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Enhancing product quality in precast concrete spun pile through the Six Sigma DMAIC

Welly Mahardhika*
Industrial Engineering Study Program, Faculty of Engineering, Universitas Tidar, Magelang 56116, Indonesia

***Corresponding Author**: wellymahardhika@untidar.ac.id ; Tel.: 082227171682

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ABSTRACT
Defects in precast concrete spun pile production pose risks to structural reliability, operational efficiency, and project costs. The Company has experienced recurring defects that increase the cost of poor quality and reduce customer satisfaction, highlighting the need for a systematic improvement approach. This study applies the Six Sigma DMAIC methodology to analyze and reduce defects using production data from 25,206 units manufactured between 2020 and 2022. Statistical analysis using P-chart control limits, DPMO calculations, and sigma-level evaluation revealed an overall defect rate of 0.63%, dominated by Broken PC Bars, Cracks in the Stock Area, and Dry Concrete, which together contributed 62.5% of total defects. The initial process performance averaged 3.4 sigma (approximately 2,150 DPMO), which improved to 4.67 sigma following the proposed corrective actions. Root cause analysis identified human factors, unstable machine calibration, procedural inconsistencies, and material variability as the primary contributors. Improvement recommendations include operator training, biweekly machine maintenance, digital standardization of work procedures, and stricter material control. The findings demonstrate the effectiveness of a data-driven DMAIC approach for enhancing product quality in precast manufacturing. Future improvements may incorporate IoT-based monitoring and stronger supplier collaboration to support long-term process stability and operational excellence.

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1. INTRODUCTION

A precast concrete spun pile manufacturer (hereafter referred to as "the Company") is engaged in the manufacturing of precast concrete components, particularly hollow driven piles or spun piles. These piles are cylindrical structural elements produced through a centrifugal process, resulting in high-density concrete with strong flexural and compressive performance [1]–[5]. Spun piles are widely used in infrastructure applications such as bridges, ports, rail structures, and high-rise buildings due to their structural reliability and transportation efficiency [6]–[9]. The demand for high-precision and high-quality components continues to increase as project complexity grows and sustainability standards become stricter [10]–[13]. Maintaining product quality has become a strategic priority for companies competing in the precast concrete industry [14], [15].

Despite technological advancements, product defects still occur during the manufacturing process, often leading to customer rejections [6], [16], [17]. A defect represents a failure to meet technical specifications or customer expectations and may compromise structural reliability [2], [3], [18]. Common defects in spun pile production include cracks, damaged prestressed wires, dry concrete, and dimensional inconsistencies, which are issues commonly found in concrete and metal-based manufacturing processes [17], [19]–[21]. These defects contribute to significant financial losses because defective products require rework, scrapping, or additional inspection activities [22]–[25]. Production data from the Company between 2020 and 2022 show an average defect rate of 0.63%, a considerable value in an industry where near-zero defects are essential for reliability and cost efficiency [16], [26].

Manufacturing spun piles requires substantial capital investment, including prestressing equipment, centrifugal casting systems, curing facilities, and precision material-handling devices [1], [3], [27]. Moreover, the Company operates under a make-to-order (MTO) system, compelling the company to adjust production capacity in response to fluctuating project demands [11], [28], [29]. Combined with the competitive nature of the precast concrete market, robust quality control is necessary for reducing defects, minimizing the cost of poor quality (COPQ), and sustaining customer satisfaction [25], [30], [31].

Six Sigma offers a systematic and data-driven methodology for reducing process variation and improving capability across industries [32]–[34]. The DMAIC approach (Define, Measure, Analyze, Improve, and Control) provides a structured framework for identifying root causes, implementing corrective measures, and validating improvements [35]–[38]. Numerous studies have demonstrated the effectiveness of Six Sigma in reducing defects in various manufacturing sectors, including cement packaging [39], concrete poles [35], construction projects [18], garment production [40], [41], metal fabrication [17], additive manufacturing [42], and laboratory testing [43], [44], as well as automotive and textile manufacturing [45]–[47].

Significant reductions in Defects Per Million Opportunities (DPMO) have also been observed across many industries using Six Sigma. Examples include tin casting [48], [49], crushed stone production [22], box culverts [20], sheet piles [21], and plastic packaging [50]. In the context of spun piles, Alfianto and Zega [51] applied Six Sigma and achieved a sigma level of 3.46 at PT Jaya Beton Indonesia Surabaya. Moreover, the integration of Six Sigma with digital manufacturing and Industry 4.0 technologies has further strengthened its relevance in modern production systems [52]–[54], including machine learning-driven quality improvement in aircraft manufacturing [55].

This research differs from most previous studies by emphasizing the financial impact of defects, especially Work-In-Progress (WIP-2) materials that incur operational costs without generating revenue [24], [31], [56], [57]. In this context, DMAIC functions not only as a quality improvement methodology but also as a tool to reduce economic waste and support financial sustainability [25], [58], [59]. Additionally, this research extends the work of Mahardhika et al. [60], who investigated quality and risk integration within the spun pile supply chain. Unlike macro-level studies, the present research implements DMAIC directly on the production floor to deliver actionable, measurable improvements. Several studies also highlight that Six Sigma contributes to long-term sustainability, operational resilience, and continuous improvement in modern industrial systems [12], [13], [61].

Overall, this approach aims to improve spun-pile product quality, reduce financial losses from defects, and strengthen the sustainability, operational efficiency, and competitiveness of the Company in the precast concrete industry.

2. METHODS

2.1. Acquisition of Research Data

This study was conducted at manufacturing company specializing in precast concrete spun piles. To evaluate the quality control performance, both quantitative and qualitative data were collected. The primary dataset consists of monthly production volumes and defect counts recorded between April 2020 and June 2022. During this period, a total of 25,206 units were produced, with 160 defective units identified. Defect categories included Broken PC Bars, Cracks in the Stock Area, Dry Concrete, and five additional defect types that were incorporated into the initial analysis.

These data were used in the Define, Measure, and Analyze phases of the DMAIC framework to identify patterns of defects, determine Critical to Quality (CTQ) characteristics, and quantify baseline process capability. Qualitative insights were obtained through discussions with operational personnel to ensure contextual understanding of production variations.

2.2. Data Analysis

This study adopts the DMAIC approach, which provides a structured and data-driven methodology for identifying and mitigating quality problems in manufacturing [62], [63]. The Define phase identified recurring defect patterns in spun pile production and established CTQ metrics based on customer requirements and rejection criteria. Preliminary screening of defect data indicated that Broken PC Bar, Cracks in Stock Area, and Dry Concrete were the most frequently occurring defects. Together, these three categories accounted for approximately 62.5% of all recorded defects, which justified their selection as CTQs for the DPMO calculation.

In the Measure phase, statistical tools are employed to evaluate the current quality performance of the spun pile production process. The primary analysis uses the P-Chart (proportion control chart), which in this study was constructed using Microsoft Excel to compute defect proportions, center lines, and control limits across multiple production batches. Control charts assist in assessing whether the process remains within statistical control thresholds, whereas DPMO provides a uniform metric for evaluating overall quality performance [64]. First, the Center Line (CL) is determined using Eq. (1), representing the average proportion of defects across all observations.

$$Cl = \bar{P} = \frac{Total\ Number\ of\ Defective\ Product}{Total\ Production\ Quantity} \tag{1}$$

The proportion of defects for each inspection point is then calculated individually using Eq. (2). Based on these values, the Upper Control Limit (UCL) and Lower Control Limit (LCL) are calculated using Eq. (3) and Eq. (4), respectively, to define the statistical boundaries for acceptable process variation.

$$Pi = \frac{xi}{ni} \tag{2}$$

$$UCL = \bar{P} + 3\sqrt{\frac{\bar{P}\,(1 - \bar{P})}{ni}} \tag{3}$$

$$UCL = \bar{P} - 3\sqrt{\frac{\bar{P}\,(1 - \bar{P})}{ni}} \tag{4}$$

where,

Pi: The ratio of defective units identified in the i-th inspection sample
xi: The count of defective items found in the i-th production batch
ni: The total number of items evaluated during the i-th quality check

After establishing the control chart parameters, process capability is assessed using the DPMO metric, which is computed using Eq. (5). This value reflects how many defects would occur in one million opportunities and provides a quantitative basis for performance benchmarking. Finally, the DPMO value is converted into a Sigma Level using Eq. (6), which is a standardized measure widely used to evaluate the maturity and stability of manufacturing processes. These calculations provide the necessary baseline to track the impact of subsequent improvements.

$$DPMO = \frac{D}{U\ x\ OP}\ x\ 1{,}000{,}000 \tag{5}$$

$$Sigma = NORMSINV\left(\frac{1{,}000{,}000 - DPMO}{1{,}000{,}000}\right) + 1.5 \tag{6}$$

where,

D : The overall quantity of non-conforming products detected during the study period (160 units)
U : The cumulative number of units manufactured across all observations (25,206 units)
OP: The count of possible defect opportunities per unit, as defined by CTQ factors (3 CTQs)

In Six Sigma-based quality control systems, the sigma level serves as a key indicator of both process performance. A higher sigma level corresponds to fewer defects per million opportunities (DPMO) [65], reflecting greater operational excellence. The sigma can be shown in Table 1.

Table 1. Level of sigma

Sigma Level	DPMO	Yield (%)
1 Sigma	691,462	31.00%
2 Sigma	308,538	69.20%
3 Sigma	66,807	93.32%
4 Sigma	6,210	99.38%
5 Sigma	233	99.98%
6 Sigma	3.4	99.99966%

The Analyze phase identifies the fundamental causes of dominant defects using Pareto analysis and Fishbone diagrams. Causes were classified into Man, Machine, Method, Material, and Environment categories to systematically explore human errors, inconsistent machine calibration, deviations from SOPs, and material inconsistencies. These factors were validated through discussions with plant personnel to ensure accuracy and relevance to production conditions.

Improvement actions were proposed based on validated root causes, including operator retraining, biweekly machine calibration, reinforcement of SOP checklists, and enhanced material quality controls. These interventions were designed to reduce variability and strengthen production stability. Sigma levels and control charts were recalculated to evaluate expected improvements. [66].

Finally, the Control phase establishes monitoring plans to ensure that improvements can be sustained over time. Control tools such as checklists, SOP audits, and periodic machine evaluations were recommended to maintain consistent product quality and reduce defect recurrence [67].

3. RESULTS AND DISCUSSION

3.1. Define

In this initial phase, problem identification is carried out by analyzing the production process of precast concrete spun piles at the Company. The focus is placed on defects that consistently recur and have a direct impact on product quality and customer satisfaction. This stage aims to define the scope of improvement using historical data related to defective products over a given period.

The primary data source is the internal production log from the Company, covering the period from April 2020 to June 2022. Table 2. presents a summary of defective spun pile production recorded during this period, while Table 3. categorizes the types of product failures that were identified. These include issues such as cracked concrete, dry mix, and structural inconsistencies, all of which represent CTQ characteristics that need to be addressed.

By creating a distinct defect baseline using these two datasets, the Define phase lays the groundwork for identifying the main issues and connecting them to customer needs and organizational quality objectives. This definition guarantees that the following stages measure, analyze, improve, and control are targeted and practical.

3.2. Measure

In the Measure phase, a comprehensive assessment of the defect rate in the spun pile production at the Company was carried out using historical data from April 2020 to June 2022. This phase aimed to verify if the production process remained statistically in control and to evaluate process performance using DPMO (Defects Per Million Opportunities) and Sigma level metrics.

The analysis utilized a total of 25,206 spun pile units, with 160 identified defective products. The monthly proportion of defects was calculated using Eq. (2), while the CL, UCL, and LCL were determined using Eqs. (1), (3), and (4), respectively.

Table 2. Spun pile production

Year	Month	Total of Production (pcs)	Total of Defect (pcs)
2020	April	13	3
	May	202	14
	June	503	12
	July	827	14
	August	873	14
	September	855	10
	October	882	11
	November	877	10
	December	950	2
2021	January	1,077	9
	February	796	8
	March	997	5
	April	896	6
	May	894	1
	June	1,286	1
	July	1,531	2
	August	962	3
	September	1,170	2
	October	861	1
	November	1,370	5
	December	1,527	3
2022	January	1,298	5
	February	1,141	5
	March	907	3
	April	959	4
	May	746	4
	June	806	3
	Total	25,206	160

Table 3. The types of product defects

No	Defect Category	Quantity (pcs)
1	Broken PC Bar	34
2	Cracks in Stock Area	34
3	Dry Concrete	32

No	Defect Category	Quantity (pcs)
4	Equipment Malfunction	19
5	End Plate Damage	16
6	Bent Pile	12
7	Failed Bending Test	11
8	Accidental Damage	2

A control chart was constructed using the P-Chart method to visually assess process stability. The calculated values for each month are presented in Table 4, which shows that early months such as April (Period 1) and May (Period 2) had a high proportion of defects (0.231 and 0.069 respectively), far exceeding the upper control limit. These out-of-control signals strongly indicate process variation and quality inconsistencies that require corrective measures. The control chart can be seen in Figure 1.

Table 4. The types of product defects

Period	Month	Production Quantity (pcs)	Product Defects (pcs)	Proportion	CL	UCL	LCL
1	April	13	3	0.231	0.006	0.357	-0.344
2	May	202	14	0.069	0.006	0.060	-0.047
3	June	503	12	0.024	0.006	0.027	-0.014
4	July	827	14	0.017	0.006	0.020	-0.007
5	August	873	14	0.016	0.006	0.019	-0.006
6	September	855	10	0.012	0.006	0.017	-0.005
7	October	882	11	0.012	0.006	0.018	-0.005
8	November	877	10	0.011	0.006	0.017	-0.004
9	December	950	2	0.002	0.006	0.011	0.002
10	January	1,077	9	0.008	0.006	0.015	-0.002
11	February	796	8	0.010	0.006	0.017	-0.004
12	March	997	5	0.005	0.006	0.013	0.000
13	April	896	6	0.007	0.006	0.015	-0.002
14	May	894	1	0.001	0.006	0.010	0.003
15	June	1,286	1	0.001	0.006	0.009	0.004
16	July	1,531	2	0.001	0.006	0.009	0.004
17	August	962	3	0.003	0.006	0.012	0.001
18	September	1,170	2	0.002	0.006	0.010	0.003
19	October	861	1	0.001	0.006	0.010	0.003
20	November	1,370	5	0.004	0.006	0.011	0.001
21	December	1,527	3	0.002	0.006	0.010	0.003
22	January	1,298	5	0.004	0.006	0.012	0.001

Period	Month	Production Quantity (pcs)	Product Defects (pcs)	Proportion	CL	UCL	LCL
23	February	1,141	5	0.004	0.006	0.012	0.000
24	March	907	3	0.003	0.006	0.012	0.001
25	April	959	4	0.004	0.006	0.013	0.000
26	May	746	4	0.005	0.006	0.014	-0.002
27	June	806	3	0.004	0.006	0.013	0.000
	Total	25,206	160				

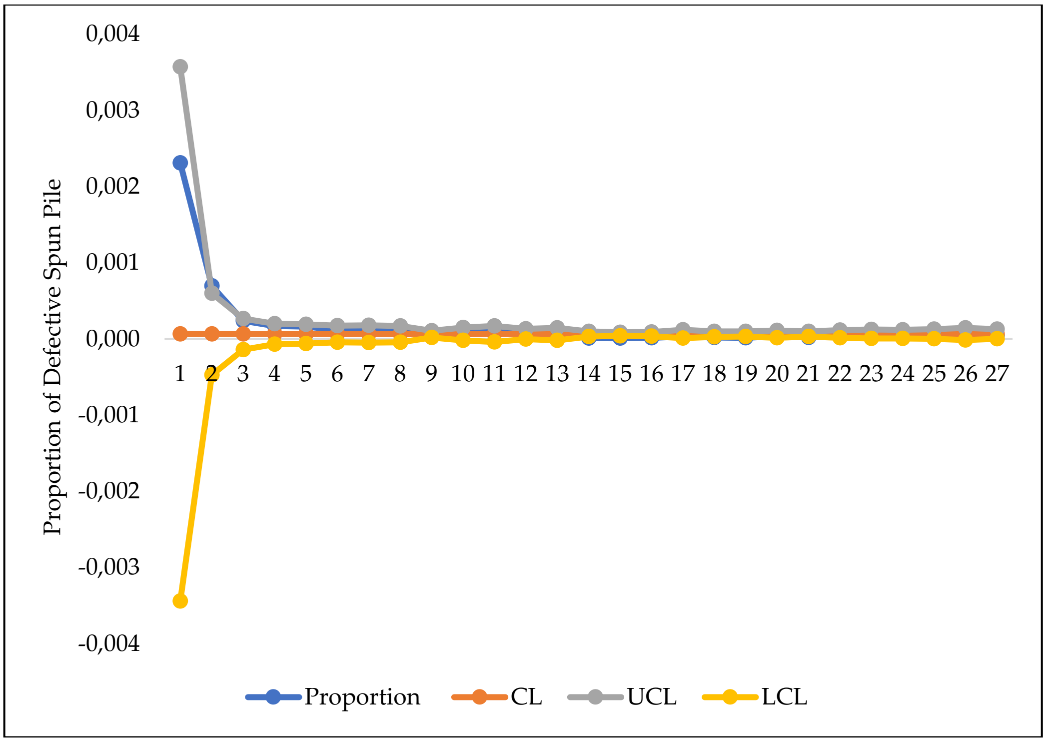

Figure 1. Control chart of spun pile defects

To evaluate the quality performance of the Company's spun pile production across a longer horizon, the Defects Per Million Opportunities (DPMO) and Sigma levels were calculated monthly from April 2020 to June 2022. This analysis uses real production data and identifies quality capability by converting DPMO values into Sigma levels, which serve as standardized indicators of process performance in Six Sigma methodology.

As shown in Table 5, Sigma levels ranged from a low of 3.398 in April 2020 to a high of 5.226 in June 2021. Monthly fluctuations in Sigma levels reflect variations in process stability and defect rates. The average Sigma level across the 27-month period was 4.67, which indicates that the process is statistically under control and operates close to world-class standards (which target a Sigma level of 6.0).

In months such as May 2021 (5.133) and June 2021 (5.226) show that the process was operating with a defect rate below 150 DPMO, approaching Six Sigma excellence (3.4 DPMO). However, earlier months, especially in 2020, exhibited much lower Sigma levels and higher DPMO, indicating periods of process instability.

These findings underscore the positive impact of continuous improvement and process control measures implemented by the Company. Nonetheless, sustaining a Sigma level above 4.5 should remain a strategic target for the company, particularly for ensuring quality compliance in structural applications and export-oriented production.

Table 5. The sigma levels of spun pile

Tahun	Bulan	DPMO	Sigma Level
2020	April	28,846.15	3.398
	May	8,663.37	3.880
	June	2,982.11	4.250
	July	2,116.08	4.360
	August	2,004.58	4.377
	September	1,461.99	4.476
	October	1,558.96	4.456
	November	1,425.31	4.483
	December	263.16	4.967
2021	January	1,044.57	4.577
	February	1,256.28	4.522
	March	626.88	4.726
	April	837.05	4.643
	May	139.82	5.133
	June	97.20	5.226
	July	163.29	5.093
	August	389.81	4.860
	September	213.68	5.023
	October	145.18	5.124
	November	456.20	4.816
	December	245.58	4.986
2022	January	481.51	4.801
	February	547.77	4.765
	March	413.45	4.844
	April	521.38	4.779
	May	670.24	4.707
	June	465.26	4.811
	Average	2,149.51	4.670

3.3. Analyze

The Analyze phase aims to identify the most dominant causes of product defects and determine their root causes. To achieve this, two primary quality control tools were used: the Pareto chart and the Fishbone (Ishikawa) diagram. The Pareto analysis ranks the defect categories based on their frequency, allowing focus on the few vital problems that contribute to the majority of quality issues.

A closer examination of the monthly proportion data presented in Table 4. shows that April and May recorded the highest defect levels, with proportions of 0.231 and 0.069 respectively. These values exceed the upper control limit, indicating that the production process was experiencing significant instability during the early months of observation. To understand these unusually high defect rates, a contextual operational review was conducted in addition to the general root cause patterns identified earlier [10], [16].

The elevated defect proportions in April and May correspond with the initial commissioning period of the newly developed production plant. Construction of the plant was completed only in February, and production was required to start immediately afterward to meet project demands. During this early operation period, several critical elements of process readiness had not yet reached a stable or controlled state. Machine calibration for the heading machine, stressing equipment, and batching plant had not been fully optimized [32], [34]. Standard operating procedures were still in the process of being standardized and communicated to the workforce. Many operators were newly deployed or adjusting to new responsibilities following the construction stage [17], [30]. Meanwhile, material quality, particularly aggregate consistency and moisture content, had not yet stabilized due to the supply chain also undergoing a transition phase, a challenge commonly noted in precast concrete production environments [1], [27].

These combined factors resulted in substantial process variability and directly contributed to the unusually high defect proportions observed in Table 4. for April and May. Such contextual conditions are not explicitly represented in the Fishbone diagrams because those diagrams summarize root causes at a general analytical level rather than capturing time specific operational disruptions. Therefore, the defect spikes in the first two months of the dataset reflect the expected instability during the transition from plant construction to full operational capacity, which is consistent with findings from other early-operation quality assessments in the construction materials industry [18], [35].

Furthermore, the sigma level analysis presented in Table 5. shows that the lowest sigma values also occurred in April and May, which aligns with the defect spikes observed in Table 4. This confirms that the early months of plant operation were characterized by significant process instability. The gradual increase in sigma levels in the subsequent months is consistent with the progressive stabilization of production activities. As machine calibration improved, operators gained experience, standard operating procedures became more consistently applied, and material supply variability decreased, the process began to operate under more controlled conditions. This trend mirrors the typical improvement curve noted in DMAIC applications, where stabilization occurs as process maturity increases and variability decreases [33], [38]. Interpreting sigma performance in relation to these real operational developments provides a clearer understanding of how production capability evolved over time and why the process eventually approached a higher and more stable sigma level.

Having established how process capability fluctuated during the early operational months and gradually improved as the plant matured, the next step is to determine which defect types were the primary drivers of the overall defect rate. The Pareto analysis shown in Figure 2. provides a clearer picture of these dominant contributors.

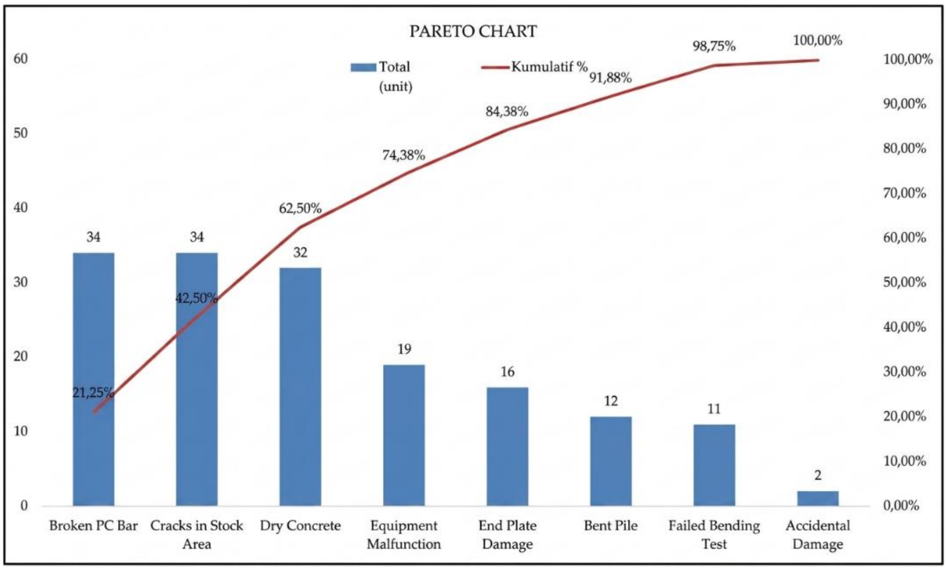

Figure 2. Pareto chart of spun pile defects

As illustrated in Figure 2., the Pareto chart for spun pile defects at the Company shows that the three leading types of defect including Broken PC Bar, Cracks in Stock Area, and Dry Concrete account for 62.5% of total product failures. This observation supports the Pareto Principle, which asserts that approximately 80% of problems originate from 20% of causes [34]. Therefore, focusing on these three dominant defect types is likely to yield the most significant improvement in product quality and reduction of waste. Accordingly, these defect categories became the focal point of the subsequent root cause analysis, ensuring that improvement efforts were directed toward the areas with the greatest potential impact on overall process performance [32], [66].

To further investigate, a Fishbone Diagram was constructed to analyze the underlying causes across five contributing factors: Man, Machine, Method, Material, and Environment. The analysis revealed that recurring issues were associated with inconsistent operator handling, improper material curing, machine calibration issues, and deviations in standard procedures. These insights form the foundation for targeted improvement actions in the next phase.

As illustrated in Figure 3., the Fishbone Diagram for *Broken PC Bars* categorizes the root causes into four main groups: Man, Machine, Method, and Material. Key findings include operator fatigue, inaccurate stressing operations, uncalibrated heading equipment, and deviations from standard procedures, all of which contribute significantly to the failure.

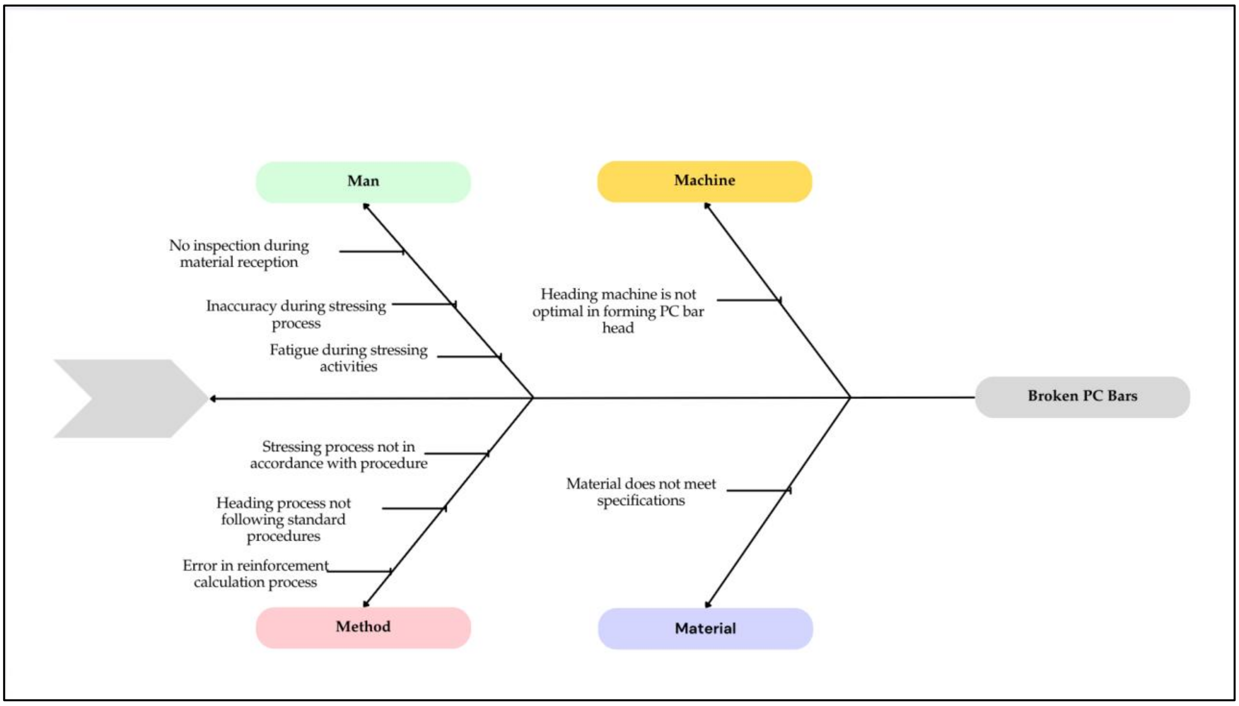

Figure 3. Fishbone diagram of broken PC bars

Similarly, Figure 4. presents the Fishbone Diagram for Cracks in Stock Area, revealing that improper lifting techniques, poor maintenance of lifting equipment, and incorrect stacking methods are among the dominant root causes. Both diagrams serve as diagnostic tools that guide the formulation of targeted improvement strategies in the next phase.

In addition to the previous two diagrams, Figure 5. illustrates the Fishbone Diagram for Dry Concrete, another major contributor to overall product defects. This defect category is attributed to factors spanning Man, Machine, Method, and Material. Key human-related causes include incorrect input on the batching plant interface and lack of focus during concrete mixing. On the machine side, inadequate calibration and maintenance of the batching plant were identified. Method-related issues involve errors in mix design calculations, while material-related problems stem from deviations in concrete composition that do not align with the prescribed Job Mix Formula (JMF). The structured visualization of these variables allows for more targeted process interventions in the Improve phase

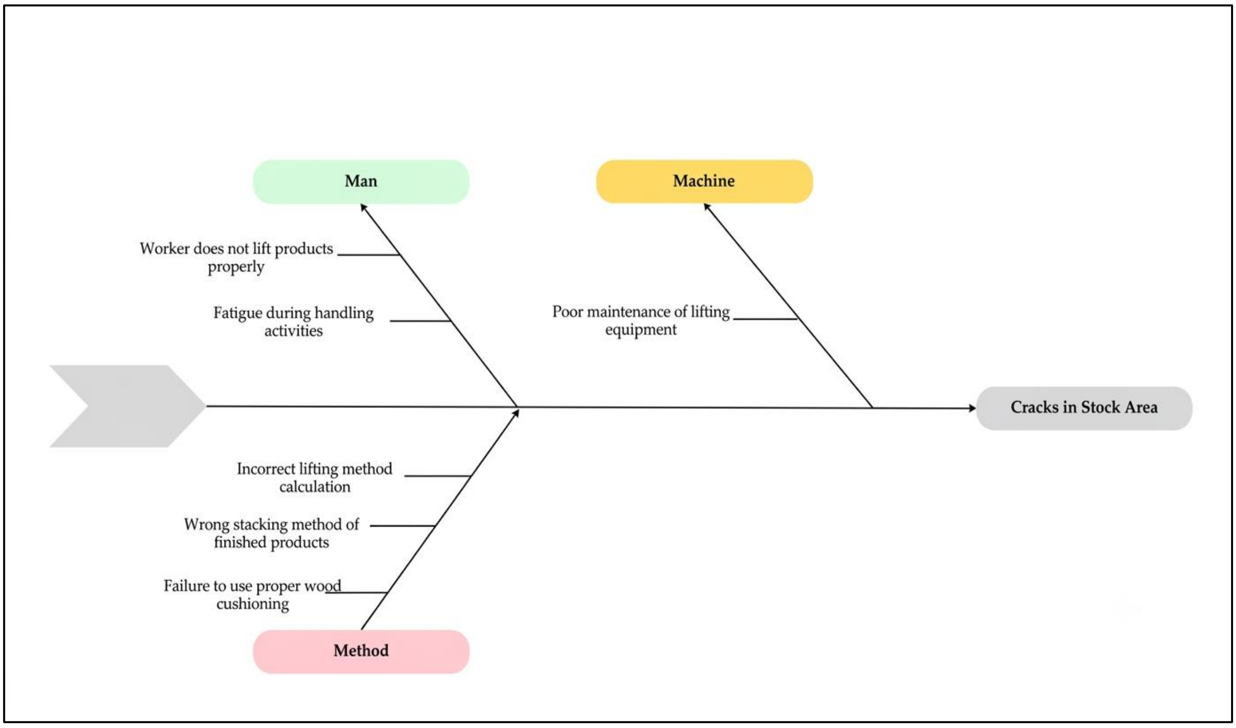

Figure 4. Fishbone diagram of broken PC bars

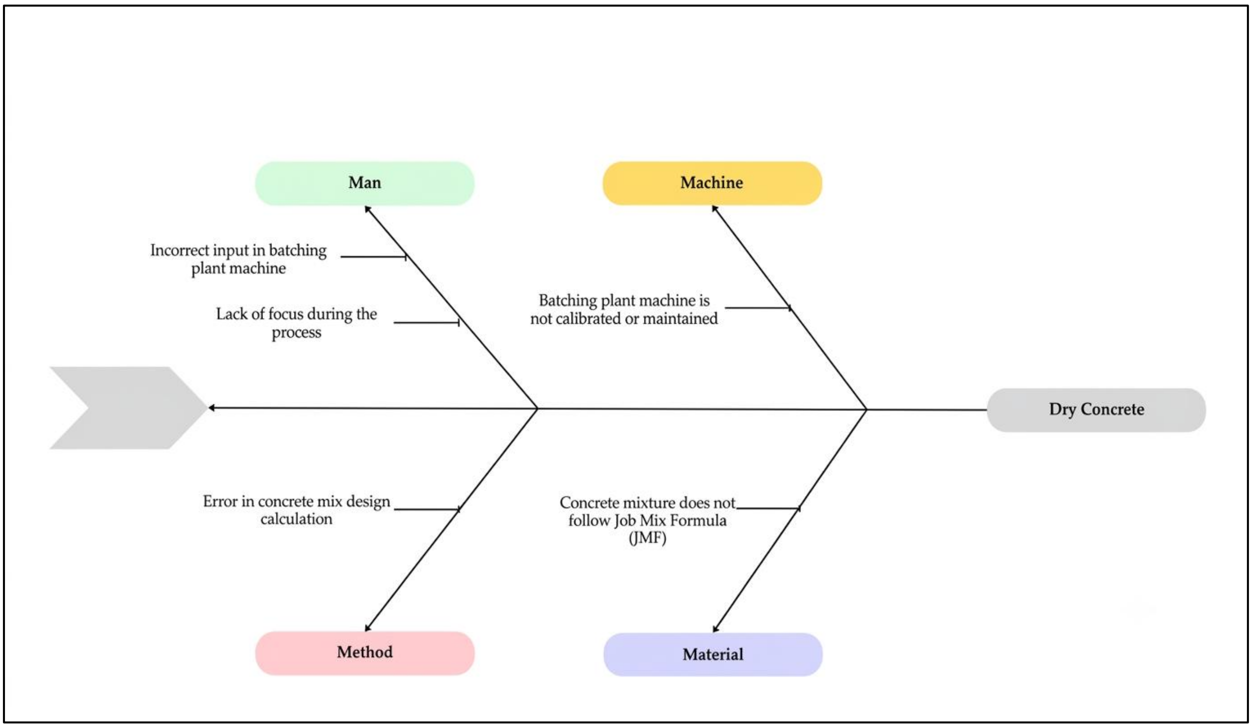

Figure 5 . Fishbone diagram of broken PC bars

3.4. Improve

The Improve phase focuses on developing targeted corrective actions based on the root causes previously identified using Fishbone and Pareto analyses. These improvements are designed to mitigate defects in spun pile production at the Company, particularly addressing key categories such as Broken PC Bars, Cracks in Stock Area, and Dry Concrete.

In developing the improvement strategies, the authors conducted a focused group discussion (FGD) with key operational stakeholders at the Company, including the plant manager, the site engineering manager, and the quality control officer. This collaborative discussion was carried out to validate the identified root causes, evaluate the feasibility of potential corrective actions, and ensure that the proposed improvements align with actual production conditions and organizational readiness. The improvement actions presented in this section therefore represent proposed recommendations that have been conceptually reviewed and refined through direct consultation with plant experts. While these actions have not yet been fully implemented, they have received preliminary approval and are expected to be adopted in future operational cycles as part of the Company's ongoing quality improvement initiatives. This collaborative foundation ensures that the proposed strategies are operationally grounded, technically justified, and capable of supporting long-term enhancements in production quality once implemented.

Each issue has been classified under the main causal factors: Man, Machine, Method, and Material. The solutions are detailed in Table 6, Table 7, and Table 8, ensuring structured interventions aligned with each defect source. For instance, to address Broken PC Bars, efforts include recalibrating the heading machine, implementing SOP checklists, retraining operators, and using digital validation tools for reinforcement calculations.

Table 6. Improvement actions for broken PC bars

Factors	Problem	Improvements
Material	Material does not meet specifications	Implement stricter material acceptance standards and supplier audits
Machine	Heading machine is not optimal in forming PC bar heads	The process of rechecking before starting production
		Periodic maintenance process every two weeks
Man	No inspection during material reception	Assign quality control staff for receiving inspection
	Inaccuracy during stressing process	Implement on the job supervision and real time feedback
	Fatigue during stressing activities	Schedule work shifts to allow adequate operator rest and introduce ergonomic aids
Method	Stressing process not in accordance with procedure	Regular maintenance and calibration of the stressing machine Retraining workers on proper stressing machine use.
	Heading process not following standard procedures	Implement SOP checklist and periodic training on proper heading procedures
	Error in reinforcement calculation process	Introduce digital tools or cross-check mechanisms for reinforcement design validation'

Table 7. Improvement actions for cracks in stock area

Factors	Problem	Improvements
Machine	Poor maintenance of lifting equipment	Establish preventive maintenance policy to avoid equipment failure
Man	Worker does not lift products properly	Conduct proper lifting technique training
	Fatigue during handling activities	Implement worker rotation schedule for lifting activities
Method	Incorrect lifting method calculation	Provide training for the technical team on concrete lifting load calculations

	Wrong stacking method of finished products	Develop standardized stacking procedures
	Failure to use proper wood cushioning	Mandate the use of wood cushioning in all stacking processes

Table 8. Improvement actions for dry concrete

Factors	Problem	Improvements
Material	Concrete mixture does not follow Job Mix Formula (JMF)	Implement strict quality control checks for each batch
		Conduct regular material audits to ensure compliance with JMF
	Batching plant machine is not calibrated or maintained	Schedule routine calibration and maintenance
		Maintain a logbook for calibration and maintenance records
Man	Incorrect input in batching plant machine	Implement a double-check system (operator + supervisor verification)
		Provide clear SOPs for machine operation
	Lack of focus during the process	Conduct fatigue management training
Method	Error in concrete mix design calculation	Require peer review of calculations before implementation

To reduce cracks in the Stock Area, preventive maintenance of lifting equipment and technical training in load calculations are proposed. Moreover, worker rotation and the introduction of standardized stacking practices and proper wood cushioning are key improvements aimed at minimizing handling-induced damage.

In the case of Dry Concrete defects, critical interventions involve enforcing Job Mix Formula (JMF) compliance, performing double-verification during batching operations, and conducting regular equipment calibration and fatigue training for staff. Method-related errors are countered through peer review mechanisms for mix calculations.

3.5. Control

This stage of monitoring proposed improvements represents the final phase of the DMAIC approach. It involves establishing control over the improvements identified in the previous phases to ensure that the expected outcomes are sustained. The Control phase is crucial to maintain the consistency of implemented improvements and to prevent a return to prior inefficiencies.

This study proposes several examples of monitoring tools that can be applied in the spun pile factory to facilitate easier control implementation. These include monitoring tools for production equipment maintenance and quality control systems.

Monitoring production equipment maintenance is essential to ensure that operations are not disrupted by unexpected equipment failures, especially for lifting machinery. Since a significant portion of production activities relies on lifting tools, sudden failure of this equipment can lead to product defects or even pose a danger to workers. Monitoring quality control involves evaluating and checking quality from the material reception phase through to the final delivery of spun piles to project sites. This ensures customer satisfaction by maintaining product quality and avoiding complaints or returns.

4 CONCLUSION

This study applied the DMAIC Six Sigma methodology to reduce defects in precast concrete spun pile production at the Company. Analysis of April 2020–June 2022 data identified a 0.63% defect rate, primarily dominated by Broken PC Bars, Cracks in Stock Area, and Dry Concrete. Root cause analysis highlighted issues in manpower readiness, machine calibration, procedural adherence, and material consistency, leading to the formulation of targeted improvement strategies. These findings demonstrate the practical value of the DMAIC framework in guiding structured quality enhancement within precast manufacturing.

This research provides a practical decision-support framework that the Company can use to prioritize defects and design feasible corrective actions. However, the proposed improvements have not yet been fully implemented or evaluated over time, and real-time monitoring technologies were not included in this study. Future work should focus on post-implementation assessment, IoT-based quality monitoring, data mining-based defect prediction frameworks such as CRISP-DM [68] and broader application across multiple production facilities to strengthen generalizability.

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