Factors Impacting Dimensional Deviations with Computerized Numerical Control Machining Processes: Solutions to Reduce Product Nonconformities

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Abstract

Oil and gas industries rely on sophisticated downhole tools used during drilling to optimize well production levels and maintain continuous flow from reservoirs. To be profitable, manufacturers must meet downhole product design specifications, ensuring production levels are maintained without downtime. Manufacturers receive millions of dollars annually from the oil and gas producers who expect equipment within tolerances to meet production schedules. A high occurrence of dimensional deviations in computerized numerical control (CNC) machining products triggers unwanted expenses on resources. Dimensional nonconformities adversely impact delivery of products to end users due to delays needed for rework or replacement. This research contributes to manufacturing companies by applying Deming's Plan-Do-Study-Act (PDSA) theoretical framework, failure modes and effects analysis (FMEA), root cause analysis (RCA), and Pareto analysis to eliminate nonconformities. Factors impacting deviations during CNC machining processes are investigated and are found to reduce nonconformities, improve cost savings, and increase customer satisfaction for competitive market advantages.

Keywords
Oil and gas drilling, Downhole tools, Computerized Numerical Control (CNC) machining, Dimensional deviations, Plan-Do-Study-Act (PDSA)

1. Introduction
A globally established and leading manufacturer, labeled as "organization" in this research study for confidentiality, has become one of the largest manufacturing suppliers of downhole tools in the oil and gas industry. Over the past 50-year period, the organization has grown from a small manufacturing shop to one of the top-tier equipment suppliers for the oil and gas service industry. From its beginnings with only a couple of manufacturing machines, the organization has expanded its manufacturing capabilities. The company now has over 100 advanced computerized numerical control (CNC) machines to produce various complicated products for the oil and gas industry.

The organization is also expanding its manufacturing capabilities by extending the branches and adding several special processes. This expansion would allow the organization to compete with other high precision manufacturing companies and further diversify industries. Figures 1 displays two examples of CNC machines used at the company to manufacture the oil and gas products according to product design and customer requirements. The CNC program and operator control these types of machines. The machine operator must set up the cutting tools, load and unload material, and perform tool adjustments—whereas the computer programs are developed to control tool path and other automated elements.

Figure 1. CNC machine to manufacture the oil and gas products

A high occurrence of dimensional deviations in CNC machining products has triggered unwanted expenses for material and resources. Figure 2 provides an example of a dimensional deviation that has caused problems in the organization. Some of the deviations in the products during the CNC machining processes needed time to be reworked or replaced. Rework or replacement would cause a delay in the shipment and create an unsatisfied customer.

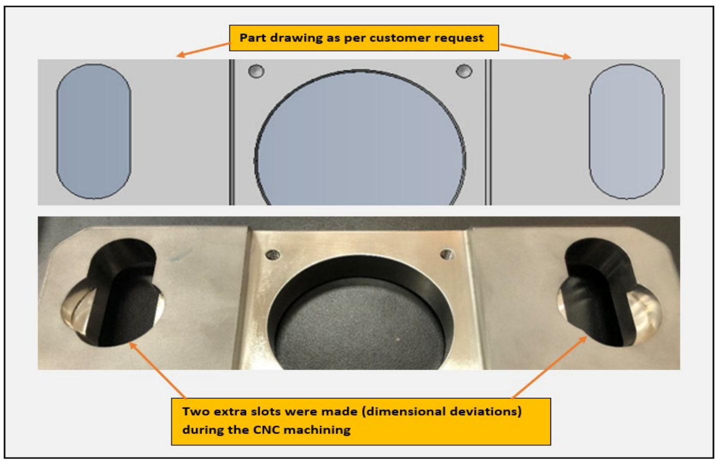

Figure 2. Dimensional deviations on two features of a machined product

1.1 Objectives

The organization has had several product nonconformities over the last five years involving the quality of manufactured products that did not conform to the customer requirements. There was a total of 87 customer complaints (product nonconformities) in 2020 that included 61 deviations due to dimensional deviations. Based on the discussion with the prime customer, the deviations related to dimensional and threading issues might negatively affect the assembly of downhole tools at customer locations or fields, resulting in the late delivery of the tools and equipment to the end-user.

This research analyzed product nonconformities at the organization by defect in 2020 and displayed the different defects in a Pareto chart (Juran 2019) to discover the specific defects that impacted the number of product nonconformities at the organization. The goal of this study was to investigate the high rate of dimensional deviations in the CNC machining process, understand what was causing the problems, and discover a solution to eliminate problems in the future.

The organization being studied encountered thousands of dollars of nonconforming products in the shop that were waiting for rework or remade to replace scrapped parts. If the parts needed to be reworked or remade, staff took time to be ready for the shipment. As a result, rework time negatively affected deliveries to the main customers. Holding large volumes of nonconforming products was a business risk. This research focused on finding a solution for reducing the number of product nonconformities to mitigate the financial risk of holding them in the shop and ensure that the parts were delivered to the customers on time. Preventing the potential recurrence of product nonconformities during the CNC machining processes decreases the cost of rework and scrap.

Figure 3 demonstrates all the product nonconformities by defect at the organization—internal and external—in 2020. This data shows that more than 80% of the problems have been due to dimensional deviations. Additionally, this study focused on investigating product deviations, the factors that have impacted the dimensional deviations at the organization, and the application of different quality tools to eliminate the cause of these nonconformities. Effective actions have been defined to reduce the number of product nonconformities caused by dimensional deviations. The corrective actions implemented were evaluated for effectiveness to ensure that the causes of product nonconformities were eliminated in the future.

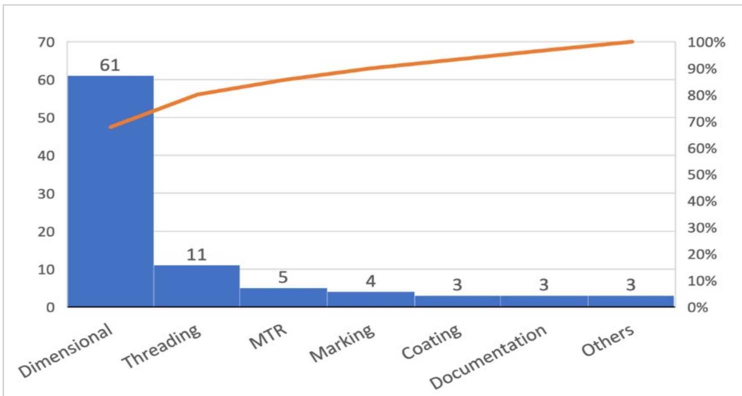

Figure 3. Product nonconformities by defect in 2020

2 Literature Review

This study has explored the root causes of dimensional deviations at the organization and defined effective corrective actions to eliminate the cause of similar issues to increase customer satisfaction. There are always opportunities in successful businesses to change and discover ways to improve the quality of their products and services (Grower 2016). Deming's (1986) theoretical quality framework PDSA was utilized to show the importance of continuous quality improvement when manufacturing products. Deming (1994) defined the cycle for learning and improving a product or process. Figure 4 shows the combining of the PDSA theoretical framework with the three questions of the Model for Improvement (Moen and Norman 2010), and also the iterative PDSA process (ConceptDraw 2022).

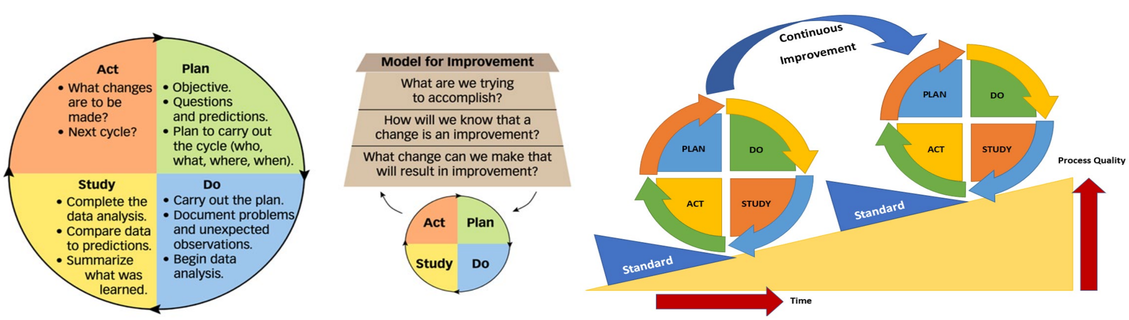

Figure 4. Deming's plan-do-study-act (PDSA) cycle and Continuous improvement using the PDSA framework

Until 2014, the oil and gas manufacturing companies earned huge profits and did not focus on product nonconformities within the operations due to high revenues. This situation has subsequently changed, and the oil and gas industry is now concentrating on two approaches: (1) increasing production and (2) reducing capital and operating expenses (British Petroleum 2016). In addition, oil and gas companies must initiate innovation practices for cost-saving and efficiency improvements and adopt new drilling technologies to meet the growing demand and remain competitive (Tarver 2022).

The company has expanded its branches and added several unique processes to compete with other high-precision manufacturing enterprises and diversify its product portfolio further. Therefore, it is critical to investigate all dimensional deviations and prepare a process improvement plan.

Farfan-Meza et al. (2019) reported that the high frequency of dimensional deviation of similar products impacts the business operation's profit. In the face of 87 product deviations in one year at the organization, applying the 80/20 rule in the Pareto chart helped the organization classify the nonconformities by defect. Findings indicated the main deviations came from 20% of nonconformities which were dimensional deviations. This study proposed that the organization investigate in detail to find the factors that affected the dimensional deviations. Moreover, a PDSA cycle and Pareto chart were among the most frequently used tools in the manufacturing continual improvement process. Any changes after the implementation of corrective actions would need to be tested individually in order to ensure the actions were, in fact, effective (Christoff 2018).

2.1 Deming's Plan-Do-Study-Act (PDSA) Theoretical Framework and Quality Methodologies

The PDSA framework is designed for improving products and services to ensure continuous progress in all parts of a business (Bustard, 2012). The framework also has been shown to be effective in complex organizational change management (Donnelly and Kirk 2015). This framework can support expanding and emerging industries regardless of their complexity or industry. The quality tools utilized in this study helped the organization reduce product nonconformities, and the actions taken were shared as lessons learned with other organizational shop departments. Different quality tools were used to discover the root causes of the deviations at the organization. Engagement of shop employees involved in manufacturing and inspection of the deviated products were the focus of this study for the RCA and corrective actions.

Gu et al. (2015) reported that one of the most significant factors for CNC machining parts with the appropriate quality for consistent performance in their assemblies was machine tool offset accuracy and repeatability. The most difficult areas were identifying and evaluating dynamic CNC machine defects quickly enough to apply the appropriate error models to compensate with prompt corrections. A technique was used to predict the global offset for a CNC machine tool based on the computed deviation between the measured and nominal dimensions of the part.

3. Methods

This study utilized the quality theoretical framework PDSA and quality techniques such as a Pareto chart, Fishbone, FMEA, 5 Whys, RCA, and 8D Model to identify and analyze needs and opportunities for continuous improvement for the organization's product nonconformities reduction. By establishing an appropriate corrective action, the proposed study aimed to reduce the number of product nonconformities at the organization due to dimensional variations. The Pareto chart is used broadly in QC settings to recognize essential variables that most affect the failures or defects in a process (Wilkinson 2016). By studying how the root cause of the investigation was connected to the cause of product nonconformities due to dimensional deviations, the method uncovered operations changes to mitigate the risk of recurrence in the future (Gurley et al. 2021).

4. Data Collection

In order to understand the Plan phase, the nonconforming product data due to dimensional deviations were collected from the NCR software of the organization. All the necessary data concerning internal Non-Conformance Reports (NCRs) and customer complaints were available within the NCR system. However, to refine our analysis, the data needed to be exported through an Excel sheet and applied filters to focus specifically on cases related to dimensional deviations. Additionally, the dimensional deviations based on CNC machining, as we observed that several dimensional issues arose due to coating, which had an impact on the product dimensions.

5. Results and Discussion

Deming's PDSA cycle of continual improvement supplied the foundation for this study to investigate the need for the organization to reduce the number of product nonconformities due to dimensional deviations. Further, the organization sought to mitigate the risk of losing several orders from prime customers due to high customer complaints—87 complaints in 2020. In order to improve customer satisfaction, the following quality tools were applied and evaluated.

5.1 Pareto Analysis Results

In order to analyze the product deviations, the issues needed to be categorized by defect. Figure 5 shows a Pareto analysis of dimensional deviations by a defect at the organization.

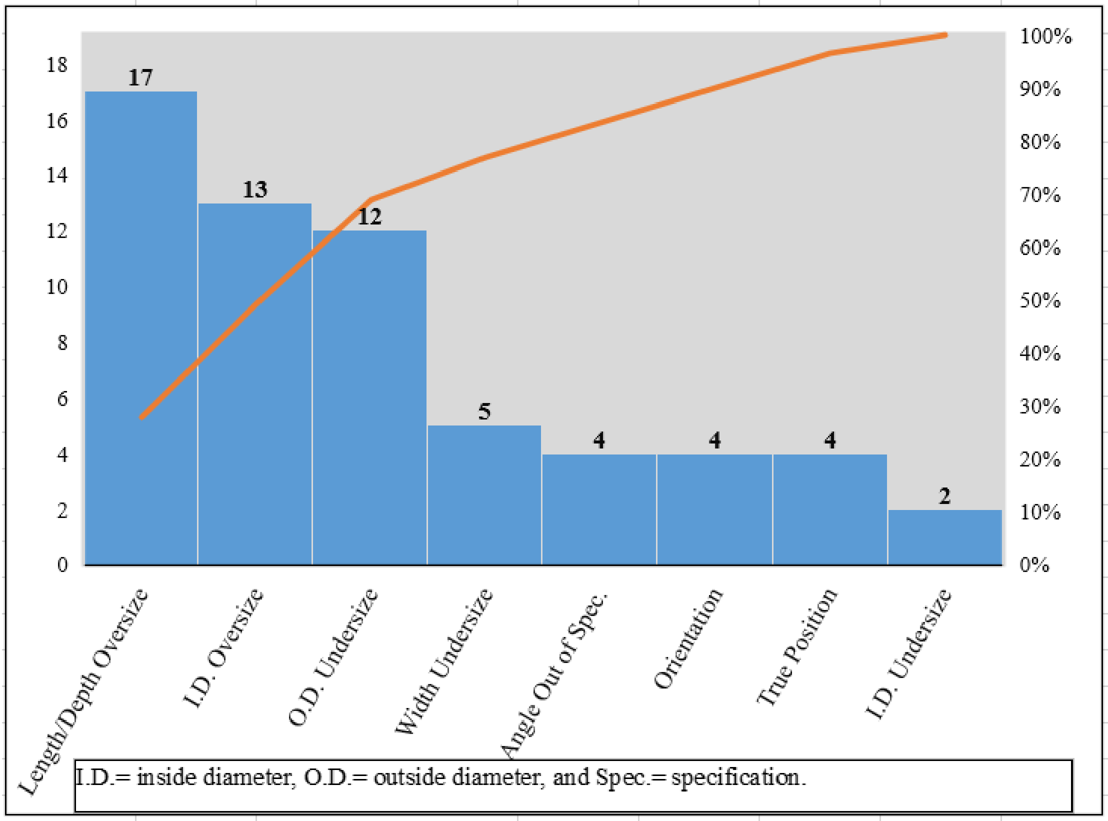

Figure 5. Number of dimensional deviations by defect

Through a Pareto analysis, the majority of defects at the organization in 2020 that affected dimensional deviations were identified as length or depth oversize (17 NCR), inside diameter oversize (13 NCR), and outside diameter undersize (12 NCR). These three defects accounted for approximately 67% of the total defects reported. The remaining five reported defects accounted for 19 occurrences or 23%. The Pareto chart results were reviewed and demonstrated that most rejections were in areas of length and depth oversize, inside diameter oversize, and outside diameter undersize.

5.2 Fishbone Diagram Results

The Cross Functional Team (CFT), including the vice president, plant manager, quality manager, and production manager, identified the causes of dimensional deviations based on the results of the Pareto chart in the following Fishbone diagram. These factors and other possible causes were diagrammed on the Fishbone to assess which areas of the organization were causing the failure modes. Figure 6 displays a Fishbone diagram with the causes and effects on management, people, method, measurement, machine, and material used at the organization to identify the problem.

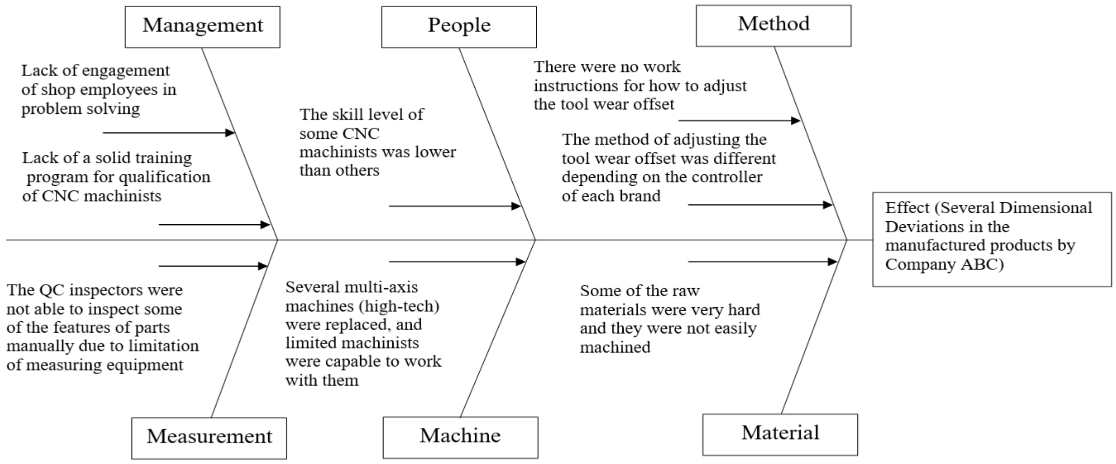

Figure 6. Fishbone diagram to identify the root cause of problems

5.3 8D Model Results

The CFT of the organization used the 8D Model as a problem-solving approach. This model helped the CFT team treat the problem immediately and eliminate the recurrence of nonconformities. The following tasks were performed during the completion of the 8D Report:
Here is one of the completed 8D Model followed by the CFT team of the organization to significantly reduce the number of product nonconformities due to dimensional deviations.

D1: Established the team: CFT team, including operations manager, quality manager and engineering manager.
D2: Problem statement: 61 customer complaints were received in 2020 due to dimensional deviations.
D3: Correction and containment plan: The opened work orders with similar part numbers in the shop were monitored by the operations manager to prevent producing any similar nonconformities.
D4: Investigation and identify the root causes and escape points:

Why 1: Why were the nonconforming products delivered to customers? It appears due to the complexity of the product features, the QC inspectors were not able to detect some of the dimensional deviations by manual inspection.
Why 2: Why could the QC inspectors not catch the dimensional deviations during the inspection process? It was determined that some tight tolerance features should have been inspected by a high-precision measuring equipment such as CMM and digital height gauge.
Why 3: Why do the CNC machinists not adjust the tool wear offsets during the machining process? It was found that some CNC machinists did not have the skill level needed to adjust the tool offset.
Why 4: Why a work instruction was not available in each station of CNC machining? There were no available work instructions because the Company ABC was relying on the experience of the CNC machinists.
Why 5: Why some of the CNC machinists did not have the skill level needed to adjust the tool offset? There was not a solid training process specifically for the qualification of the CNC machinists.

Root Cause: As per the investigation during the 5Why analysis as indicated above, and the results from Fishbone diagram, the root cause of the product nonconformities were identified below:

1. It was found that the majority of dimensional deviations were due to incorrect tool offset setup during the CNC machining processes.
2. There were no available instructions because the Company ABC was relying on the experience of the CNC machinists. However, some CNC machinists did not have the skill level needed in adjusting the tool offset.

Escaped Points: Due to complexity of the product features, it was found that the QC inspectors were not able to detect some of the dimensional deviations by manual inspection. It was determined that some of the tight tolerance features should have been inspected by a high-precision measuring equipment such as CMM and digital height gauge.

D5 & D6: Define “and” implement corrective actions:

1. Several meetings were held with the quality engineering and CNC programming departments to develop seven work instructions on how to adjust the tool offset during the CNC machining. The work instructions were communicated with all the CNC machinists.
2. The qualifications of the CNC machinists were revised so going forward, all the CNC machinists must be qualified in a period of 3 months.
3. A new CMM and digital height gauge were purchased and setup to help the QC team to measure the tight tolerances features.

D7: Effectiveness of the implemented actions:

1. An audit was conducted to ensure all the required work instructions are available in each station and interviewed some of the new machinists to ensure they had understood the instructions.
2. The number of product NCRs were monitored daily and the dimensional deviations have been reduced significantly.

D8: Congratulate the team: Thanks to all the participants for their active participation and valuable input in root cause investigation and implementation of the effective corrective actions.

5.4 Failure Modes and Effects Analysis (FMEA) Results

The FMEA matrix determined which defects were seen as frequent occurrences at the organization. The CFT team identified the required risks at the organization based on their experience and the results from the Pareto chart and Fishbone diagram (see Figures 5 and 6). The purpose of the FMEA was to take actions to eliminate or reduce failures starting with the highest-priority risks. First, risks identified were assessed and quantified by calculating the risk resulting from severity, occurrence, and detection using the FMEA method. Then, the identified risks were assessed, and a recommended action was defined to mitigate the risk score. The organization identified and controlled all the potential risks associated with the delivery and quality of products. The output of high-risk scores was used to develop contingency plans, and the output of the medium risk scores was used for an activity associated with corrective or preventive actions (American Petroleum Institute 2013). Figure 7 shows risk assessment by use of the FMEA method.

FAILURE MODE AND EFFECTS ANALYSIS

Item:	To evaluate the risks (items of concerns) of implementing the use of best practices when adjusting/verifying tool wear offsets.	**Responsibility:** Quality Engineering **Core Team:** Cross Functional Team	**FMEA number:** 69	**Page :** 1 of 1 **FMEA Date (Orig):**

Process Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Class	Potential Cause(s)/ Mechanism(s) of Failure	Occur	Current Process Controls	Detec	RPN	Recommended Action(s)	Responsibility and Target Completion Date	Action Results: Actions Taken	Sev	Occ	Det	RPN
CNC Manufacturing Process	Improper offset entry without verification, could lead to machine a non-conforming part (dimensional deviations)	This non-conforming part would not meet quality specifications that may incur additional rework or repair costs to bring back into specification, or may be scrapped. In addition, this could also adeversely impact on-time delivery commitments.	9		Operators not being instructed to follow generally accepted best practices for adjusting and verifying tool wear offsets for each respective machine. During the root cause investigation, human factor was taken into consideration, including fatigue, stress, etc, and found that none of these factors contrubuted to the cause of this non-conformity.	8	- No available work instruction on how to adjust the tool wear offsets. - First off inspection and final inspection process.	7	504	Initiate a work instruction to document the best practices of adjusting and verifying tool wear offset change for respective CNC machines.	Production and Quality Engineering	All adjustment and verification process work instructions have been created, distributed and communicated out to each CNC department. An assessment review of the NCRs due to dimensional deviations directly attributable to offset eror. Assessed the actions effectively implemented.	9	4	3	108

Sev: Severity, Occur: occurrence, Detec: Detection

Figure 7. FMEA to assess the risks of improper adjusting tool wear offsets during the CNC machining process

5.5 Proposed Improvements

After reviewing the items indicated in the Pareto chart, Fishbone diagram, assessment of the identified risks from the FMEA and 8D Model results, it was found that the Quality Control (QC) team inspected the products 100% during the in-process and final inspection. However, they were unable to detect some part deviations during the manual inspection due to the complexity of the products. Some of the tight tolerance dimensions should have been inspected by high precision measuring equipment such as a coordinate measuring machine (CMM). The organization had a large CMM; however, due to the high volume of batches that needed inspection from these types of machines, there was a constant backlog that adversely affected on-time delivery to customers. The senior management decided to procure a CMM and a height gauge to help the QC team inspect the tight tolerances of dimensions during the inspection process. Figure 8 shows CMM and digital height gauge examples. This equipment was obtained to measure the complicated products so the parts could be inspected accurately and delivered to customers on time.

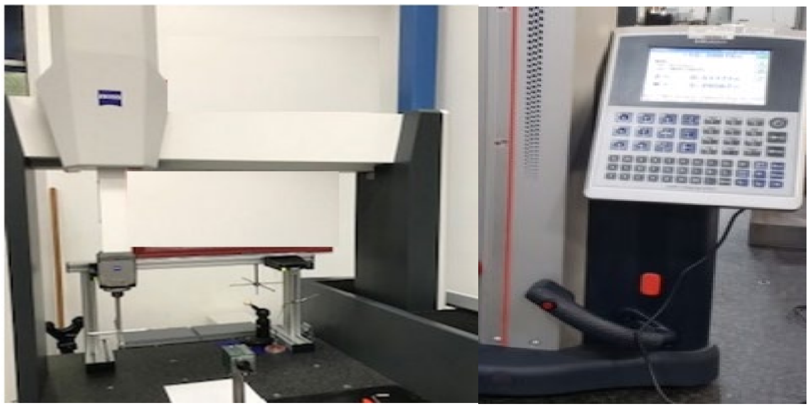

Figure 8. Precision coordinate measuring machine (CMM) and digital Height gauge

It was discovered that many of the defects that affected the dimensional deviations reported in the Pareto chart were derived from the CNC machinist not adjusting the tool wear offset during the machining processes. Some of the machinists did not have the necessary skill level needed for adjusting the tool wear offset, and the organization relied on the presumed experience of the machinists. Moreover, there were no work instructions available for adjusting the tool wear offset in each station of the CNC machines. Different brands of CNC machines in the organization with different controllers compounded the situation, causing the organization to develop a specific work instruction for each brand of controller.

A gap was found where the skill level of each machinist was not the same. Therefore, the organization developed and implemented a new training program provided by the production supervisors, which all CNC machinists completed to ensure they were competent in running the CNC machines independently. This training program allowed all machinists to be competent at the same skill level.

5.6 Validation

Since March 2021, all the relevant shop employees have been engaged in the investigation of avoidable nonconformities to identify the root causes of the deviations and define effective corrective actions to eliminate the causes of identified issues. In addition, a monthly audit was conducted for the effectiveness of the corrective actions. Figure 9 displays that the number of NCR fluctuated from January 2021 until the second week of June 2021. Further, the number of NCR fluctuated with fewer variations and showed a consistent downward trend in the number of weekly nonconformities. The number of weekly NCR in the first and second quarters of 2021 were between four and 10 NCR, and in the third and fourth quarters, were between three and six nonconformities. This reduction in the third and fourth quarters of 2021 was attributable to defining effective corrective actions and evaluating the effectiveness of implemented corrective actions.

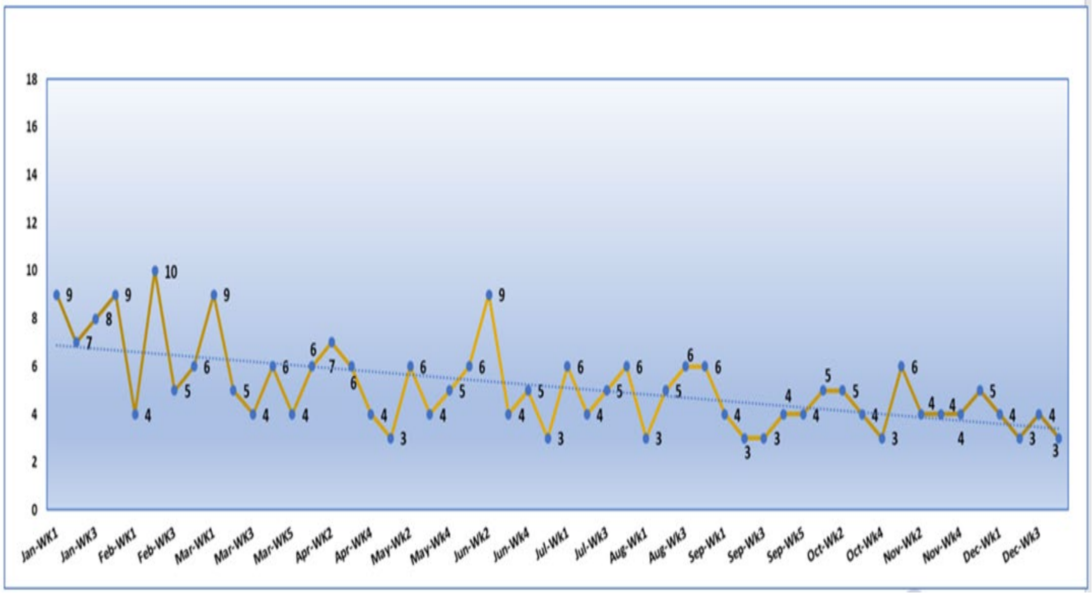

Figure 9. Trend of in-house nonconformities at the organization in 2021

Combining the results from the Pareto chart, Fishbone diagram, and FMEA, an 8D Report was completed to correct the issues on similar parts in the shop and identify the root causes of nonconformities by applying the 5 Whys and RCA quality methods. Effective corrective actions were defined to eliminate the causes of the dimensional issues. After evaluating the effectiveness of implemented corrective actions provided by the FMEA and 8D Report, the number of in-house NCRs was analyzed in December 2021 and compared with the NCR reported in 2020. Figure 10 demonstrates that the number of NCR decreased by 40%, while at the same time, the organization shipped three times more parts to the prime customer than in 2020.

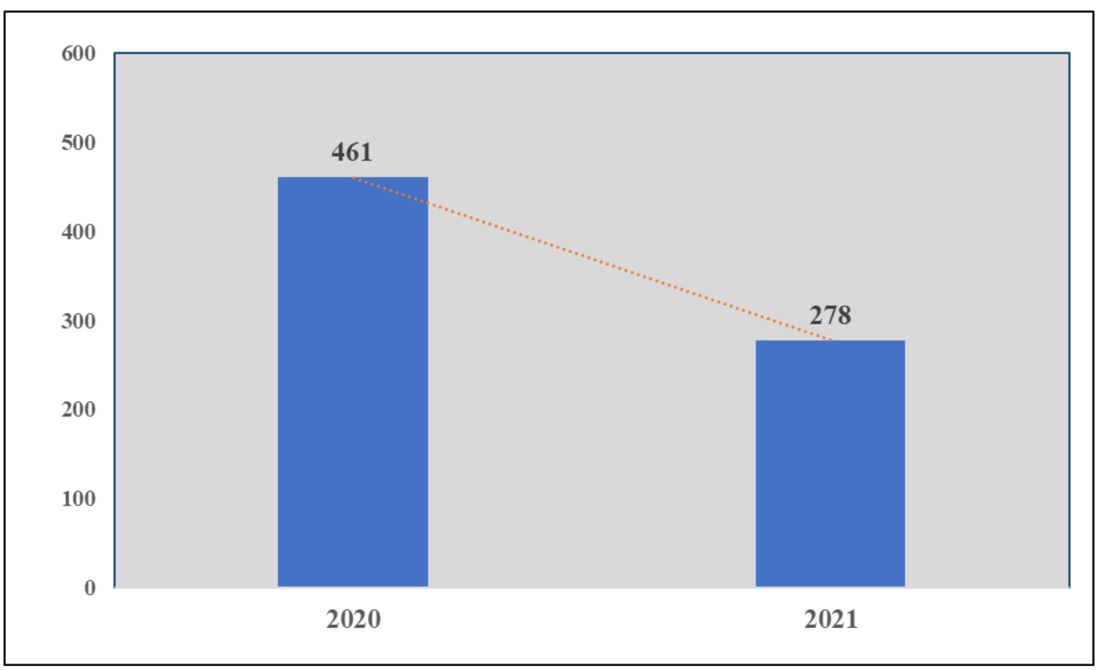

Figure 10. Number of internal NCR in 2021 compared with 2020

Finally, the NCR system software of the organization summarized all the activities and tracked the implementation of improvement plans in the reduction of product nonconformities due to dimensional deviations. The proposed improvement program demonstrated a 40% reduction in the number of NCRs saving hundreds of thousands of dollars due to a reduction in the cost of scrap and rework in 2021 compared to 2020.

6. Conclusions

The organization is one of the manufacturing leaders of downhole tools in the oil and gas industry. The company can produce complex parts for global downhole tool companies. Due to the complexity of products, the QC department must inspect the parts 100% during in-process and final inspections.

Dimensional deviations were common in CNC machining products that caused unwanted resource costs. The organization received 87 customer complaints in 2020 that were primarily due to dimensional deviations. Following discussions with the prime customer, dimensional variations were found that could negatively impact the assembly of downhole tools at the customer's location or in the field, resulting in late delivery of the tools and equipment to the customer. In terms of the domino effect, the organization's prime customer complained in 2020 that 87 product nonconformities negatively impacted the delivery of major projects. Furthermore, if the organization did not take effective action to reduce the number of product deviations by the end of 2021, competitors would supply similar products. The 87 customer complaints in 2020 impacted the reputation of the organization, potentially leading to a loss of market share. This study provided the organization with guidance in assessing the potential risk of losses in the oil and gas market due to 87 product nonconformities involving CNC machining processes in a year. Investigating solutions to reduce the product nonconformities to satisfy customer requirements was necessary for the organization.

Thousands of dollars' worth of nonconforming products were waiting to be reworked or remade at the organization. If parts needed to be reworked or remade, it took time for the organization to assure that the parts were ready for shipment. As a result of the rework time, the primary customer's deliveries were negatively impacted. A business risk existed in keeping large quantities of nonconforming products. A focus of this study was to find a solution to reduce the number of product nonconformities to mitigate the financial risk of holding these nonconforming parts in the shop while also ensuring that reworked or remade parts were delivered to the customers on time.

This study showed how the PDSA cycle was used as a continuous process improvement strategy in an iterative planned sequence involving empirical data collection and analysis. New information was created from the current cycle to ensure that the next cycle used the new learning to plan and make changes for continuous improvement. The four phases of the PDSA continuous improvement framework produced the following outcomes:

- The Plan phase determined the problem and created the action plan to execute in the next phase.
- The Do phase executed the actions outlined in the Plan phase.
- The Study phase reviewed and analyzed the result from the Do phase.
- The Act phase decided whether to cancel the investigation or proceed to another PDSA cycle.

Quality tools were used in conjunction with the PDSA theoretical framework and learning cycle. Pareto charts were used as a visual and quantitative tool to show the frequency of the nonconforming defect counts from highest to lowest and helped determine a priority sequence of problems to resolve. The most frequent defect was chosen as the first problem to resolve. The Fishbone diagram was another visual tool used to brainstorm the causes of the nonconforming defects due to dimensional deviations. A FMEA provided a quantitative tool to identify potential failure modes, causes, and effects within the CNC machining process. Then, an 8D Methodology was used to determine the root causes of deviations using 5 Whys analysis and RCA. To complete all eight disciplines of the 8D Methodology, a corrective action was defined and implemented to eliminate the cause of a problem. The effectiveness of the corrective action taken was evaluated to ensure that the causes of the problem had been eliminated. Lastly, the team was congratulated for their active participation and valuable input to prevent the repetition of similar nonconformities. Each of these quality tools were implemented within the PDSA cycle.

The quality improvement actions taken helped the organization reduce the number of product nonconformities and prevent the recurrence of NCR throughout the CNC machining processes while substantially reducing rework and scrap costs. During the research, all the product nonconformities due to dimensional deviations were analyzed using the Pareto chart with the majority of defects caused by errors in length or depth oversize, inside diameter oversize, and outside diameter undersize. All the causes affecting the dimensional deviations were addressed. However, one of the causes of the nonconformities resulted from a lack of a robust training program for the qualifications of the CNC machinists. Therefore, a training course was developed and conducted to ensure consistency of the skill level of all CNC machinists.

All the potential risks associated with the dimensional deviations and timely delivery of products were identified and assessed by the FMEA method. A required action was taken for the high-risk events to mitigate the occurrence of the risk. One of the recommended actions for the high-risk events was to develop a work instruction for adjusting the tool wear offset so that all CNC machinists could follow the same instructions during the set-up process. The implemented corrective action was evaluated by the FMEA method and found to be effective in reducing defect occurrence.

After implementing the above corrective actions in 2021, the results demonstrated a 40% reduction in NCR numbers that saved hundreds of thousands of dollars due to the reduced cost of scrap and rework compared to 2020. During the same period, the organization shipped three times more products to its prime customer compared with 2020.

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Biographies

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Dr. Milton Krivokuca is Chair Emeritus and subject matter advisor of the Master of Science Quality Assurance program at California State University, Dominguez Hills, Carson, CA. He has also taught master's classes in critical thinking and quality theories at several universities. Additionally, he has presented contemporary quality topics at conferences in Europe, Middle East, Africa, and Asia, locations throughout the United States and Canada. He is past chair of ASQ, Quality Management Division, an ASQ Fellow, ASQ Los Angeles Section 700 Simon Collier Quality Award recipient and 2020 ASQ Section 701 Orange Empire Quality Guru of the Year. Quality 4.0 Thought Leader.

Robert Spencer, MSQA, MA, has worked for more than 40 years in quality systems implementation in large government and private enterprise. As a retired professor, he taught for 34 years in the California State University in two master's degree programs: Master in Public Policy and Administration for California State University, Long Beach, CA, and the Master of Science Quality Assurance program at California State University Dominguez Hills, Carson, CA. For four years he served as ASQ Chief Editor of the peer-reviewed *Quality Management Forum* journal reaching 24,000 ASQ members quarterly. He has consulted with organizations such as Raytheon, Los Angeles International Airport, Sunkist Growers, City of Anaheim, CA, and Korean Airlines. He currently helps graduate students write their thesis papers for graduation.