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Analysis of ceramic product quality: A Six Sigma approach

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ABSTRACT

In the industrial world, the quality and productivity of products play a crucial role in the success of various production systems. The ceramic industry encounters challenges related to defective products due to various factors. When COVID-19 struck, one ceramic tile company temporarily laid off workers and suspended operations at several plants due to a decrease in orders. In January 2023, the company only opened three plants. It was found that many problems were encountered particularly with the production of SL-type ceramic tiles (25 cm × 25 cm). They were still striving to reduce these issues and ensure smooth production processes. The problems that frequently occur can be attributed to the production process, materials, machinery, or human factors. Consequently, research has been conducted to control defective products, thereby enhancing production quality using the Six Sigma DMAIC method. The DMAIC methodology is the cornerstone of Six Sigma problem-solving, involving sequential improvement steps. These steps in the DMAIC method include Define, Measure, Analyze, Improve, and Control. Based on the conducted calculations, an average DPMO (Defects per Million Opportunities) value of 8621.2 was obtained, with an average sigma value of 3.91. DPMO, which measures failure in the DMAIC method, indicates failures per million opportunities. Based on this, it suggests that production falls within the average category of the Indonesian industry and is deemed sufficiently satisfactory. This study also provides improvement steps that need to be taken to reduce defective products.

1. Introduction

Currently, the manufacturing industry is one of the rapidly growing sectors, in line with the advancement of human knowledge and technology. Companies in the manufacturing sector producing similar products engage in fierce competition to win over consumers' preferences and capture existing markets. Generally, the goal of the manufacturing industry is to complete production on time with more economical costs and to achieve maximum profit.

Product quality within a company is a crucial factor for staying competitive in the global market. Product quality refers to a product's ability to perform its functions, including overall durability, reliability, accuracy, ease of operation, repairability, and other product attributes [1]. Quality control in a company is essential because effective quality control impacts the quality of products produced by the company, such as minimizing errors or defects in the products [2]. One method that can be used to analyze quality control in a company is the Six Sigma method. For over two decades, Six Sigma has been extensively employed as a quality improvement methodology in both manufacturing and service organizations [3], [4]. Six Sigma is a method that helps develop products close to perfection or with minimal losses or errors. The two primary viewpoints on Six Sigma are statistical and business improvement. Statistically, Six Sigma aims for fewer than 3.4 defects per million opportunities, which corresponds to a success rate of 99.9997% [5], [6], [7]. The application of the Six Sigma method involves steps known as DMAIC, which stands for Define, Measure, Analyze, Improve, and Control [8], [9].

One of the manufacturing companies in the Tangerang area specializes in fragile goods, producing ceramics and granites. It has plants 1 through 8, each producing different types of products. The specialization lies in ceramic floor products with various sizes, including SC (20 cm × 20 cm), SL (25 cm × 25 cm), GE (30 cm × 30 cm), SX (40 cm × 40 cm), SZ (50 cm × 50 cm), and so on. These products are divided into 5 quality levels: KW 1, KW 2, KW 3, KW 4, and KW 5. In January 2019, it only opened plants 1, 2, and 3. Based on interviews conducted, it was found that at the beginning of January 2019, many problems were found

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in plant 1 with the production of SL (25 cm × 25 cm) ceramic tiles, such as cracks, craters, and blisters in some tiles. Plant 1 is still trying to reduce these problems and carry out the production process properly. The issues that often occur at plant 1 can be caused by production processes, materials, machinery, or human factors.

Based on the company's condition, this research aims to identify the dominant factors causing product defects and provide improvement proposals using the Six Sigma DMAIC method. Several research studies can serve as a source of inspiration for developing a solution methodology. For instance, one study used Six Sigma to identify defects in sugarcane quality with recommended improvements, including enhancing sugarcane quality inspection, increasing thoroughness in cleaning, and setting a maximum daily defect proportion limit [10]. In a separate study, door-panel alignment defects in built-in ovens at a household appliances company were analyzed. These defects significantly impact product aesthetics, influencing customer satisfaction. The goal was to improve the manufacturing process from a 3.1-sigma level to at least 4-sigma by reducing the predominant alignment defect.

Using Six Sigma tools and lean principles, including workflow analysis, Pareto analysis, and process capability analysis, the process performance improved to a 4.4 sigma level, significantly decreasing alignment defects [11]. Lastly, a different study examined the effects of Six Sigma on the footwear industry, which encompasses processes like cutting, assembly, sewing, and finishing. Ensuring quality and customer satisfaction is crucial, necessitating the control of process variables, skilled labor, high-quality materials, and thorough inspections. The research intends to apply the Six Sigma DMAIC methodology to lower the rejection rate to 3.365 per million opportunities, thereby reaching a four-sigma level [12].

2. Material and method

The research method used in this study is Six Sigma which is quantitative with a descriptive approach. This research was conducted at a ceramic tiles company located in Tangerang, Banten. The sample used in this study consists of the production quantity and defective products with quality levels KW 4 and KW 5, or in other words, rejected products. This research was only conducted at plant 1 with the production of SL (25 cm × 25 cm) ceramic tiles in January 2023. Issues arising must be followed up with improvements to the quality of the products by identifying processes that have been consistently good over time. This can be achieved by applying the DMAIC methodology from Six Sigma.

2.1. Six Sigma

Six Sigma is a systematic statistical method to reduce variation in every process of key business areas directly related to customers [13]. It is also referred to as a comprehensive system, which is a strategic system, scientific discipline, and tool for achieving and supporting success [14]. It is called a strategy because it focuses on improving customer satisfaction, a scientific discipline because it follows a formal model, DMAIC (Define, Measure, Analyze, Improve, Control), and a tool because it is used in conjunction with others such as Pareto charts and histograms [15].

2.1.1. Define

Define is the initial step in problem-solving where we identify issues within the ongoing process. During this phase, we prioritize what aspects are critical to quality and create Pareto diagrams to highlight the most common types of defects. This helps us understand where improvements are needed to enhance overall performance and efficiency.

2.1.2. Measure

The Measure phase is dedicated to assessing the level of defects within a production process. This crucial step allows us to quantitatively evaluate the performance of the process. During this stage, activities include constructing *p*-control charts, calculating Defects Per Million Opportunities (DPMO), and determining sigma values [16]. These metrics provide valuable insights into the effectiveness and capability of the production process, helping us identify areas for improvement and optimize quality standards.

2.1.3. Analyze

The Analyze phase is dedicated to examining the factors contributing to defects. This critical stage involves conducting root cause analysis using tools such as the cause-and-effect diagram. The cause-and-effect diagram illustrates the relationships between various causes and their effects [17], [18]. By dissecting these relationships, we gain a comprehensive understanding of the underlying causes of defects, enabling us to develop targeted solutions for improvement. This phase is crucial for identifying areas of intervention that will yield the most significant improvements in product quality and process efficiency [19].

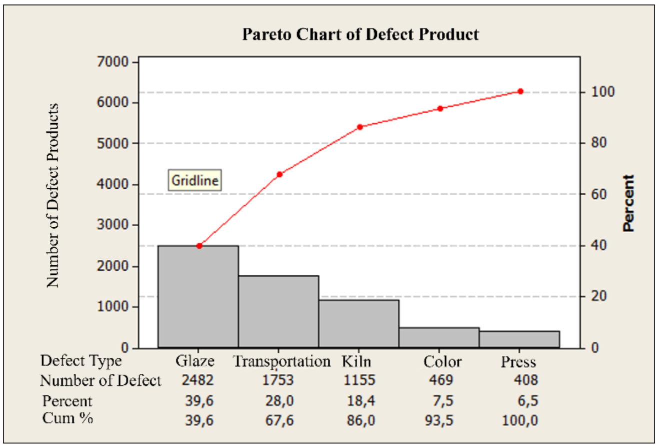

Figure 1. Pareto diagram

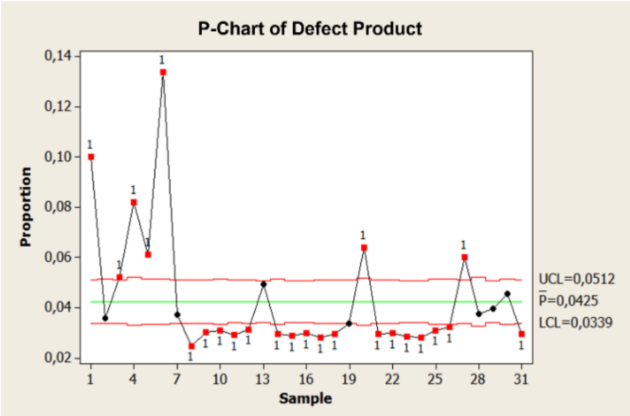

Figure 2. p-chart of defect product

2.1.4. *Improve*

In this phase, technical improvement proposals and controls are derived from the interpretation of results using Failure Mode and Effect Analysis (FMEA) [20]. FMEA is one of the systematic techniques used to analyze failures or a systematic approach that applies a method of tabulation to aid the thought process employed by engineers in identifying potential failure modes and their effects [21]. This structured methodology enables us to proactively anticipate and mitigate risks associated with potential failures, ensuring robust product design and manufacturing processes.

2.1.5. *Control*

This stage is about keeping track of what we've done so far to improve quality. We do this by documenting everything accurately. This way, if we need to, we can repeat the changes we've made. We also keep an eye on things to make sure we're sticking to the plan and maintaining the quality we want. By staying organized and vigilant, we ensure that our efforts lead to consistent quality enhancements over time [22].

3. Results and discussions

This research is conducted to analyze defective products employing the six sigma DMAIC method. By utilizing this approach, we aim to systematically identify, analyze, and improve processes to enhance product quality and efficiency.

3.1. *Define*

In this Define stage, problem identification is conducted, including the identification of Critical to Quality (CTQ) factors [23], [24]. The study was conducted at a manufacturing company known for producing glassware, including ceramic floor tiles. Understanding the types of defects that are critical to the quality of these products is essential for improving their overall quality and customer satisfaction. The types of defects considered as CTQs for these products are as follows: press defect, transportation defect, glaze defect, kiln defect, and color defect.

Floor ceramic products with press defects have problems during the molding of raw ceramic materials. This happens when the pressure on the raw material isn't even or strong enough, maybe because of changes in temperature or pressure, or because the machines are old or not well-maintained. These issues can result in various defects in ceramic products, affecting their quality and appearance.

Transportation defects occur when ceramic products are moved from one production stage to another. During this process, mishandling or inadequate packaging can lead to chips, cracks, or other damage to the ceramics. Glaze defects arise when there are problems with the application of the glaze layer on the ceramic surface. This layer is crucial not only for aesthetic purposes but also for protecting the ceramic and enhancing its durability. Issues such as uneven application, air bubbles, or impurities in the glaze can compromise the final product's quality.

Kiln defects occur during the firing process in the kiln, which is essential for curing and hardening the ceramics. Problems like uneven heating, improper temperature control, or kiln malfunctions can result in defects such as warping, cracking, or discoloration in the finished products. Color defects refer to issues with coloring or undesired color changes in ceramic products. These problems can arise at various stages of production, including during material mixing, glaze application, or firing. Factors like inconsistent pigment distribution, improper firing temperatures, or chemical reactions during firing can lead to color defects in ceramics.

Fig. 1 shows Pareto chart for defect at BG. Based on Fig. 1, the press defect type has a percentage of 6.52%, transportation defect has a percentage of 27.97%, glaze defect has a percentage of 39.61%, kiln defect has a percentage of 18.43%, and color defect has a percentage of 7.48%. From these results, it can be concluded that by addressing the glaze defect issue, it can address other defect issues because the percentage of glaze defects is higher compared to other defect types.

3.2. *Measure*

In this stage, data collection is conducted to measure the performance of the process before improvements are made. The steps carried out include the creation of a p-chart to determine the proportion of defective products and the calculation of DPMO (Defects per Million Opportunities) and the sigma quality level. Fig. 2 shows the p-chart graph. Based on Fig. 2, it can be observed that the obtained value of $\bar{p}$ is 0.0425 with an upper control limit (UCL) of 0.0512 and a lower control limit (LCL) of 0.0339. From the figure, it is evident that the data is not yet under control, as there are still many data points exceeding the UCL and LCL. Therefore, improvement in the process data is necessary. This indicates a need to identify and address the factors contributing to the variability to achieve stable and consistent performance.

Table 1.
DPMO measurement

Period	Quantity of Production	Quantity of Defects	CTQ	DPU	DPO	DPMO	Sigma Level
1	4712	472	5	0,100	0,020	20034,0	3,55
2	4698	169	5	0,036	0,007	7194,6	3,95
3	4862	254	5	0,052	0,010	10448,4	3,81
4	4027	330	5	0,082	0,016	16389,4	3,63
5	4363	267	5	0,061	0,012	12239,3	3,75
6	4544	608	5	0,134	0,027	26760,6	3,43
7	4919	183	5	0,037	0,007	7440,5	3,94
8	4857	121	5	0,025	0,005	4982,5	4,08
9	4766	145	5	0,030	0,006	6084,8	4,01
10	4558	142	5	0,031	0,006	6230,8	4,00
11	5088	149	5	0,029	0,006	5856,9	4,02
12	4758	150	5	0,032	0,006	6305,2	3,99
13	5223	259	5	0,050	0,010	9917,7	3,83
14	4372	130	5	0,030	0,006	5946,9	4,02
15	5206	151	5	0,029	0,006	5801,0	4,02
16	5146	154	5	0,030	0,006	5985,2	4,01
17	4771	134	5	0,028	0,006	5617,3	4,04
18	4733	140	5	0,030	0,006	5915,9	4,02
19	4713	160	5	0,034	0,007	6789,7	3,97
20	4166	267	5	0,064	0,013	12818,1	3,73
21	4881	145	5	0,030	0,006	5941,4	4,02
22	5014	150	5	0,030	0,006	5983,2	4,01
23	5202	149	5	0,029	0,006	5728,6	4,03
24	5332	150	5	0,028	0,006	5626,4	4,03
25	4492	140	5	0,031	0,006	6233,3	4,00
26	4490	146	5	0,033	0,007	6503,3	3,98
27	4903	295	5	0,060	0,012	12033,4	3,76
28	3857	145	5	0,038	0,008	7518,8	3,93
29	5225	207	5	0,040	0,008	7923,4	3,91
30	4617	210	5	0,045	0,009	9096,8	3,86
31	4907	145	5	0,030	0,006	5909,9	4,02
			Average			8621,2	3,91

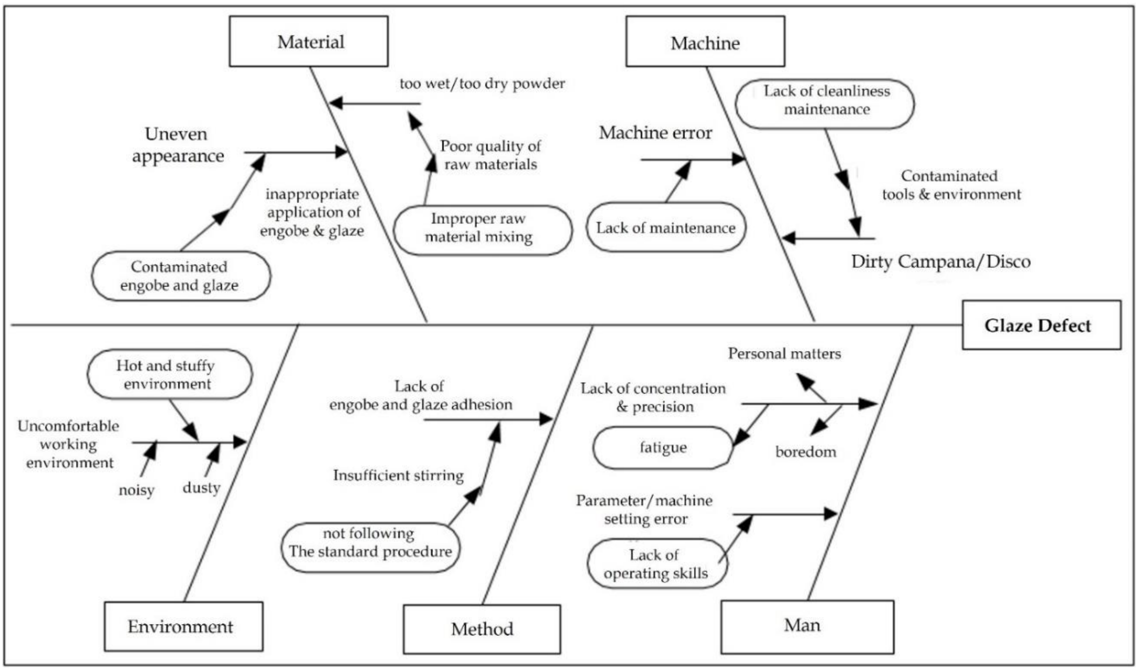

Figure 3. Cause and effect diagram

Table 2.
FMEA

Made of Failure	Cause of Failure	Effect of Failure	Severity	Occurance	Chance	RPN	Rank
Lack of concentration and precision	Fatigue/illness, personal matters, and boredom	Worker makes mistakes or careless errors	5	5	3	75	8
Parameter or machine setting errors	Lack of operating skills	Scraper is not optimal or water spray is not appropriate	6	4	4	96	7
Machine errors	Lack of machine maintenance	Machine error or machine operation is suboptimal	6	4	5	120	5
Dirty campana or disk	Failure to maintain machine cleanliness	Clumping in glaze or contaminated surface	7	5	6	210	2
Lack of engobe and glaze adhesion	Non-compliance with SOP	Glaze peeling off from ceramic surface	7	4	5	140	3
Excessively wet or dry powder	Incorrect raw material mixing	Ceramic becomes sticky or cracked	7	4	4	112	6
Uneven appearance	Contaminated engobe and glaze	Clumps of glaze, crawling, pinholes	8	5	6	240	1
Uncomfortable working environment	Hot and stuffy environment, noisy and dusty	Worker discoomfort and distraction leading to glaze contamination	5	5	5	125	4

After completing the initial step of creating the control chart, the next step involves measuring process performance. This process performance calculation utilizes the DPMO calculation, which can be seen in Table 1. Based on Table 1, it is known that the average DPMO value for defective products is 8621.2, with a sigma level of 3.91. This indicates that the production falls within the average category for the Indonesian industry and is considered quite satisfactory. Achieving a sigma level of 3.91 reflects a commendable effort in quality improvement, suggesting that the manufacturing processes have been effectively managed to minimize defects and enhance overall product quality. This result underscores the importance of continuous monitoring and improvement initiatives to further elevate production standards and ensure consistent performance.

3.3. Analyze

From the results of the measurement process, the next step is to analyze the improvement of six sigma quality. In this stage, the key task is to analyze the results obtained in the measurement stage and identify the sources and root causes of defects or failures. This stage is conducted using tools, namely cause-and-effect diagrams and Failure Mode and Effect Analysis (FMEA), to systematically identify potential failure modes and their effects on the process.

Based on Fig. 3, there are 5 factors that describe the issues: human, method, environment, material, and machine. The root causes identified include human factors such as lack of concentration and precision, and errors in setting machine parameters; machine factors such as machine errors and dirty campana or disk; method factors such as lack of engobe and glaze adhesion; material factors such as excessively wet or dry powder and uneven appearance; and environmental factors such as discomfort. These factors play crucial roles in influencing the quality of the final product. Identifying and addressing these root causes is essential for implementing effective quality improvement measures and achieving desired outcomes in the manufacturing process.

Based on Table 2, the highest rank obtained is an RPN value of 240, which corresponds to uneven appearance errors, indicating the severity and likelihood of occurrence associated with this issue. Conversely, the lowest rank is attributed to a lack of concentration and precision, with a rank of 8 and an RPN value of 75. This disparity in RPN values underscores the varying levels of risk posed by different root causes identified during the analysis process. Addressing these root causes in order of priority based on their RPN values is essential for effectively managing risks and implementing targeted quality improvement measures in the manufacturing process.

3.4. Improve

In this stage, the root cause improvements identified and explained in the analyze phase are addressed. Table 3 shows the action plan table for FMEA. These proposed actions aim to address the root causes identified during the analysis phase and mitigate the occurrence of defects in the manufacturing process. For instance, to address glaze defects attributed to human factors, measures such as providing periodic short breaks for operators and offering training sessions can enhance concentration and precision. Additionally, resetting the scraper and water spray can optimize equipment performance. Considering the impact of temperature on the ceramic manufacturing process, adjustments to the water spray system are deemed necessary to maintain optimal conditions.

Table 3.
Action plan for FMEA

Rank	Made of Failure	Cause of Failure	Effect of Failure	Action Planning
1	Uneven appearance	Contaminated engobe and glaze	Presence of glaze lumps, crawling, or pinholes	Filtering or replacing engobe and glaze with fresher ones
2	Dirty campana or disk	Failure to maintain machine cleanliness	Presence of lumps in the glaze or contaminated surface	Cleaning the campana and disk, as well as the surrounding environment, regularly
3	Lack of adhesion of engobe and glaze	Not adhering to SOP	Glaze peels off from the ceramic surface	Exercising more control over engobe and glaze SOPs and adding CMC as an adhesive
4	Uncomfortable working environment	Hot and humid environment, noisy and dusty	Worker discoomfort and disturbance, and potential glaze contamination	Adding blowers or air ventilation and regularly cleaning the work environment
5	Machine errors	Insufficient machine maintenance	Machine error or machine operation is not optimal	Performing maintenance and scheduling routine machine maintenance
6	Excessively wet or dry powder	Inappropriate raw material mixing	Ceramics become sticky or cracked	Monitoring the raw material manufacturing process and powder humidity periodically
7	Errors in setting parameters or machines	Lack of operator skills	Scraper is not optimal or water spray is not appropriate	Providing training for operators and resetting the scraper and water spray
8	Lack of concentration and precision	Fatigue/illness, personal matters, and boredom	Worker makes mistakes or is careless	Providing periodic short breaks before the main break time

Moreover, proposed improvements targeting machine factors emphasize the importance of regular maintenance scheduling and thorough cleaning of machinery components and the surrounding environment to prevent malfunctions and contamination. Method-related defect causes call for enhanced control over standard operating procedures (SOPs) for engobe and glaze application, along with the incorporation of suitable adhesives like Carboxy Methyl Cellulose (CMC) to improve bonding.

Furthermore, material-related defect causes necessitate diligent monitoring of raw material manufacturing processes and powder humidity levels to ensure consistent quality, alongside the implementation of filtration mechanisms or the replacement of engobe and glaze with fresh alternatives when necessary. Lastly, addressing environmental factor-related defect causes involves the installation of additional blowers or air ventilation systems and regular cleaning practices to create a conducive work environment conducive to quality production.

3.5. Control

The control phase is crucial because, without it, the process tends to deteriorate over time due to the influence of external factors [25]. The limitation of the study is that the Six Sigma steps performed only reached the define, measure, analyze, and improve stages. Further research is needed to determine if the improvements made can reduce the DPMO value. Additionally, the control phase is necessary to ensure that this ongoing process is not affected by external factors.

4. Conclusions

The study identifies five Critical To Quality (CTQ) values: press defects (6.5%), transportation defects (28.0%), glaze defects (39.6%), kiln defects (18.4%), and color defects (7.5%). Glaze defects are the dominant issue in SL-type ceramics, influenced by human, machine, method, material, and environmental factors. Using 31 data points, the average DPMO is 8,621.2, corresponding to a sigma level of 3.91, which is within the average range for the Indonesian industry. To address the eight factors causing glaze defects, the study proposes improvements such as providing breaks for concentration, training operators, performing regular machine maintenance, and implementing standard operating procedures. Additionally, the Control stage involves monitoring process performance and ensuring defect prevention by implementing and supervising these improvements.

Declaration statement

Asep Ridwan: **methodology, supervision, validation, formal analysis**. Atia Sonda: **data curation, writing-review & editing.** Athariq Zilardhi: **Resources, writing, visualization**.

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The authors report there are no competing interests to declare.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article or its supplementary materials.

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