAIC 4.0 framework consists of five stages: Define (define the problem), Measure (measure current performance), Analyze (find the root cause of the problem), Improve (implement a solution), and Control (ensure the sustainability of the improvement) as presented in Figure 1.

The Define stage consists of detailing the project goals and problem statement, Data structuring and analysis, Real-time data Collection, Customer needs identification based on collected data, Data technical requirements, and Trend data analysis for goal setting.

At the Measure stage, the Six Sigma measurement and capability process is used. Six Sigma is a quality improvement methodology that reduces variations and defects in production processes or services. From a statistical perspective, Six Sigma is defined as having fewer than 3.4 defects per million opportunities (DPMO) or a success rate of 99.9997% [10, 12]. At this measure stage, process stability prediction improved data collection, big data collection, online measurement system analysis, UCL, CL, LCL, Cp, and Cpk measurement analysis, as well as DPMO measurement analysis.

At the Analyze stage, data analysis of crane operation, identify and evaluate potential causes with a fishbone diagram, real-time analysis of measurement data, data processing at the source for accurate real-time measurements, find the inefficient tasks, generate ideas for reducing waste with 5W + 1H, process modelling to identify inefficiencies. At this stage of the analysis, the lean process improvement is used. Lean Process is a business philosophy that eliminates waste to create more efficient and faster workflows. Unlike Six Sigma, which emphasizes quality, lean focuses more on speed and efficiency by eliminating waste, such as overproduction, waiting time, or unnecessary movement [11, 32].

At the Improve stage, optimization of the solution, automation of tasks, implementation of the solution with interconnection of systems, validation of the improvement of SOP based on historical data, Simulation of improvement solutions, Automation tasks, rescheduling to accommodate improvements, Scheduling training, and scheduling of operators

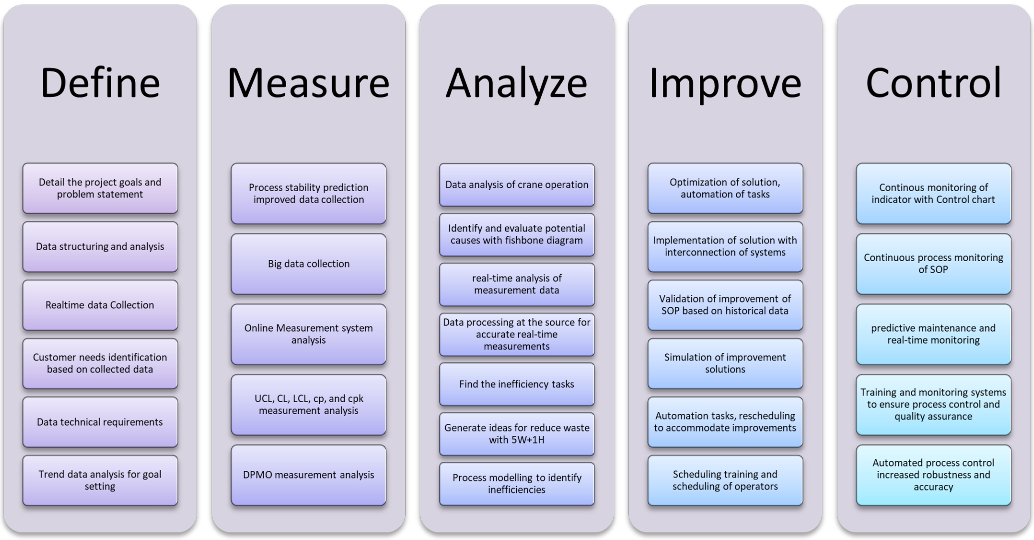

Figure 1. Adaptive DMAIC 4.0 research framework [11, 26]

At the Control stage, continuous monitoring of indicators with control charts, continuous process monitoring of SOPs, predictive maintenance, and real-time monitoring are employed. Training and monitoring systems are implemented to ensure process control and quality assurance. Automated process control increases robustness and accuracy.

At the port, the flow of loading and unloading operations is illustrated in Figure 2. A Cargo Ship (1) is docked with a fully loaded cargo of containers ready to be unloaded. The crane (2) moves to carefully lift the items. Some containers are directly loaded into the Loading Cargo Truck (5) to be delivered immediately to the Customer (6), ensuring fast delivery without going through storage. Meanwhile, other containers were transferred from the Unloading Cargo Truck (3) to the warehouse (4) for temporary storage before being transported back by the Loading Cargo Truck (5) to their destination. The process depicts harmonizing heavy equipment, transportation, and supporting facilities in an integrated logistics chain [18]. However, this study only discusses the process of unloading dry bulk from ships using harbor mobile cranes equipped with a grab bucket to cargo trucks (processes 1, 2, and 3).

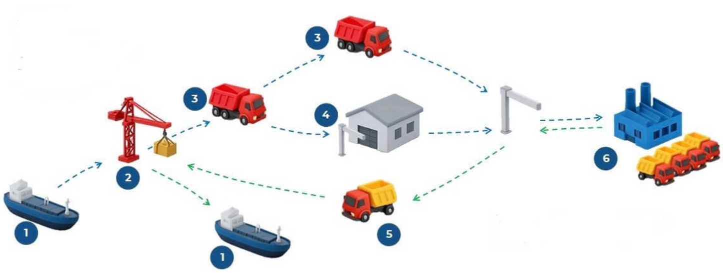

Figure 2. Loading and unloading operation flow at the port

3.3 Research Location and Duration

The research was conducted at a major international seaport in Cilegon City, Indonesia, focusing on optimizing dry bulk cargo handling services. The research location for this case study was chosen because this port is one of the busiest ports, which shares similar characteristics with dry bulk ports in Indonesia, including the loading and unloading service process and the loading and unloading technology used, namely the harbour mobile crane (HMC). The products unloaded at this port are corn, meal, soybeans, coal, gypsum, sugar, and iron ore. This study spanned three months from September to November 2024, during which various operational aspects of the port were analyzed. The choice of location was influenced by the port's strategic importance in Indonesia's maritime logistics network, aligning with recent studies on global dry bulk shipping patterns and efficiency optimization.

3.4 Data Collection Techniques

This research was conducted by collecting primary and secondary data. This primary data collection is carried out by taking direct data through interviews and field data. Meanwhile, secondary data were obtained from previous research, literature studies, and relevant journals related to the studied problems [12, 15]. This research is field research, which involves direct observation of the object of study. The research is quantitative and conducted through observation and data processing. The data used in this study include loading and unloading supporting equipment and port facilities, operation time data for loading and unloading handlers, and information on the number of loading and unloading ships. The data were processed using the Six Sigma DMAIC, fishbone, and Lean Process methods, as well as the 5W + 1H approach [12, 33]. The data on operating time for loading and unloading handling refers to the time spent on loading and unloading activities carried out 24 hours a day. Table A in Appendix presents data on the operating times for loading and unloading handling at the port.

After that, the results of the calculations for Cp, Cpk, and Six Sigma were discussed through focus group discussions and direct interviews with port operators, operations managers, and loading and unloading supervisors at the port. All of these factors were validated and agreed upon collectively, allowing for the collection of data on the root cause of waste and loading and unloading delays, as outlined in the fishbone diagram and the 5W + 1H method.

4 Result

Based on Table A in Appendix, the operating time data on each ship that loads and unloads at the port is the time of commencing, time of finish, alley, number of bulks loaded and unloaded, operation time (hours), number of bulks per hour handled, operation time per bulk (minutes). The commencement time is when the ship begins the loading and unloading process. Furthermore, the time of completion is when the vessel has finished the loading and unloading operation process. An alley is the number of workers in a single working group at the port. Furthermore, the number of bulk loads and unloads is the amount of bulk unloaded and loaded.

Meanwhile, operation time (in hours) refers to the operating time per hour. Furthermore, the number of bulks per hour handled refers to the total number of bulks processed, and the operation time per bulk (in minutes) represents the time required for each bulk. Furthermore, the collected data will be verified to ensure the absence of outlier data, and whether the data has a normal distribution will be determined through the results of the Kolmogorov-Smirnov and Shapiro-Wilk Tests [10, 18].

4.1 Data Normality Test

The normality test aims to determine whether the disruptive or residual variables follow a normal distribution. Below are the output results of SPSS. The results of the data normality test are presented in Table 2. The Kolmogorov-Smirnov and Shapiro-Wilk tests are used because the sample size exceeds 50 [18]. The results of the Kolmogorov-Smirnov and Shapiro-Wilk tests are as follows:.

Table 2. Results of the kolmogorov-smirnov and shapiro-wilk test

	Kolmogorov-Smirnov[a]			**Shapiro-Wilk**		
	Statistic	df	Sig.	Statistic	df	Sig.
Operation time (min)	0.094	52	0.200*	0.958	52	0.064

Note: *. This is a lower bound of the true significance; a. Lilliefors Significance Correction

As shown in Table 2, the normality test results confirm that the operation time data follows a normal distribution. This is demonstrated through two statistical tests: the Shapiro-Wilk and Kolmogorov-Smirnov tests. In the Shapiro-Wilk test, a statistical value of 0.958 was obtained with a degree of freedom (df) of 52 and a p-value of 0.064. Meanwhile, the Kolmogorov-Smirnov test yielded a statistical value of 0.094 with the same degree of freedom and a p-value of 0.200. Both test results showed a p-value greater than 0.05, indicating that the data were normally distributed. Furthermore, DPMO measurement can be calculated [10, 18].

4.2 DPMO Measurement

Based on Table 3 below, the operation time per bulk (in minutes) at the port, with the number of samples collected, this research utilized 52 samples. The following is Table 3 of the operating time data statistics:

Based on Table 3 of the operating time data statistics, the average operation time is 2.040 minutes, and the standard deviation is 0.4243. The calculation of the average X, Standard Deviation, and DPMO is as follows:

$$\bar{X} = \frac{\sum_{i=1}^{m} \overline{Xi}}{n} = \frac{106.01}{52} = 2.040 \tag{1}$$

Table 3. Data statistics of operation time Adaptive DMAIC 4.0

Statistics		
Operation time per bulk		
N	Valid	52
	Missing	0
	Total	106.01
	Mean	2.040
	Std. Deviation	0.4243

$$S = \sqrt{\frac{\sum_{i=1}^{n} \left(X_i - \bar{X}\right)^2}{n-1}} = 0.4243 \tag{2}$$

In this study, the international USL standard set according to consumer demand is 3 minutes/bulk, so that the calculation Z_{USL} is as follows:

$$Z_{USL} = \frac{(USL - \bar{X})}{S} = \frac{(3 - 2.040)}{0.4243} = 2.2625 \tag{3}$$

If known Value, Z_{USL} = 2.2625 $\rightarrow P\left(Z_{USL}\right) \cong$ 0.9882, and U_{LS} = 0, then, $Z_{satisfied}$, Z_{defect}, and the value of $DPMO_{current}$ can be determined through the following formula:

$$Z_{satisfied} = P\left(Z_{USL}\right) - P\left(Z_{LSL}\right) \tag{4}$$

$$\begin{gathered} Z_{satisfied} = 0.9882 - 0 = 0.988 \\ Z_{defect} = 1 - P\left(Z_{satisfied}\right) = 1 - 0.9882 = 0.0118 \end{gathered} \tag{5}$$

$$\begin{gathered} DPMO_{current} = P\left(Z_{defect}\right) \times 1,000,000 \\ DPMO_{current} = 0.0118 \times 1,000,000 = 11,800 \end{gathered} \tag{6}$$

Based on the calculations above, DPMO (Defects Per Million Opportunities) currently stands at 11,800. It can be concluded that the surgical process has a relatively high defect rate. This value shows that out of 1 million surgery opportunities, it is estimated that 11,800 surgeries exceed the upper specification (USL) limit. In the context of quality control, industry standards, such as Six Sigma, target a DPMO of below 3.4 (an almost defect-free level). Therefore, the current value indicates how much process performance is at Indonesia's industry average sigma 3 level. The process with 11,800 DPMOs is already good because it is close to the average US industry standard; however, it still needs improvement to achieve world-class quality.

Next, to examine whether the average unloading time using the Adaptive DMAIC 4.0 method (C_2) is significantly shorter than that of the conventional DMAIC method (C_1). From the results of the T-Statistic using Minitab, the performance of loading and unloading of dry bulk before and after the application of Adaptive DMAIC 4.0 shows that the value of T-value = 6.39, P-value (two-tailed) = 0.000; one-tailed P-value = 0.000/2 = 0.000; and significance level (α) = 0.05. (See Table 4).

Based on the one-tailed t-test in Table 4, the results show a t-value of 6.39 with a one-tailed P-value $<$ 0.000 (α = 0.05). Since the p-value is below the significance level, the null hypothesis is rejected. These results indicate that the Adaptive DMAIC 4.0 method significantly improves unloading efficiency by reducing the average unloading time from 3.5 minutes to 2.04 minutes. There is strong statistical evidence that the Adaptive DMAIC 4.0 method significantly reduces unloading time compared to the conventional DMAIC method. The average time decreased from 3.5 minutes to 2.04 minutes, indicating a clear improvement in operational efficiency. This testing concludes that the one-tailed p-value is less than 0.05, indicating that H_0 is rejected and H1 is accepted.

This result is better than the results of a study by Wang et al. [19], which examined the quality of service in the container loading and unloading process at the container terminal in port of Keelung in Taiwan which found that the sigma level in the port was still at the level of 1.24 and the resulting defect value was 531,900. Likewise, the calculation of process capability is also poor, with negative Cpk and Ppk values (-0.03). This indicates that measures proposed should be implemented to improve capability [18].

Table 4. Dry bulk performance DMAIC conventional vs Adaptive DMAIC 4.0

T-Statistics Testing		
	Operation time per bulk	
N	Valid	53
	Missing	0
	Total	185.40
	Mean	3.50
	Std. deviation	1.60
	Difference = mu(C_1)-mu(C_2)	
	Estimate for the difference	1.458
	95% C_1 for difference	(1.001:1.914)
	T-test of difference	0
	T-value	6.39
	P-value	0.000
	df	59

5 Analysis and Discussion

5.1 Process Capability Analysis

After understanding the current level of process quality, the next step is to understand the centrality and variations of the process using the control diagram method. The process capabilities were used to assess the degree of dispersion and centralization. The value of process capabilities is calculated using Minitab software.

Figure 3 shows the results of the capability process calculation using the Minitab software. The stability of the capability process is reflected in the value of the UCLx, CLx, LCLx, UCL_R, CL_R, and LCL_R. Based on the I-MR graph method, the values of graph I and the MR graph are plotted, as shown in Table 5.

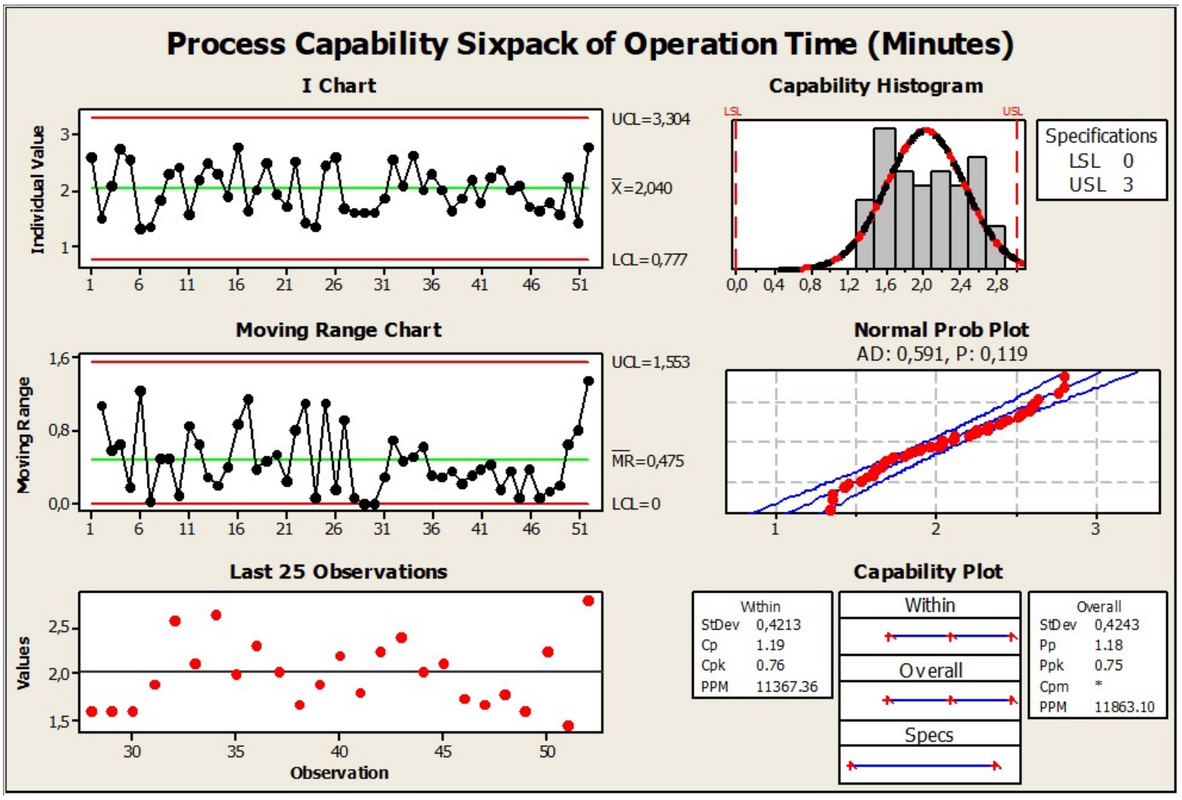

Figure 3. Loading and unloading operation flow at the port

Based on Table 5, the *I-Chart* (Individual Chart) shows an upper control limit (UCLx) of 3,304, a middle line (CLx) of 2,040, and a lower control limit (LCLx) of 0.777, also depicted in Figure 4 of the individual control chart.

Figure 4, *I-Chart*, monitors process stability based on individual data. The graph shows that 52 data points were

Table 5. Calculation of I chart and MR chart

I Chart		MR Chart	
UCLx	3.304	UCL_R	1.553
CLx	2.040	CL_R	0.475
LCLx	0.777	LCL_R	0

between the upper limit of the control (UCL = 3.304) and the lower limit of the control (LCL = 0.777), with the mean of the process ($\bar{X}$) of 2.040. No points beyond the control limits or suspicious patterns, such as successive up/down trends, indicate the process is stable and statistically controlled. The visible variation is natural, so no special corrective action is currently required. Thus, the process can be considered consistent and feasible, although periodic monitoring is necessary to ensure quality.

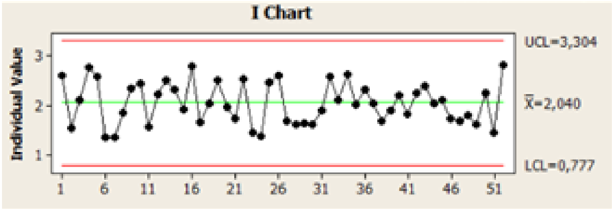

Figure 4. Individual control chart

Meanwhile, in Figure 5, the *Moving Range Chart* is used to monitor how much variation between successive values in the process. This graph shows 52 *moving range values* from individual data, with an average ($\bar{MR}$) of 0.475, an upper limit of control (UCL_R) of 1.553, and a lower limit of control (LCL_R) of 0. Most of the points were within the control limits, but there was one point at the end of the observation that reached the UCL_R, which could indicate a spike in variation between the last two points. In addition, there are some sharp fluctuation patterns at the beginning and middle of the chart, followed by a steady period in the 35th to 51th point range. It shows that there is still irregularity or inconsistency in the movement of data. Therefore, although there is no significant boundary violation other than at the last point, there are indications that the process may alter short-term stability. Consequently, it is necessary to conduct further observations or checks against the causes of increased variation at specific points.

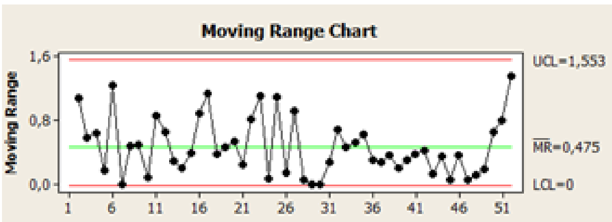

Figure 5. Moving range control chart

Figure 6 illustrates that the Capability Histogram is used to assess a process's ability to meet the product specifications' limits. This graph displays the distribution of data (in histogram form) concerning the specification limits: Lower Specification Limit (LSL) = 0 and Upper Specification Limit (USL) = 3. The red curve indicates the normal distribution of the actual data.

The data distribution is concentrated between the lower specification limit (LSL) and the upper specification limit (USL), with the peak distribution around 1.6 to 1.8. This result indicates that most of the data is within the expected range and is nowhere near the tolerance limit. The shape of the histogram resembles a normal distribution and does not show a significant slope (skew), indicating that the process is running stably and consistently. Additionally, no data exceeded the specification limit, indicating that the entire output remains within the established quality standards.

Furthermore, in the Six Sigma methodology, Cp and Cpk are process capability indices used to measure the extent to which a process can meet specified specifications. Cp is used to measure process capability based on process variation compared to allowable tolerances. In contrast, Cpk is used to calculate actual process capability by considering the process center (mean) and variation. This capability process demonstrates good capabilities, as

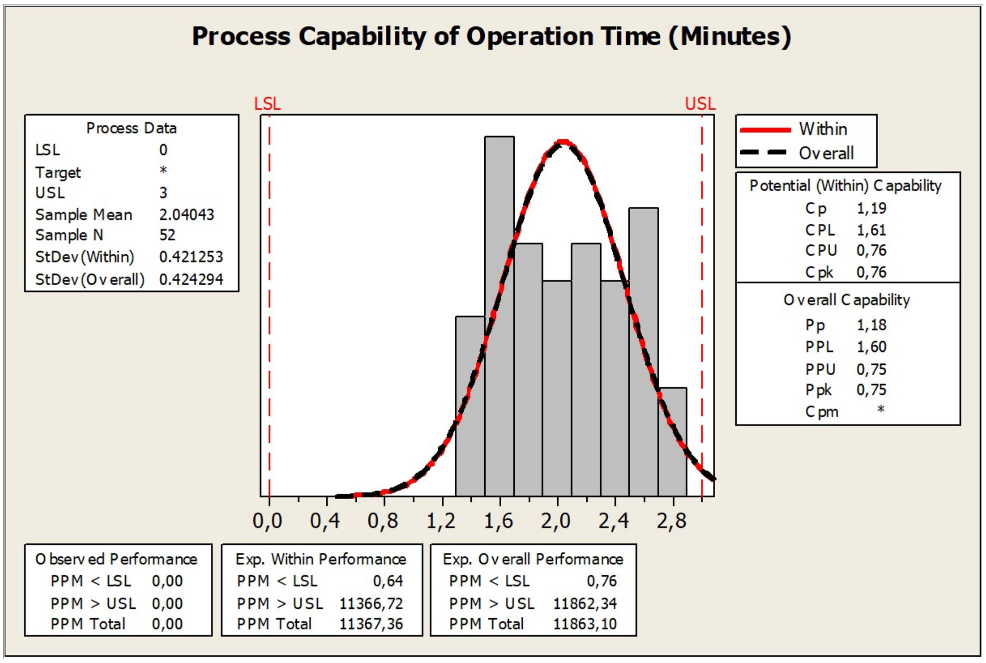

Figure 6. Process capabilities

all data falls within the specification limits, and the distribution is symmetrical, indicating that the process is stable and capable of producing outputs that meet the required quality standards.

From the data calculated using Minitab software, it shows that the value Cp = 1.19, which means that the potential for process capabilities is theoretically quite good because it exceeds the minimum limit of 0, however, the value of Cpk = 0.76 indicates that the actual process is not able to meet the specifications because the value is still below 1.0, and average process of 2.04 is too close to the upper limit of the specification (USL = 3.0), so the risk of cargo handling targets exceeding the 3.0-minute target in each process remains high. Meanwhile, the distance to the limit where LSL = 0 is still safe, as indicated by the value of CPL = 1.61.

To improve process performance, it is necessary to maintain the average loading and unloading process time near the midpoint, which is 1.5 minutes, thereby achieving a more balanced distribution. The process variation (standard deviation = 0.42) needs to be reduced through parameter optimization or stricter control. By following these steps, the Cpk value can be increased to meet the minimum standard of 1.33, thereby improving the process efficiency. The minor difference between the Cpk (0.76) and Ppk (0.75) values also suggests that the variation comes from internal sources.

5.2 Analysis of the Causes of Waste

The international standard for the operational performance of dry bulk loading and unloading at the port is set at three minutes/bulk [18]. Based on the results of Six Sigma calculations and process capability analysis, it is possible to infer that the overall operational performance is relatively good, with an average of 2.04 minutes/bulk, still within the specified standard limits. However, the analysis also revealed that in some cases, the operating time exceeded the established standards. Some of the primary factors contributing to this mismatch include adverse weather conditions, equipment damage, and varying operator skills.

To better understand the root cause of the problem, the fishbone diagram approach, as shown in Figure 7, is used. This diagram categorizes potential causes into five categories: port capacity, climate change, loading and unloading workers, work procedures, and equipment/machines. This analysis shows that operator skills, inefficiencies in work procedures, suboptimal tool conditions, and external factors such as weather are crucial factors that need immediate attention.

One of the critical findings from field observations is that the skills of crane operators significantly determine productivity. Harbor mobile crane (HMC) operators with only about three months of work experience tend to exhibit suboptimal performance, characterized by less efficient tool movements, such as lifting the grab bucket too high. The shift work system in the Loading and Unloading Workforce (TKBM) has also proven ineffective. Some shifts last up to 24 hours without adequate division of work time, leading to physical exhaustion. As a result, work is often completed early (for example, before 07:00), and there are delays in shift changes, such as the third shift, which should start at 00:00 but is often delayed until 01:00 due to more extended rest periods.

The hook cycle time on the new HMC was also found to be slower due to operators not being fully trained, resulting in inefficient tool movement. The loading and unloading process is also often disrupted by equipment damage, both on a small scale, such as overheating engines and stalled conveyors, or on a large scale, such as module malfunctions or the condition of old ship hatches. Additionally, idle time has increased significantly due to the truck dispatch system, as delays in truck arrival cause heavy equipment to stop operating. This problem is exacerbated by the mismatch between the number of trucks and projected needs, the distance of the consignee warehouse, and external disturbances such as congestion and flooding, especially during the rainy season.

Weather factors, especially rain, also greatly affect the smooth loading and unloading activities. Because dry bulk loads are easily damaged if exposed to water, loading and unloading activities are usually stopped as soon as clouds appear in the sky, without waiting for rain to fall, and giving time to close the ship's hatch, which is the full authority of the ship's captain. In addition, unpredictable conditions around warehouses, such as flooding, congestion, or long distances from the port, also significantly impact delays in trucks returning to the terminal.

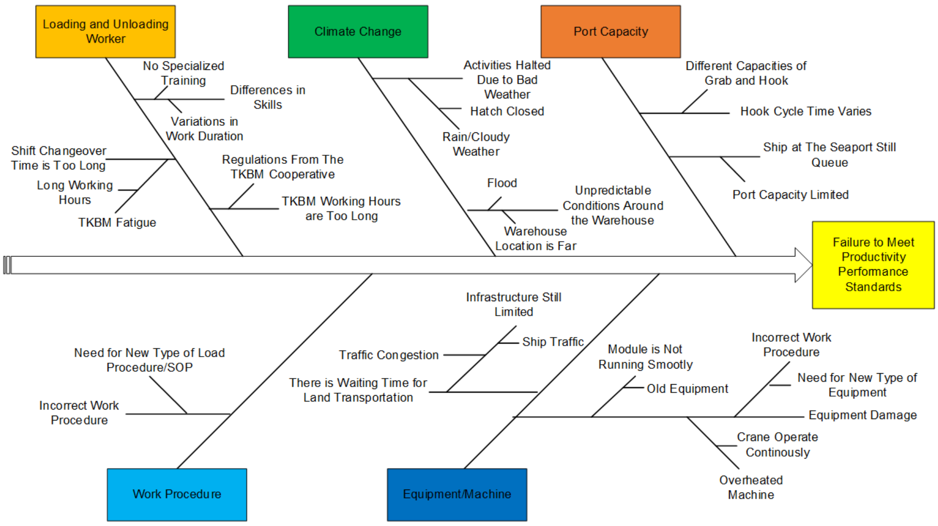

Figure 7. Fishbone diagram

The type of charge also affects the duration of the hook cycle time. Bulk loads such as corn and soybean meals have a faster cycle time than cargo in bag packaging, due to the larger crane carrying capacity for bulk loads. Nevertheless, lifting bulk loads requires a certain pause to avoid spills, while bag loads have volume limitations per cycle that slow down the process. The Lean Six Sigma analysis revealed that ship cranes generally yielded lower productivity than HMCs, despite the latter's proven ability to meet performance targets. Nonetheless, the high rental cost of HMCs presents a significant constraint to maximizing their use. The process capability index (Cp) was calculated at 1.19 (with USL = 3 min and LSL = 0 min), indicating that the process is not fully capable due to high execution variability.

To address these findings, several strategic recommendations were developed:

- Specialized training programs for heavy equipment operators should be aligned with Standard Operating Procedures (SOPs) tailored to specific cargo types and conditions.
- A cost-efficiency reassessment of HMC leasing schemes should be carried out to facilitate wider utilization.
- Preventive maintenance routines should be enhanced and systematically scheduled to reduce technical disruptions.
- The shift system for dock workers needs to be restructured to minimize fatigue and maintain operational continuity.
- Stakeholder coordination should be strengthened, involving port operators, equipment providers, trucking companies, and consignees to ensure synchronized and efficient unloading processes.

5.3 Lean Process Analysis and Waste Reduction Strategy

Building upon the root cause analysis using the 5W + 1H framework and fishbone diagram, several process improvement proposals were designed to enhance efficiency and minimize waste in dry bulk unloading operations at the port. The proposed improvements include:

1. Regular and targeted Training for TKBM personnel to enhance their skills following operational needs.
2. Revised shift scheduling, ensuring efficient transitions while maintaining workers' right to adequate rest.

3. Enhanced weather monitoring systems and emergency response training to reduce full work stoppages during adverse weather.

4. Reorganized operational planning, incorporating contingencies for logistical challenges such as traffic and warehouse distance, and identifying alternative storage sites.

5. Standardize port capacity, crane capacity, and cargo packaging types to achieve consistency and operational efficiency.

In the Control phase, several follow-up strategies were implemented to monitor and sustain the improvement process:

1. Dissemination of recommendations across all personnel and stakeholders to ensure shared understanding and commitment.

2. Phased implementation, prioritizing urgent improvements while maintaining overall alignment with operational goals.

3. Hands-on continuous Training for personnel on revised work methods based on updated SOPs.

4. Regular internal audits to track implementation effectiveness and compliance with new procedures.

5. Performance re-evaluation, comparing pre- and post-implementation data to assess the impact and success of the interventions.

If some obstacles or results do not reach the desired target, corrective action or revision will be taken to improve follow-up. The proposed improvements are expected to significantly improve the quality and reliability of port loading and unloading services.

This study employs problem-based improvement analysis to identify operational inefficiencies in loading and unloading activities, with a particular focus on the performance and coordination of Loading and Unloading Personnel (TKBM) or dock workers. Table B in Appendix explained a qualitative-descriptive approach, supported by structured observation, document analysis, and stakeholder interviews, to address the waste problem in loading and unloading dry cargo at the port. Each identified problem is analyzed through the 5W + 1H (What, Why, Where, When, Who, and How) framework to formulate appropriate and practical corrective actions. Furthermore, each of these problems is described in detail and solved by the Lean Six Sigma and Adaptive DMAIC 4.0 integration method as shown in Figure 8.

Figure 8 presents a comprehensive analysis that serves as the foundation for developing targeted recommendations and future action plans to optimize operational performance, reduce inefficiencies, and enhance the overall loading and unloading process, thereby increasing safety and reliability.

5.4 Controlling TKBM Performance

The results of the Adaptive DMAIC 4.0 application enabled the identification of an increase in the efficiency level of dry bulk loading and unloading time, reducing it from an average of 3.3 minutes to 2.04 minutes. However, in this study, the Sigma Level value remains at the Sigma 3 level, corresponding to a DPMO value of 11,800, indicating that the level of Sigma is still the national industry average. The process capability is quite good, with a Cp value of $1.19 > 0$ and a Cpk value of $0.76 < 1$. This value indicates that the implementation of DMAIC 4.0 continues to encourage service improvement and continuous supervision, particularly through the standardization of capabilities among all crane operators via intensive Training. Loading and unloading workforce training at dry bulk ports includes technical, safety, regulatory, and operational aspects. On the technical aspect, TKBM must understand the characteristics of various types of dry bulk cargo product services, TKBM must also understand and be able to operate multiple sophisticated loading and unloading equipment such as harbor mobile crane (HMC), understand the working mechanism of conveyor belts, grab cranes, hoppers, loaders, ship unloaders, and stacker-reclaimers, including the management of warehouse storage systems.

In the aspect of safety and health (K3), it includes identifying risks during loading and unloading, such as dust hazards, material landslides, fires, and accidents involving heavy equipment. TKBM must understand the proper use of personal protective equipment (PPE), including helmets, masks, safety harnesses, safety shoes, and earplugs. The regulatory system's port rules are also introduced, as are labor rules, including employment insurance.

In the management aspect of TKBM, they must understand how to coordinate and work as a team, involving the stevedore, foreman, operator, checker, supervisor, and crew members. This Training is theoretical and practical for 40–80 hours. The measurement system comprises written tests, practice sessions, and interviews. TKBM training is conducted continuously to maintain and update TKBM's professionalism. The effectiveness of the loading and unloading workforce can be measured by examining the targets set for loading and unloading that have been carried out. If the target is not achieved, an evaluation of the cause of the error will be conducted, with a focus on the technical requirements that were not met.

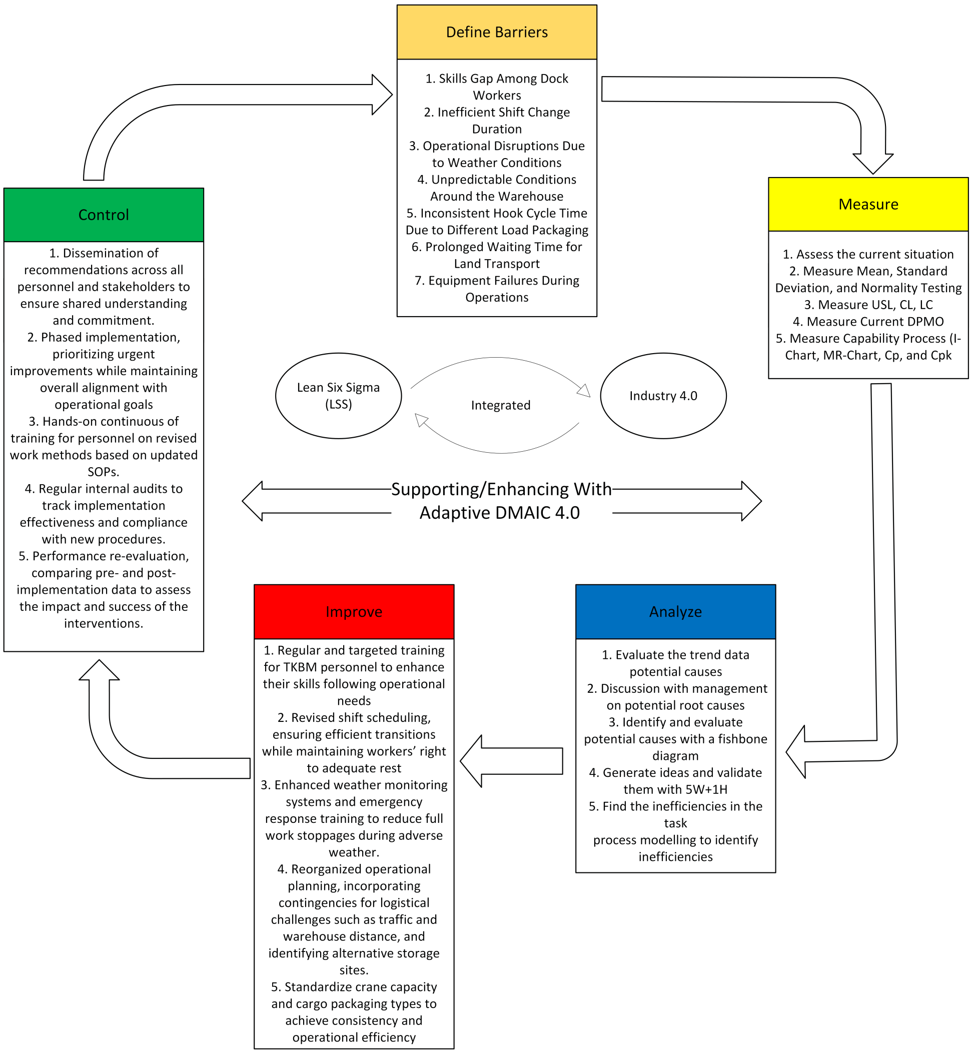

Figure 8. Model of new adaptive integrated Lean Six Sigma and DMAIC 4.0 in the port [11, 26]

5.5 Theoretically and Practically Implications

Theoretically, this study formulates an Adaptive DMAIC 4.0 framework concept in the dry bulk loading and unloading process in the port service industry. This concept represents an innovative methodology that builds upon previous quality management concepts, including Lean Process, Six Sigma, Industry 4.0, and the DMAIC Method itself. The findings of this study provide a measurable model to enhance the competitiveness of port logistics, thereby enriching the quality management literature in the port service industry.

Practically, this method can be applied directly to the loading and unloading process of dry bulk ports and ports in general. This concept has been proven to efficiently improve the performance of dry bulk loading and unloading at the port. In addition, Adaptive DMAIC 4.0 can enhance the capacity, ability, and professionalism level of TKBM to achieve zero human error, as continuous improvements are made. In terms of company performance, the Adaptive DMAIC 4.0 framework can enhance equipment automation programs, digitize the loading and unloading process, and continually implement adaptive standard operating procedures in response to the latest business and technological developments. The implementation of the DMAIC 4 Application will create a system that is more responsive to internal and external disturbances, allowing the performance level to continue increasing towards zero defects and a sigma level of 6.

6 Conclusion

This research develops the Adaptive DMAIC 4.0 framework on the dry bulk loading and unloading process at the port. This method integrates Six Sigma principles, Lean Process management, Industry 4.0, and the DMAIC methodology. The application of the Adaptive DMAIC 4.0 framework in the port industry differs significantly from that in the manufacturing sector. Manufacturing usually relies on product variation or tolerance standards as a reference in identifying defects. Meanwhile, in the port service industry, service quality is measured based on the Critical to Quality targets set by consumers and the industry, as well as the operational readiness of the handling equipment. The faster the cargo handling process is carried out, the higher the customer satisfaction and the more efficient the port's operational performance.

The measurement method employs the Adaptive DMAIC 4.0 framework methodology to achieve greater precision and accuracy, while also identifying the most common errors and waste that occur during loading and unloading processes at dry bulk ports. The Adaptive DMAIC 4.0 framework has significantly improved the efficiency of dry bulk loading and unloading times at the Indonesian port, reducing the average time from 3.3 minutes to 2.04 minutes. However, in this study, the Sigma Level value remains at the Sigma 3 level, or a DPMO value of 11,800, which is still the national industry average. The process capability is quite good, with a Cp value of $1.19 > 0$ and a Cpk value of $0.76 < 1$.

However, there are still some problems that must be improved systematically and continuously. To improve process performance, it is necessary to maintain the average loading and unloading process time near the midpoint, which is 1.5 minutes, thereby stabilizing the distribution. Additionally, the process variation (standard deviation = 0.42) needs to be reduced through parameter optimization or stricter control. By following these steps, the Cpk value can be increased to meet the minimum standard of 1.33, thereby making the process more efficient and consistent.

To improve efficiency as an effort to eliminate waste and human error in the bulk loading and unloading several root problems are found to be immediately monitored and improved, including the prediction of dire weather predictions that stop loading and unloading activities, delays in the arrival of transportation fleets, damage to loading and unloading equipment such as cranes, conveyors, and differences in operator skill levels. Therefore, this study recommends improvement efforts, namely the need to train and certify operators so that all operators have the same standard capabilities, improve the shift system to be more efficient, increase the frequency of equipment maintenance to prevent damage, increase port capacity, modernize and digitize all loading and unloading processes and equipment, and complete standard loading and unloading operation procedures according to the type of load so that operators understand how to works correctly.

Author Contributions

Conceptualization, S., and M.; methodology, S., D.L.T., A.R.; data analysis, S., M.; data validation, A.R., D.L.T., and S.; formal analysis, S., M.; investigation, D.L.T.; resources, S., M.; data curation, S., M., H.D.Y.; writing—original draft preparation, S., M., H.D.Y.; writing—review and editing, S., D.L.T., H.D.Y.; visualization, S., M.; supervision, A.R.; project administration, A.R., D.L.T.; funding acquisition, S., A.R.; All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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Appendix

Table A. Operation time data

Ship Name	Time of Commencing	Time of Finish	Equipment (Gang) (E)	Number of Bulk Loaded and Unloaded (Ton) (NBL)	Operation Time (Hours) (OT)	Number of Bulk per Hour Handled (NBHH) NBL/(E*OT)	Operation Time per Bulk (Minutes) 60/NBHH
MV, a	2024-08-30 20:56:00	2024-09-01 23:55:00	2	2,348.49	50.98	23.03	2.61
BG, b	2024-09-07 01:11:00	2024-09-08 23:20:00	3	5,460.46	46.15	39.44	1.52
BG, b	2024-09-07 16:50:00	2024-09-09 18:24:00	1	1,408.84	49.57	28.42	2.11
KM, c	2024-09-09 13:30:00	2024-09-12 00:39:00	3	3,856.60	59.15	21.73	2.76
MV, a	2024-09-12 21:50:00	2024-09-14 19:45:00	1	1,068.86	45.92	23.28	2.58
BG, b	2024-09-17 03:15:00	2024-09-19 01:25:00	1	2,075.78	46.17	44.96	1.33
BG, b	2024-09-18 22:16:00	2024-09-21 06:00:00	3	7,439.00	55.73	44.49	1.35
MV, a	2024-09-19 13:53:00	2024-09-22 04:01:00	2	4,063.26	62.13	32.70	1.83
MV, a	2024-09-20 16:43:00	2024-09-23 03:01:00	2	3,000.13	58.30	25.73	2.33
MT, d	2024-09-22 01:36:00	2024-09-24 15:11:00	2	3,051.09	61.58	24.77	2.42
MT, d	2024-09-20 02:00:00	2024-09-21 12:38:00	7	9,305.01	34.63	38.38	1.56
KM, c	2024-09-26 07:45:00	2024-09-30 00:16:00	3	7,167.22	88.52	26.99	2.22

Ship Name	Time of Commencing	Time of Finish	Equipment (Gang)	Number of Bulk Loaded and Unloaded (Ton)	Operation Time (Hours)	Number of Bulk per Hour Handled (NBHH)	Operation Time per Bulk (Minutes)
			(E)	**(NBL)**	**(OT)**	**NBL/(E*OT)**	**60/NBHH**
BG, b	2024-09-28 01:10:00	2024-09-30 03:23:00	4	4,790.15	50.22	23.85	2.52
MV, a	2024-09-29 16:48:00	2024-10-01 18:00:00	3	3,830.73	49.20	25.95	2.31
KM, c	2024-09-30 14:28:00	2024-10-02 20:45:00	2	3,407.30	54.28	31.38	1.91
MV, a	2024-09-30 04:59:00	2024-10-04 01:25:00	4	7,920.69	92.43	21.42	2.80
MV, a	2024-10-02 02:01:00	2024-10-04 02:51:00	2	3,539.72	48.83	36.24	1.66
KM, c	2024-10-02 16:46:00	2024-10-04 15:00:00	3	4,080.69	46.23	29.42	2.04
MV, a	2024-10-04 19:11:00	2024-10-07 16:15:00	2	3,306.97	69.07	23.94	2.51
BG, b	2024-10-07 13:05:00	2024-10-10 09:40:00	5	10,482.43	68.58	30.57	1.96
MV, a	2024-10-10 17:30:00	2024-10-13 08:41:00	4	8,841.64	63.18	34.98	1.72
BG, b	2024-10-12 09:20:00	2024-10-14 11:00:00	3	3,525.83	49.67	23.66	2.54
BG. b	2024-10-12 16:16:00	2024-10-14 21:46:00	2	4.494.33	53.50	42.00	1.43
KM, c	2024-10-15 14:35:00	2024-10-17 18:35:00	4	9,225.23	52.00	44.35	1.35
BG, b	2024-10-18 16:39:00	2024-10-20 23:40:00	3	4,049.81	55.02	24.54	2.45
BG, b	2024-10-18 01:00:00	2024-10-22 07:05:00	3	7,062.47	102.08	23.06	2.60
MV, a	2024-10-20 04:51:00	2024-10-23 04:31:00	1	2,556.77	71.67	35.68	1.68
MV, a	2024-10-21 19:00:00	2024-10-24 02:46:00	2	4,157.56	55.77	37.28	1.61
BG, b	2024-10-20 04:15:00	2024-10-22 07:05:00	5	9,457.77	50.83	37.21	1.61
BG, b	2024-10-22 11:07:00	2024-10-24 03:11:00	3	4,495.87	40.07	37.40	1.60
BG, b	2024-10-24 15:26:00	2024-10-27 16:05:00	5	11,524.63	72.65	31.73	1.89
BG, b	2024-10-27 19:25:00	2024-10-31 22:35:00	5	11,523.38	99.17	23.24	2.58
MV, a	2024-11-03 15:57:00	2024-11-05 13:51:00	1	1,304.47	45.90	28.42	2.11
BG, b	2024-11-04 23:10:00	2024-11-07 03:41:00	3	3,588.35	52.52	22.78	2.63
BG, b	2024-11-05 15:11:00	2024-11-08 13:30:00	3	6,308.83	70.32	29.91	2.01

Ship Name	Time of Commencing	Time of Finish	Equipment (Gang)	Number of Bulk Loaded and Unloaded (Ton)	Operation Time (Hours)	Number of Bulk per Hour Handled (NBHH)	Operation Time per Bulk (Minutes)
			(E)	(NBL)	(OT)	NBL/(E*OT)	60/NBHH
MV, a	2024-11-07 09:51:00	2024-11-09 10:56:00	3	3,814.23	49.08	25.90	2.32
MT, d	2024-11-07 14:06:00	2024-11-09 10:50:00	3	3,958.81	44.73	29.50	2.03
BG, b	2024-11-08 20:26:00	2024-11-09 19:50:00	5	4,205.73	23.40	35.95	1.67
MV, a	2024-11-09 14:20:00	2024-11-11 20:46:00	2	3,466.41	54.43	31.84	1.88
KM, c	2024-11-11 21:50:00	2024-11-13 21:41:00	3	3,924.06	47.85	27.34	2.19
MV, a	2024-11-12 12:50:00	2024-11-14 17:00:00	2	3,452.44	52.17	33.09	1.81
BG, b	2024-11-12 08:35:00	2024-11-15 03:15:00	2	3,561.86	66.67	26.71	2.25
MV, a	2024-11-13 01:31:00	2024-11-15 02:31:00	3	3,689.62	49.00	25.10	2.39
BG, b	2024-11-17 15:15:00	2024-11-20 00:30:00	2	3,384.17	57.25	29.56	2.03
BG, b	2024-11-21 17:01:00	2024-11-24 05:56:00	2	3,475.36	60.92	28.53	2.10
MV, a	2024-11-18 16:31:00	2024-11-22 15:30:00	4	13,194.73	94.98	34.73	1.73
BG, b	2024-11-23 18:59:00	2024-11-24 11:31:00	2	1,192.95	16.53	36.08	1.66
MV, a	2024-11-20 20:50:00	2024-11-23 08:30:00	5	10,018.20	59.67	33.58	1.79
BG, b	2024-11-23 11:15:00	2024-11-25 22:45:00	4	8,944.54	59.50	37.58	1.60
BG, b	2024-11-25 05:00:00	2024-11-26 15:41:00	3	2,773.46	34.68	26.66	2.25
MV, a	2024-11-25 21:08:00	2024-11-27 11:01:00	3	4,722.83	37.88	41.56	1.44
MV, a	2024-11-25 08:15:00	2024-11-28 08:51:00	3	4,663.64	72.60	21.41	2.80

Table B. Proposed improvement of 5W + 1H analysis

Problem	What	Why	Where	When	Who	How
	What is the target of improvement	**Why should improvement be done**	**Where improvement is done**	**When improvement can be done**	**Who carries out the improvement**	**How to carry out the improvement**
Skills Gap Among Dock Workers	There are notable differences in skill levels among TKBM	No specialized training programs are provided to standardize or enhance their skills	In the stevedoring operational environment	Whenever higher performance and efficiency are demanded	TKBM requires technical upskilling	Develop and implement dedicated skill enhancement programs tailored to TKBM operational requirements. Conduct regular skill assessments to identify gaps and plan targeted training interventions.
Inefficient Shift Change Duration	Excessive time taken during the TKBM shift changes	Leads to fatigue due to prolonged working hours and operational delays	At the designated shift changeover points	During routine shift transitions	TKBM is undergoing a shift rotation	Optimize shift scheduling to ensure smoother transitions and adequate rest periods. Implement rotational systems to prevent fatigue buildup among workers.
Operational Disruptions Due to Weather Conditions	Supervisors and operational personnel	Hatch covers must be closed for safety, halting loading/unloading processes	At the port operational zones	During periods of bad weather	Supervisors and operational personnel	Strengthen real-time weather monitoring to allow for better planning and scheduling. Provide training on adaptive protocols during inclement weather to minimize disruption.
Unpredictable Conditions Around the Warehouse	Operational delays due to unexpected environmental issues, such as traffic congestion or remote warehouse locations	Inefficiencies arise from poor infrastructure and inadequate contingency planning	Around the warehouse and related transportation nodes	When external disturbances impact logistics operations	Field personnel and logistics coordinators	Integrate environmental risk factors into logistics planning. Identify and prepare alternative warehouse sites with more strategic locations to enhance operational flexibility.

Problem	What	Why	Where	When	Who	How
	What is the target of improvement	**Why should improvement be done**	**Where improvement is done**	**When improvement can be done**	**Who carries out the improvement**	**How to carry out the improvement**
Inconsistent Hook Cycle Time Due to Different Load Packaging	Varying hook cycle times caused by differences in cargo packaging	Due to inconsistent capacities and compatibility of hooks and grabs used	At cargo loading and unloading sites	During material handling operations	Operators and Stevedoring personnel	Assess and standardize equipment used (hooks/grabs) to handle a broader range of packaging types. Improve coordination with cargo suppliers to align packaging standards with operational capabilities.
Prolonged Waiting Time for Land Transport	Delays due to long waiting times for land transportation	Environmental factors like flooding or traffic jams frequently hinder vehicle movement	At the port access roads and the surrounding logistics areas	During transport disruptions caused by environmental conditions	Logistics personnel and ground supervisors	Enhance transportation planning by incorporating weather and traffic forecasts into route decisions. Consider using more reliable alternative ground transport methods in emergencies.
Equipment Failures During Operations	Mechanical failures impacting stevedoring processes	Inadequate work procedures and incompatibility with new cargo types	At the cargo handling zones	During routine operations	Equipment operators and technical maintenance teams	Strengthen preventive maintenance programs to reduce unexpected breakdowns. Update standard operating procedures to reflect new cargo requirements and ensure compliance through continuous operator training.