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Optimizing the Yield of Multi-process Wheelchair Components Using the Six Sigma Define, Measure, Analyze, Improve, Control Approach

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Amid growing consumer awareness, quality management and risk control have become paramount in manufacturing. Inadequate quality assurance systems can escalate production costs through yield deficiencies and provoke adverse market responses due to inconsistent product quality. In this study, we employed the Six Sigma Define, Measure, Analyze, Improve, Control (DMAIC) methodology to enhance quality in wheelchair accessory parts manufacturing. In the Define phase, the production process for the sampling stage is mapped using a flowchart, incorporating inspection checkpoints at critical junctures. The Measure and Analyze phases utilize Failure Mode and Effects Analysis (FMEA) to identify potential failures, evaluating their severity, occurrence, and detectability to devise preventive strategies. Concurrently, a Control Plan is established, specifying quality attributes encompassing equipment, inspection protocols, process parameters, evaluation techniques, sampling ratios, frequencies, and analytical methods, along with corrective actions for anomalies. In the Improve and Control phases, process capability indices are applied to assess product quality stability during ongoing production, targeting defect containment within three standard deviations. This approach minimizes customer complaints, reduces carbon emissions from defect-related transportation and maintenance, fosters environmental sustainability, lowers manufacturing costs, and bolsters customer loyalty. The findings provide a replicable framework for quality optimization in precision manufacturing sectors.

1. Introduction

In wheelchair manufacturing, the hub component is critical, not only supporting the user's weight but also enabling seamless mobility, navigating uneven terrain, and mitigating road surface vibrations.(1) Minor defects in production can result in severe risks, such as user injury due to component failure.(2) To address these challenges within the stringent standards of global supply chains, in this study, we employed the Six Sigma Define, Measure, Analyze, Improve, Control (DMAIC) methodology, a proven approach for enhancing process quality and reducing

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defects.(3) The methodology systematically identifies potential failure modes in multi-process manufacturing, assesses the severity of undetected risks, and categorizes them to develop targeted preventive measures.(4) By prioritizing proactive source management, this approach optimizes manufacturing processes, improves product reliability, and reduces production costs, aligning with established quality management frameworks.(5)

2. Literature Review

We employed the Six Sigma DMAIC methodology to assess potential defect risks in multi-process product manufacturing. The Six Sigma DMAIC methodology is a structured, data-driven framework designed to enhance process quality and efficiency by minimizing defects. It encompasses five key phases: Define , Measure, Analyze, Improve, and Control. Widely adopted across industries such as manufacturing, healthcare, pharmaceuticals, education, and food services, DMAIC leverages quantitative analysis to achieve a defect rate below 3.4 parts per million, driving significant cost reductions, enhanced customer satisfaction, and improved productivity.(6)

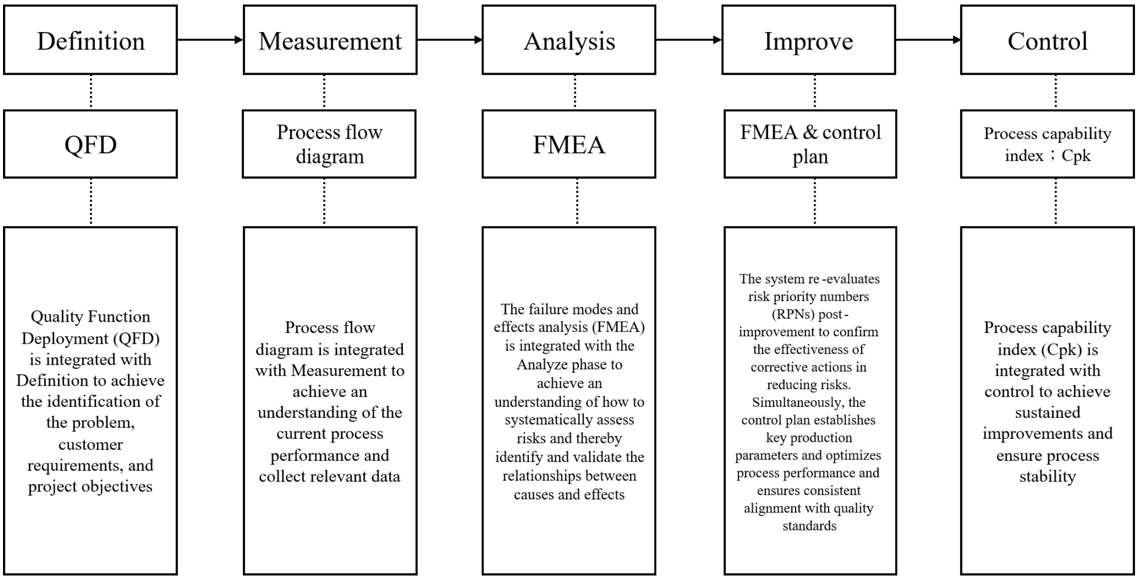
Six sigma is a strategic optimization approach that enhances a company's profitability by reducing waste, scrap, and inefficiencies.(7) Quality Function Deployment (QFD) facilitates product development by translating customer requirements into precise design specifications during the conceptual stage, with the House of Quality as its central framework.(8,9) Failure Mode and Effects Analysis (FMEA) is utilized to assess product reliability and safety,(10) while Control Plans document the systems and procedures implemented to minimize variations in products and processes.(11) Additionally, Process Capability Indices (PCI) evaluate a process's ability to consistently meet specifications defined by customers, engineers, or designers.(12) Together, these methodologies ensure high-quality outcomes and operational excellence.

3. Methodology

As shown in Figure 1, the tools utilized and the research flowchart are presented based on the definition of the Six Sigma DMAIC methodology in Ref. 13.

3.1 Definition

As outlined in Table 1, the primary objective of the Define phase within the DMAIC framework is to "define the problem, customer requirements, and project objectives." In this study, QFD is integrated with product engineering diagrams to effectively achieve these objectives. Using wheelchair components as a case study, we systematically establish project goals and construct a robust foundational framework. The QFD methodology ensures that customer needs are precisely translated into technical specifications, while Product Engineering Diagrams provide a structured visualization of the product's design and functional requirements. The resulting House of Quality, generated through the QFD process, maps customer requirements to technical specifications and is presented in Table 2.



Quality Function Deployment (QFD) is integrated with Definition to achieve the identification of the problem, customer requirements, and project objectives

Process flow diagram is integrated with Measurement to achieve an understanding of the current process performance and collect relevant data

The failure modes and effects analysis (FMEA) is integrated with the Analyze phase to achieve an understanding of how to systematically assess risks and thereby identify and validate the relationships between causes and effects

The system re-evaluates risk priority numbers (RPNs) post-improvement to confirm the effectiveness of corrective actions in reducing risks. Simultaneously, the control plan establishes key production parameters and optimizes process performance and ensures consistent alignment with quality standards

Process capability index (Cpk) is integrated with control to achieve sustained improvements and ensure process stability

Fig. 1. Research flow chart.

Table 1
DMAIC objectives and quality tools correspondence table.

Stage objectives		Quality tools
Definition	Define the problem, customer requirements, and project objectives.	QFD
Measurement	Understand the current process performance and collect relevant data.	Process Flow Diagram
Analysis	Identify and validate the relationships between causes and effects.	FMEA
Improve	Enhance process performance by implementing solutions	FMEA & Control Plan
Control	Sustain improvements and ensure process stability.	Process Capability Index; Cpk

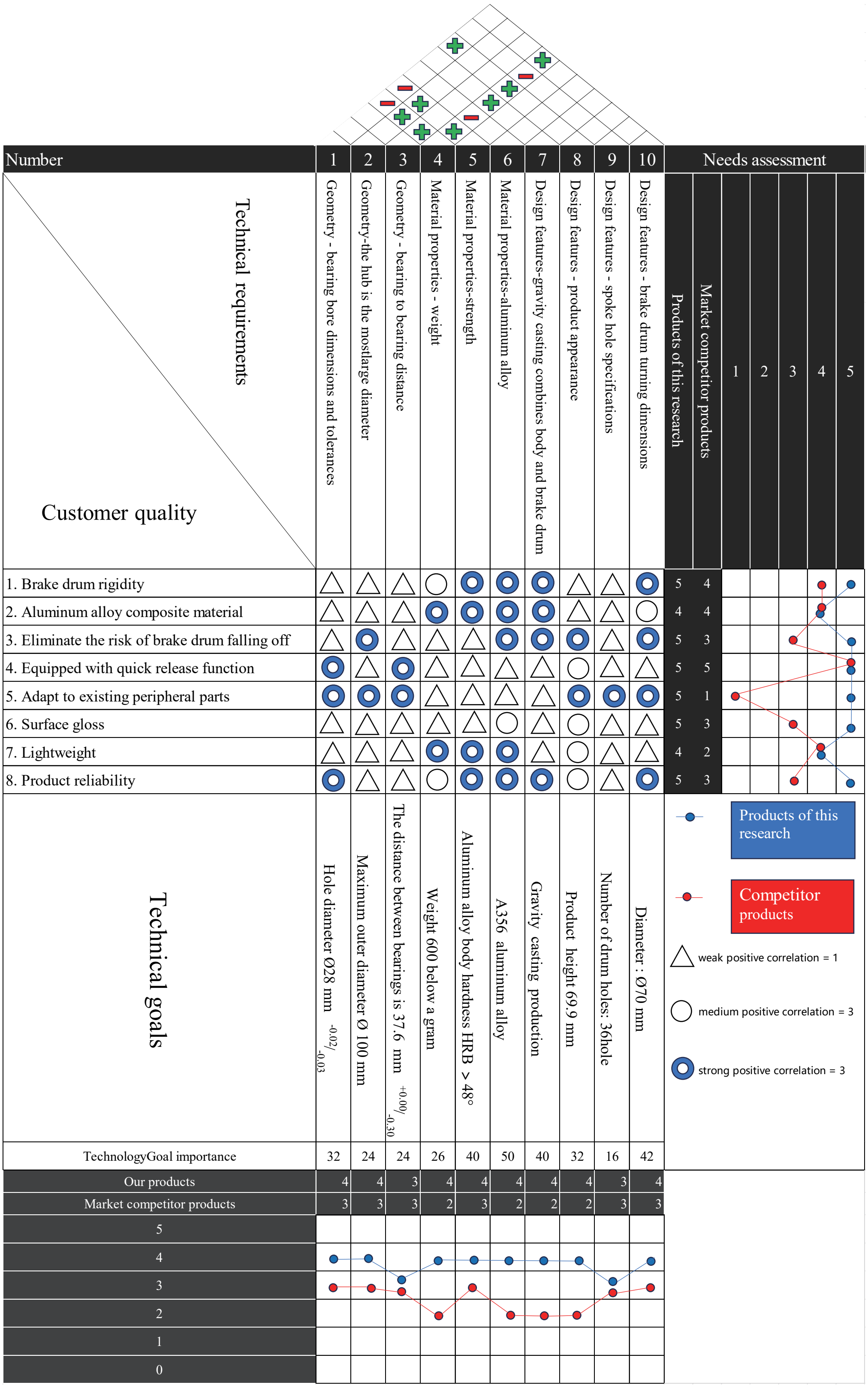
3.2 Measurement

In the Measurement phase of the DMAIC framework, the primary objective is to comprehensively understand the current process performance and gather pertinent data to establish a baseline for improvement, as highlighted in Table 1. To achieve this, a Process Flow Diagram (PFD) is employed to map the existing production process for wheelchair components, providing a structured visualization of operational stages. Refer to Table 3 for the details of the PFD.

On the basis of the product characteristics and requirements identified in the House of Quality and Engineering Diagrams during the Define phase, the production process is systematically organized into four key processing blocks within the PFD.

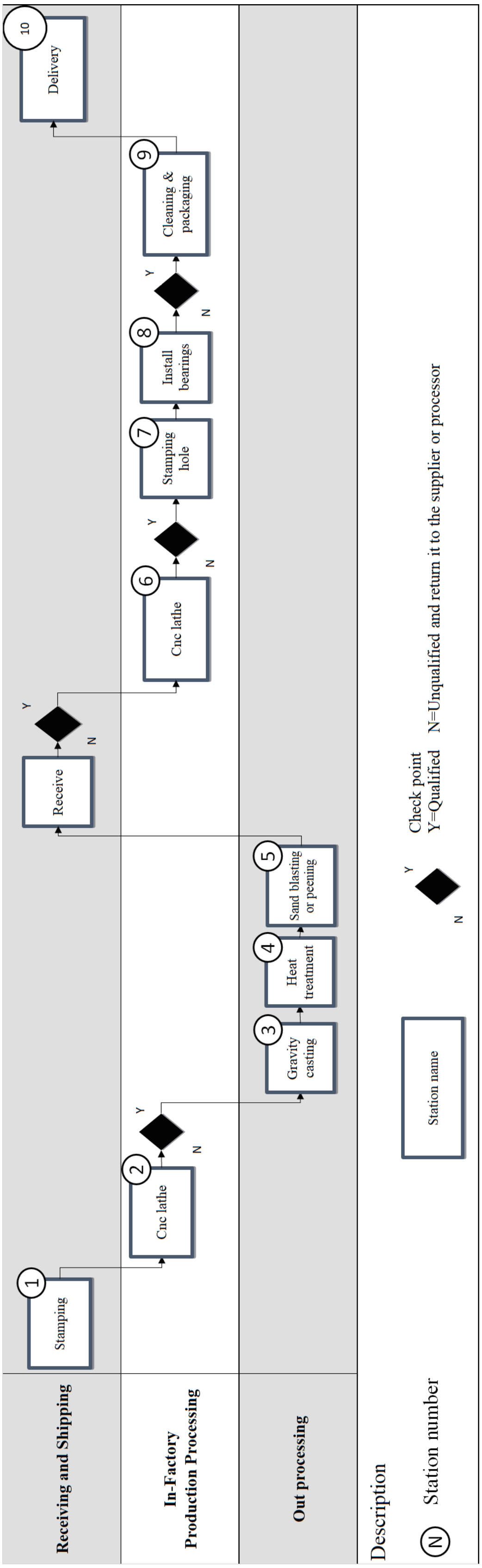
(1) Receiving and Shipping: Encompasses the initial receipt of raw materials and final dispatch of finished components.
(2) In-factory Production Processing: Covers internal manufacturing stages tailored to the defined product requirements.
(3) Outsourcing: Involves external production processes critical to meeting specific component specifications.

Table 2
(Color online) Quality house table.



Number	1	2	3	4	5	6	7	8	9	10	Needs assessment	
Technical requirements / Customer quality	Geometry - bearing bore dimensions and tolerances	Geometry-the hub is the mostlarge diameter	Geometry - bearing to bearing distance	Material properties - weight	Material properties-strength	Material properties-aluminum alloy	Design features-gravity casting combines body and brake drum	Design features - product appearance	Design features - spoke hole specifications	Design features - brake drum turning dimensions	Products of this research	Market competitor products
1. Brake drum rigidity	△	△	△	○	◎	◎	◎	△	△	◎	5	4
2. Aluminum alloy composite material	△	△	△	◎	◎	◎	◎	△	△	○	4	4
3. Eliminate the risk of brake drum falling off	△	◎	△	△	△	◎	◎	◎	△	◎	5	3
4. Equipped with quick release function	◎	△	◎	△	△	△	△	○	△	△	5	5
5. Adapt to existing peripheral parts	◎	◎	◎	△	△	△	△	◎	◎	◎	5	1
6. Surface gloss	△	△	△	△	△	○	△	○	△	△	5	3
7. Lightweight	△	△	△	◎	◎	◎	△	○	△	△	4	2
8. Product reliability	◎	△	△	○	◎	◎	◎	○	△	◎	5	3
Technical goals	Hole diameter Ø28 mm $^{-0.02}/_{-0.03}$	Maximum outer diameter Ø 100 mm	The distance between bearings is 37.6 mm $^{+0.00}/_{-0.30}$	Weight 600 below a gram	Aluminum alloy body hardness HRB > 48°	A356 aluminum alloy	Gravity casting production	Product height 69.9 mm	Number of drum holes: 36hole	Diameter : Ø70 mm		
TechnologyGoal importance	32	24	24	26	40	50	40	32	16	42		
Our products	4	4	3	4	4	4	4	4	3	4		
Market competitor products	3	3	3	2	3	2	2	2	3	3		

Table 3
PFD.


Receiving and Shipping
In-Factory Production Processing
Out processing
1 Stamping
2 Cnc lathe
3 Gravity casting
4 Heat treatment
5 Sand blasting or peening
Receive
6 Cnc lathe
7 Stamping hole
8 Install bearings
9 Cleaning & packaging
10 Delivery
Y
N
Description
N Station number
Station name
Check point
Y=Qualified
N=Unqualified and return it to the supplier or processor

Given the complexity of the production processes outlined in the Define phase, the PFD integrates both outsourcing and in-house production strategies to optimize efficiency. To minimize quality variations, the PFD incorporates designated quality issue handling protocols and strategically placed inspection points. These inspection points are denoted by diamond-shaped markers, with “Y” indicating a pass and “N” indicating a fail. Components that fail to meet quality requirements at these inspection points are deemed unqualified and returned to the supplier or processor for corrective action. Detailed specifications and protocols for these inspections will be elaborated in the Improve phase to ensure robust quality control.

To facilitate seamless integration with the FMEA tool from the Analyze phase and the Control Plan from the Design phase, each production process is assigned a unique workstation number. These are clearly marked with a circled identifier in the upper right corner of the workstation name, ensuring clarity and traceability throughout the production workflow.

This structured approach in the Measurement phase establishes a solid foundation for data-driven decision-making, enabling precise identification of process inefficiencies and quality control measures for subsequent phases of the DMAIC framework.

3.3 Analysis

As delineated in Table 1, the core objective of the Analyze phase within the DMAIC methodology is to “identify and validate the relationships between causes and effects”. To achieve this, the FMEA method is employed to systematically evaluate potential defects in the production process of wheelchair components. The FMEA framework assesses three critical dimensions of failure modes: severity (S), occurrence frequency (O), and detection probability (D), collectively known as the SOD criteria, with detailed specifications provided in Table 4.

This structured analysis enables the identification of critical failure modes, their underlying root causes, and their potential impact on product quality. By quantifying the severity of defects, the likelihood of their occurrence, and the efficacy of existing detection mechanisms, the Analyze phase provides a robust foundation for prioritizing targeted corrective actions and process enhancements. This systematic approach ensures that subsequent DMAIC phases are well-informed, facilitating data-driven improvements to optimize production quality and efficiency.

To enhance the rigor of the Analyze phase within the DMAIC framework, the FMEA method is systematically integrated with the PFD outlined in Table 3. By aligning the SOD criteria, with the workstation numbers specified in the PFD, a comprehensive FMEA assessment table is analyzed, as presented in Table 5.

The FMEA evaluation, conducted in alignment with the PFD workstation numbers and the assessment standards in Table 4, identified two critical issues in the production process of wheelchair components. These findings, detailed below, highlight potential failure modes, their impacts, and associated Risk Priority Numbers (RPNs) to guide subsequent process improvements.

Table 4
FMEA assessment standards form.

Grade	Severity level		Grade	Occurrence frequency		Grade	The probability of being discovered during detection		
1	No failure	No impact	1	Little chance	The probability of failure is very small, the probability is less than 1/30,000	1	Almost	Prevent errors without detection	Errors can be automatically detected or prevented through mechanical design, fixture design or part design, so defective or failed parts will not be produced.
2	Very slight	Minor flaws that only customers with higher standards will notice	2	Low	The probability of failure is very small, the probability is less than 1/10,000	2	Very high	error detection	Detect errors at checkpoints through automatic control devices and prevent the production of defective or failed parts
3	Slight	Minor flaws that some customers may notice	3	Low	The probability of failure is very small, the probability is less than 1/5,000	3	High	Root cause detection	Detect errors at checkpoints through automatic control devices and alert to isolate defective or failed parts
4	very low	Minor flaws that most customers will notice	4	Ordinary	Sporadic failure, probability less than 1/1,000	4	Middle to high	Process problem detection	Detect errors at checkpoints through automatic control devices and alert to isolate defective or failed parts
5	Low	The main function of the product still works, but the secondary or auxiliary functions are reduced	5	Ordinary	Sporadic failure, probability less than 1/400	5	Ordinary	Root cause detection	Operator inspects product by visual/tactile/auditory methods
6	Middle	The main function of the product still works, but the secondary or auxiliary functions fail	6	Ordinary	Sporadic failure, probability less than 1/80	6	Low	Process problem detection	Operator inspects product by visual/tactile/auditory methods
7	High	Product main functions reduced	7	High	Repetitive failure, 1 failure will occur every 20 times	7	Very low	Root cause detection	Operator inspects product visually/tactile/auditory
8	Very high	Product loses main features	8	High	Repetitive failure, 1 failure will occur every eight times	8	Very low	Process problem detection	Operator inspects product visually/tactile/auditory
9	Danger warning	Product failure will affect operational safety or violate legal regulations, but there are warnings	9	Very high	Unavoidable failure, 1 failure will occur every three times	9	Little chance	Low chance of detection	Defective or failed parts are not easy to detect
10	Danger without warning	Product failure will affect operational safety or violate legal regulations without warning.	10	Very high	Unavoidable failure, one failure will occur every two times	10	Unable to check out	No chance of testing	Unable to detect or analyze

Table 5
FMEA assessment form.

PFD work station number	FMEA number	Work process	Potential anomalies/failure modes	Potential impacts caused by anomalies/failures	Severity	Potential causes of exceptions/failures	Existing process				RPN
							Preventive control at this stage	Occurrence frequency	Detectable control methods	Detection probability	
1	1	Brake drum stamping forming	Using wrong steel	Speed up wear and tear	**3**	Using the wrong steel for processing	Upon receipt, suppliers must provide material certificates, and a label card will be created to identify the material	**2**	Check whether the incoming materials and labels are correct	**2**	**12**
2	2	Brake drum cnc turning	Wrong part size	Product main functions reduced	**8**	Too small clamping area causes deformation of parts	Set checkpoints in the process	**7**	Vernier caliper measurement 2.5D projection measurement	**5**	**280**
3	3	Gravity casting	Part body has air holes	Reduced strength of parts	**3**	The air is not completely exhausted during casting	Set up inspection station	**3**	Visual inspection	**6**	**54**
3	4	Gravity casting	Hub deformation	Reduced strength of parts	**2**	Part was removed from the mold before cooling and setting” is recommended	Set up standard operating procedures	**6**	Visual inspection	**5**	**60**
4	5	Aluminum alloy heat treatment	Hardness does not meet requirements	Reduced strength of parts	**7**	Hardness after heat treatment does not meet production specifications	Require suppliers to provide test reports when receiving materials	**2**	Visual inspection	**5**	**70**
5	6	Sandblasting	Uneven spraying	Part appearance defects	**5**	Sandblasting time is too short	Increase and fix sandblasting machine operation time	**2**	Visual inspection	**7**	**70**
6	7	Hub cnc turning	Wrong part size	The function of the part is reduced or the appearance is abnormal	**3**	Tool loss and abnormal machine parameters	Tool life management	**3**	Vernier caliper measurement height gauge combined with fixture measurement	**6**	**54**
7	8	Hub drum hole stamping	Wrong part size	The function of the part is reduced or the appearance is abnormal	**5**	Operator negligence	Set up sampling inspection station	**3**	Visual inspection	**7**	**105**
8	9	Press-in bearing	Wrong part size	The function of the part is reduced or the appearance is abnormal	**5**	Operator negligence	Set checkpoints in the process	**2**	Vernier caliper measurement height gauge combined with fixture measurement	**3**	**30**
9	10	Clean	Residual chemicals and burrs	The parts are dirty and have sharp angles	**2**	Operator negligence	Correct standard work manual	**3**	Visual inspection	**7**	**42**
10	11	Package	Wrong packing quantity	Customer received insufficient product	**3**	Negligence on the part of the packing staff	Correct packaging manual	**4**	Weighing inspection	**5**	**60**

3.3.1 Issue 1: workstation 3, FMEA ID 4: CNC lathe clamping issue

During the CNC lathe operation, improper clamping causes deformation of the workpiece, as shown in Fig. 2, leading to misalignment with the mold during gravity casting. This misalignment results in the leakage of molten aluminum alloy into the component, which may cause brake drum failure, compromising the primary function of the braking system. On the basis of the FMEA assessment standards (Table 4), this defect is classified as a loss of primary product function, with an S rating of 8 (indicating critical impact on product functionality). The occurrence frequency is approximately one defective brake drum per five units produced, yielding an O rating of 7 (repetitive failure occurring approximately once every 20 cycles). Because of the absence of dedicated inspection equipment, detection relies on operator measurements or visual inspections, resulting in a D rating of 5 (detection through operator use of measuring tools during setup and first-piece inspections). The calculated RPN for this failure mode is 240 ($S \times O \times D = 8 \times 7 \times 5$).

3.3.2 Issue 2: workstation 7, FMEA ID 8: hub hole punching issue

The hub hole punching process involves four operations: two punching steps and two chamfering steps. During chamfering, residual punching debris on the hub surface, if not properly cleared by the operator, leads to material extrusion into the hub hole. This causes damage to the hub hole, as shown in Fig. 3, preventing proper insertion of steel spokes or effective bonding with damaged holes, resulting in reduced product functionality. According to Table 4, this defect is assigned an S rating of 5 (indicating that the primary function remains operational, but secondary or auxiliary functions are compromised). The occurrence frequency is approximately one defective hub hole per 1300 units produced, resulting in an O rating of 3 (low probability of failure, less than 1 in 5000 cycles). Current detection relies on visual inspection, supplemented by an inspection station established after bearing insertion to prevent defective products from being shipped, yielding a D rating of 7 (detection through operator visual, tactile, or auditory methods). The calculated RPN for this failure mode is 105 ($S \times O \times D = 5 \times 3 \times 7$).

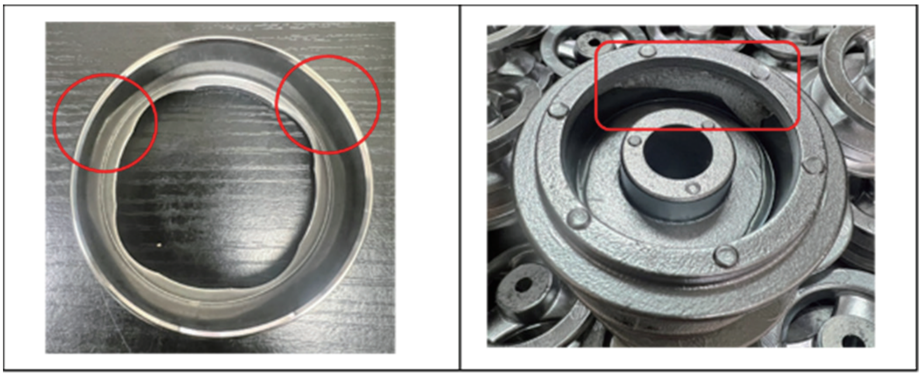


Fig. 2. (Color online) Significant issue 1.

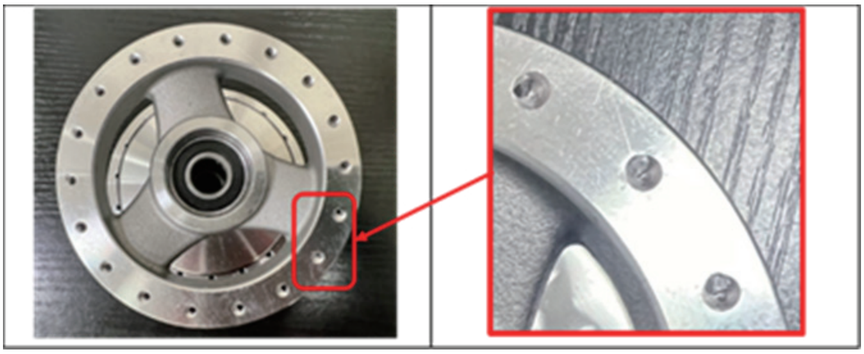


Fig. 3. (Color online) Significant issue 2.

3.4 Improve

As seen in Table 1, the key focus of the Improve phase in the DMAIC methodology is to enhance process performance by implementing solutions. In this phase, significant issues identified during the Analysis phase are addressed through targeted solutions. Subsequently, FMEA is employed to reassess the process, ensuring that the product does not result in critical failures. Additionally, a Control Plan is established to finalize critical production elements, including processes, equipment, locations, quality characteristics, specification tolerances, measurement conditions, and analysis methods. This ensures optimization of customer requirements, production conditions, and inspection standards.

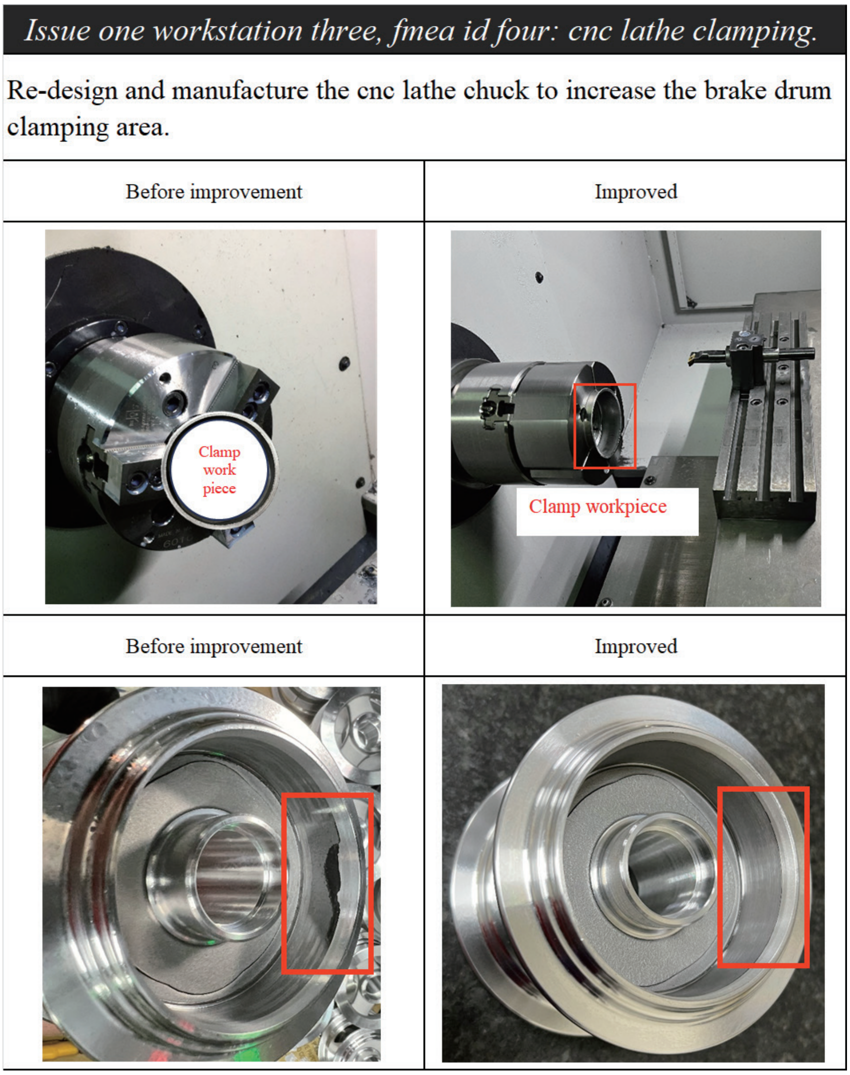
The Control Plan outlines how to monitor, evaluate, and manage critical product or service characteristics during manufacturing, production, or service delivery to ensure compliance with predefined quality standards, specifications, and customer expectations. It integrates seamlessly with the PFD and FMEA. Initially, the PFD defines workstation numbers and operational tasks. FMEA is then used to analyze potential failure modes, their severity, occurrence frequency, and detection probability for each workstation's process. Finally, the Control Plan links these elements to define and optimize the equipment, measurement methods, conditions, and corrective actions for addressing anomalies, ensuring a robust and controlled production process.

3.4.1 Solutions to major issues

Following the FMEA evaluation, as detailed in the Analyze phase, two critical issues were identified in the production process of wheelchair components. To address these issues, targeted solutions were developed and implemented to enhance process reliability and product quality, as described below.

3.4.1.1 Workstation 3, FMEA ID 4: CNC lathe clamping issue

To mitigate this issue, our team designed a clamping fixture that fully encases the stamping ring, significantly reducing deformation during the clamping process. This redesigned fixture ensures precise alignment with the mold, enhancing the structural integrity of the brake drum and minimizing the risk of critical failures, as shown in Fig. 4.



Issue one workstation three, fmea id four: cnc lathe clamping.

Re-design and manufacture the cnc lathe chuck to increase the brake drum clamping area.

Fig. 4. (Color online) Issue 1 workstation 3, FMEA ID 4: CNC lathe clamping.

3.4.1.2 Workstation 7, FMEA ID 8: hub hole punching issue

To address this issue, we redesigned the punching mold to improve precision and transitioned the process to a semi-automated system. Additionally, an automated air-blowing mechanism was integrated to remove residual punching debris immediately after each operation, ensuring a clean surface for chamfering, and thus preventing hub hole damage. The reassessment of the two issues for FMEA after improvement is as follows.

3.4.1.3 Workstation 3, FMEA ID 4: CNC lathe clamping issue

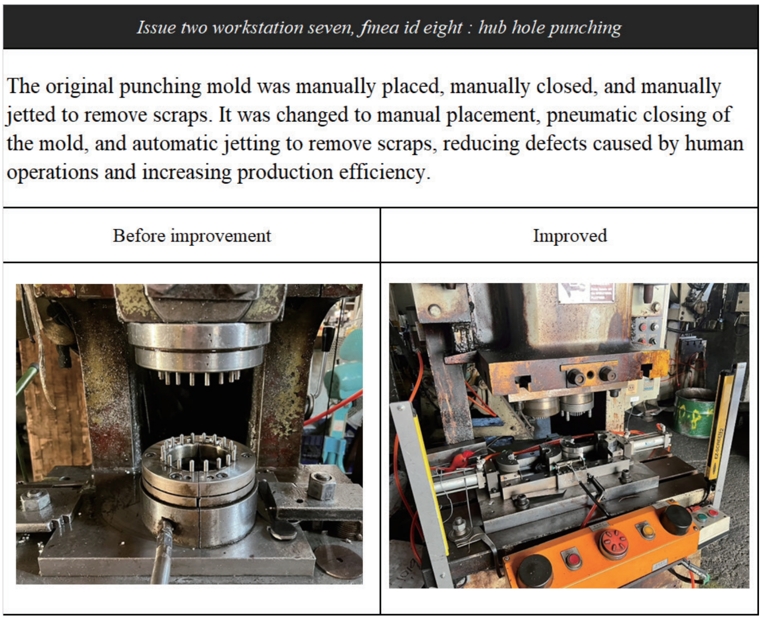
After improvements, the severity rating is reduced to 3 (minor flaws that some customers may notice, with minimal impact on functionality). The occurrence frequency decreases to 3 (very low probability of failure, less than 1 in 5000 cycles). However, the detection probability remains at 7 (relying on operator inspection through visual, tactile, or auditory methods). These improvements indicate a substantial reduction in deformation risks during CNC lathe clamping, enhancing overall product integrity. The calculated RPN for this failure mode is 63 ($S \times O \times D = 3 \times 3 \times 7$).

3.4.1.4 Workstation 7, FMEA ID 8: hub hole punching issue

Post-improvement, the severity rating is reduced to 4 (minor flaws noticeable to most customers, with limited impact on functionality). The occurrence frequency is reduced to 2 (extremely low probability of failure, less than 1 in 10000 cycles). The detection probability remains at 7 (operator inspection via visual, tactile, or auditory methods). These enhancements, driven by the adoption of redesigned molds and automated debris removal, as shown in Fig. 5, significantly minimize hub hole damage and improve process consistency. The calculated RPN for this failure mode is 56 ($S \times O \times D = 4 \times 4 \times 7$).

3.4.2 Control Plan

Following the implementation of solutions to major issues, a comprehensive Control Plan is established to formalize and optimize critical production elements, including processes, equipment, locations, quality characteristics, specification tolerances, measurement conditions, analytical methods, and corrective actions. This plan ensures alignment with customer requirements, finalizes production conditions, and defines rigorous inspection standards and constraints to sustain process excellence. The final results are detailed in Table 6.



Issue two workstation seven, fmea id eight : hub hole punching

The original punching mold was manually placed, manually closed, and manually jetted to remove scraps. It was changed to manual placement, pneumatic closing of the mold, and automatic jetting to remove scraps, reducing defects caused by human operations and increasing production efficiency.

Fig. 5. (Color online) Issue 2 workstation 7, FMEA ID 8: hub hole punching.

Table 6
Control plan form.

Manufacturing process			Tools or locations used for machines and equipment fixtures	Product properties			Standardization and testing				Analytical method	Improvement measures after abnormality is discovered
FMEA number	Station number	Process name process description		Effect size balloon number	Quality characteristics	Process parameters	Product process specification tolerances	Measurement tools	Measurement conditions			
									Measurement percentage	Detection frequency		
1	1	Iron ring stamping forming	Direct punch press		Material correctness	Ensure the use of theright materials	SPHC steel plate	Factory material certificate	N/A	Per order	Testing report	Return to supplier
2	2	Brake drum cnc turning	Cnc lathe	15	Inner diameter size Height size	Ensure the use of the size is correct	Ø 68.7mm ± 0.1 Height 23mm ± 0.1	Vernier caliper	5%	Per order	Measuring tools	Stop production/separate abnormal products/notify management/load improvement plan
3	3	Gravity casting	Gravity casting related machines	2, 3	Cosmetic defects	Ensure there are no pores during casting	Blank casting mold production	Visually	100%	Per order	Visual inspection	Return to supplier
4	4	Aluminum alloy heat treatment	Heat treatment stove		Aluminum alloy hardness	Ensure the material hardness is correct	HRB 48~55	Hardness tester	1%	Per order	Hardness measurement	Return to supplier for rework
5	5	Sandblasting	Ring belt sandblasting machine		Remove carbonized layer	Ensure the carbonized layer is removed	#100~150 Steel balls	Visually	5%	Per order	Visual inspection	Return to supplier for rework
6	6	Hub cnc turning	Cnc lathe	1~15	Outer diameter dimensions Inner diameter dimensions Height dimensions	Ensure the size is correct	Ø 100mm ± 0.15 Ø 67.9mm ± 0.15 Ø 59.82mm ± 0.15 Ø 3.35mm ± 0.05 Ø 38.1mm ± 0.15 Ø 82.1mm ± 0.15 Ø 28.6mm ± 0.10 Ø 28.0mm $^{-0.02}/_{-0.03}$ Ø 8.0mm ± 0.10 Ø 37.6mm ± 0.15 Ø 32.96mm ± 0.15 Ø 23.75mm ± 0.10 Ø 70mm$^{+0.15}/_{-0.00}$	Vernier caliper height gauge + inspection fixture three-point inner diameter micrometer	5%	Per order	Measuring tools	Stop production/separate abnormal products/notify management/load improvement plan
7	7	Hub drum hole stamping	Direct punch press		Inner diameter size	Ensure the size is correct	2.8mm±0.1mm	Vernier caliper	5%	Per order	Measuring tools	Return to supplier for rework
8	8	Push in bearing	4Ton hydraulic press		Confirm bearing specifications	Ensure the bearing is bonded to the workpiece	6001 Specification bearings	Visually	100%	Per order	Visual inspection	Stop production/separate abnormal products/notify management/load improvement plan
9	9	Clean	Cotton		Parts quality control	Ensure the surface of the part is clean and free of burrs	Cotton cloth wipe	Visually	100%	Per order	Visual inspection	Stop production/separate abnormal products/notify management/load improvement plan
10	10	Package	Carton		Correct parts, quantities, packaging and labeling	Ensure correct parts, quantities, packaging and labeling	60 Pcs/carton	Electronic scale	100%	Per order	Visual inspection	Stop production/separate abnormal products/notify management/load improvement plan

3.5 Control

As outlined in Table 1, the primary objective of the Improve phase within the DMAIC methodology is to “sustain improvements and ensure process stability.” To achieve this, we employ the Process Capability Index (Cpk) to evaluate and enhance the manufacturing process for wheelchair components. The Cpk index quantifies the process’s ability to produce products within specified tolerances, assessing whether the output consistently meets design requirements.

In this study, dimensional tolerances for hub components were established using the fine grade of the ISO 2768-1 standard for linear measures, as specified in Table 7. By applying the target dimensional values of the hub components to this standard, a precise set of dimensional and tolerance specifications was derived, as presented in Table 8. This rigorous approach ensures compliance with tolerance requirements, promoting consistency and quality in the manufacturing of wheelchair components.

Table 7
Iso 2768-1 linear measures.

SS-ISO 2768-1								Values is mm
Tolerance class		Permissible deviations for basic size range						
Designation	Description	Over 0.5 up to 3	Over 3 up to 6	Over 6 up to 30	Over 30 up to 120	Over 120 up to 400	Over 400 up to 1000	Over 1000 up to2000
		±	±	±	±	±	±	±
f	fine	0.05	0.05	0.10	0.15	0.20	0.30	0.50
m	medium	0.1	0.10	0.20	0.30	0.50	0.80	1.20
c	coarse	0.2	0.30	0.50	0.80	1.20	2.00	3.00
v	very coarse	—	0.50	1.00	1.50	2.50	4.00	6.00

For nominal sizes below 0.5 mm, the deviations shall be indicated adjacent to the relevant nominal sizes. For dimensions <0.5 mm that do not have individually indicated tolerances, please confirm with the designer or request supplementary notation.

Table 8
Product measurement standards and specifications table.

	No.	Characteristic	Dimension	Upper tolerance	Lower tolerance	USL	LSL	Measuring equipment
Unit: mm	1	Diameter	100.0	0.15	−0.15	100.15	99.85	Caliper
	2	Height	67.90	0.15	−0.15	68.05	67.75	Caliper
	3	Height	59.82	0.15	−0.15	59.97	59.67	Caliper
	4	Height	3.35	0.05	−0.05	3.40	3.30	Caliper
	5	Diameter	38.10	0.15	−0.15	38.25	37.95	Caliper
	6	Diameter	82.10	0.15	−0.15	82.25	81.95	Caliper
	7	Diameter	28.60	0.10	−0.10	28.70	28.50	Caliper
	8	Diameter	28.00	−0.02	−0.03	27.98	27.97	Bore gauge
	9	Diameter	8.00	0.10	−0.10	8.10	7.90	Height gauge
	10	Height	37.60	0.15	−0.15	37.75	37.45	Height gauge
	11	Height	8.00	0.10	−0.10	8.10	7.90	Height gauge
	12	Height	23.75	0.10	−0.10	23.85	23.65	Height gauge
	13	Diameter	28.00	−0.02	−0.03	27.98	27.97	Bore gauge
	14	Diameter	32.96	0.15	−0.15	33.11	32.81	Caliper
	15	Diameter	70.00	0.15	−0.15	70.15	70.00	Caliper

Table 9
Measurement results.

Measuring equipment	caliper	caliper	caliper	caliper	caliper	caliper	caliper	Bore gauge	Height gauge	Height gauge	Height gauge	Height gauge	Bore gauge	caliper	caliper
Sample No. / Drawing No.	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8	No.9	No.10	No.11	No.12	No.13	No.14	No.15
1	100.00	67.92	59.82	3.36	38.10	82.09	28.60	27.975	8.00	37.65	7.99	23.74	27.975	32.96	70.08
2	100.00	67.90	59.81	3.35	38.11	82.11	28.62	27.976	8.01	37.64	8.00	23.70	27.976	32.98	70.10
3	100.00	67.90	59.82	3.35	38.10	82.10	28.61	27.975	8.00	37.65	8.01	23.75	27.974	32.96	70.08
4	100.00	67.92	59.81	3.35	38.10	82.11	28.60	27.975	7.99	37.66	8.00	23.72	27.975	32.97	70.10
5	100.00	67.90	59.82	3.36	38.10	82.11	28.60	27.975	8.00	37.65	7.99	23.73	27.976	32.96	70.08
6	100.00	67.92	59.82	3.36	38.11	82.10	28.60	27.973	8.01	37.65	8.00	23.75	27.977	32.96	70.09
7	100.01	67.90	59.81	3.35	38.11	82.10	28.62	27.975	8.00	37.68	7.98	23.70	27.975	32.97	70.08
8	100.00	67.90	59.82	3.36	38.10	82.10	28.61	27.974	7.99	37.65	7.99	23.75	27.977	32.96	70.09
9	100.00	67.90	59.80	3.35	38.11	82.12	28.60	27.975	8.00	37.65	8.00	23.81	27.974	32.98	70.08
10	100.00	67.93	59.82	3.35	38.10	82.11	28.62	27.975	8.00	37.65	8.00	23.75	27.976	32.96	70.08
11	99.99	67.90	59.80	3.35	38.11	82.10	28.60	27.975	8.01	37.62	7.98	23.74	27.975	32.97	70.06
12	100.00	67.90	59.82	3.36	38.10	82.10	28.60	27.973	8.00	37.65	8.00	23.75	27.974	32.99	70.10
13	100.00	67.90	59.82	3.35	38.12	82.11	28.61	27.974	7.99	37.68	8.00	23.82	27.975	32.96	70.07
14	100.01	67.94	59.82	3.35	38.10	82.10	28.61	27.975	8.00	37.65	7.98	23.74	27.975	32.98	70.08
15	100.00	67.90	59.82	3.35	38.12	82.12	28.60	27.975	7.98	37.62	7.98	23.75	27.976	32.96	70.07
ADV.	100.001	67.9087	59.8153	3.35333	38.106	82.1053	28.6067	27.9747	7.99867	37.65	7.99333	23.7467	27.9753	32.968	70.0827
SD.	0.00458	0.01356	0.00743	0.00488	0.00737	0.00834	0.00816	0.00082	0.00834	0.01648	0.00976	0.03266	0.00098	0.01014	0.01163

Table 10
(Color online) MINITAB-calculated results.

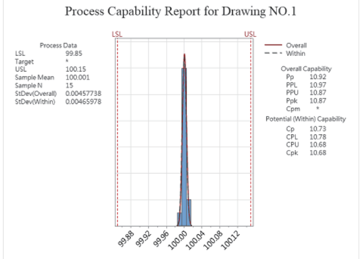
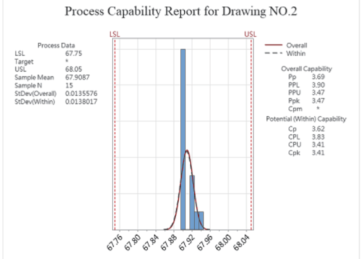
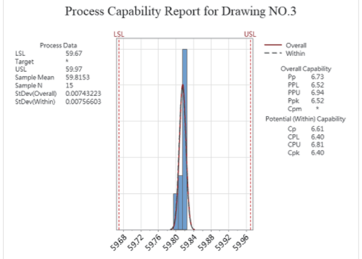
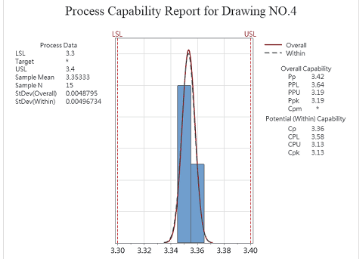
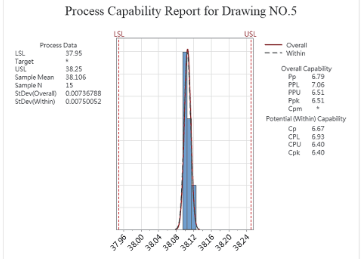
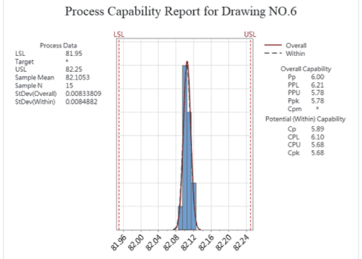
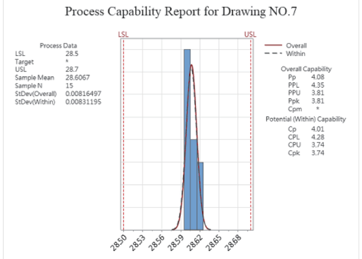
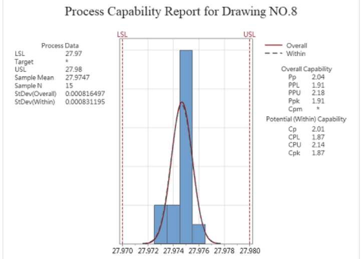
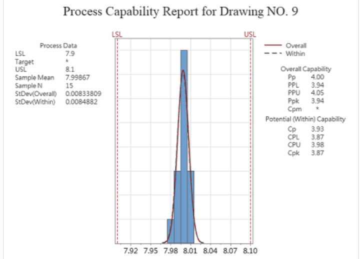
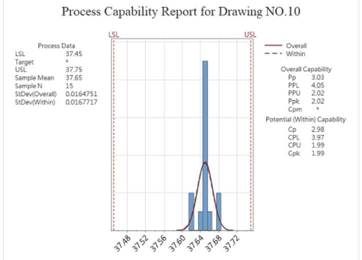
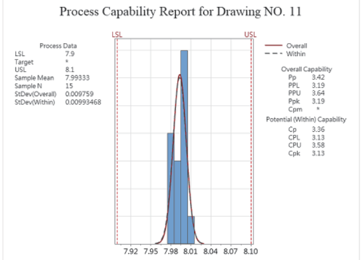
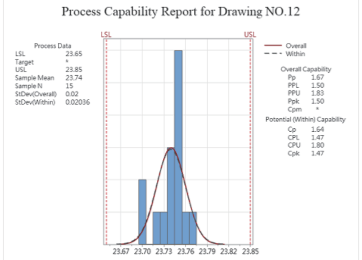
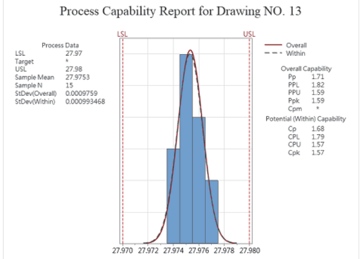
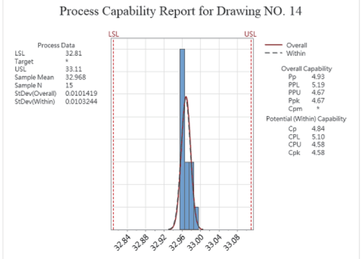
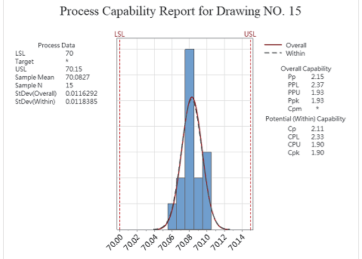
NO. 1	NO. 2	NO. 3
 Process Capability Report for Drawing NO.1 Process Data LSL 99.85 Target * USL 100.15 Sample Mean 100.001 Sample N 15 StDev(Overall) 0.00457738 StDev(Within) 0.00465978 Overall Capability Pp 10.92 PPL 10.97 PPU 10.87 Ppk 10.87 Cpm * Potential (Within) Capability Cp 10.73 CPL 10.78 CPU 10.68 Cpk 10.68 	 Process Capability Report for Drawing NO.2 Process Data LSL 67.75 Target * USL 68.05 Sample Mean 67.9087 Sample N 15 StDev(Overall) 0.0135576 StDev(Within) 0.0138017 Overall Capability Pp 3.69 PPL 3.90 PPU 3.47 Ppk 3.47 Cpm * Potential (Within) Capability Cp 3.62 CPL 3.83 CPU 3.41 Cpk 3.41 	 Process Capability Report for Drawing NO.3 Process Data LSL 59.67 Target * USL 59.97 Sample Mean 59.8153 Sample N 15 StDev(Overall) 0.00743223 StDev(Within) 0.00756603 Overall Capability Pp 6.73 PPL 6.52 PPU 6.94 Ppk 6.52 Cpm * Potential (Within) Capability Cp 6.61 CPL 6.40 CPU 6.81 Cpk 6.40
NO. 4	NO. 5	NO. 6
 Process Capability Report for Drawing NO.4 Process Data LSL 3.3 Target * USL 3.4 Sample Mean 3.35333 Sample N 15 StDev(Overall) 0.0048795 StDev(Within) 0.00496734 Overall Capability Pp 3.42 PPL 3.64 PPU 3.19 Ppk 3.19 Cpm * Potential (Within) Capability Cp 3.36 CPL 3.58 CPU 3.13 Cpk 3.13 	 Process Capability Report for Drawing NO.5 Process Data LSL 37.95 Target * USL 38.25 Sample Mean 38.106 Sample N 15 StDev(Overall) 0.00736788 StDev(Within) 0.00750052 Overall Capability Pp 6.79 PPL 7.06 PPU 6.51 Ppk 6.51 Cpm * Potential (Within) Capability Cp 6.67 CPL 6.93 CPU 6.40 Cpk 6.40 	 Process Capability Report for Drawing NO.6 Process Data LSL 81.95 Target * USL 82.25 Sample Mean 82.1053 Sample N 15 StDev(Overall) 0.00833809 StDev(Within) 0.0084882 Overall Capability Pp 6.00 PPL 6.21 PPU 5.78 Ppk 5.78 Cpm * Potential (Within) Capability Cp 5.89 CPL 6.10 CPU 5.68 Cpk 5.68
NO. 7	NO. 8	NO. 9
 Process Capability Report for Drawing NO.7 Process Data LSL 28.5 Target * USL 28.7 Sample Mean 28.6067 Sample N 15 StDev(Overall) 0.00816497 StDev(Within) 0.00831195 Overall Capability Pp 4.08 PPL 4.35 PPU 3.81 Ppk 3.81 Cpm * Potential (Within) Capability Cp 4.01 CPL 4.28 CPU 3.74 Cpk 3.74 	 Process Capability Report for Drawing NO.8 Process Data LSL 27.97 Target * USL 27.98 Sample Mean 27.9747 Sample N 15 StDev(Overall) 0.000816497 StDev(Within) 0.000831195 Overall Capability Pp 2.04 PPL 1.91 PPU 2.18 Ppk 1.91 Cpm * Potential (Within) Capability Cp 2.01 CPL 1.87 CPU 2.14 Cpk 1.87 	 Process Capability Report for Drawing NO. 9 Process Data LSL 7.9 Target * USL 8.1 Sample Mean 7.99867 Sample N 15 StDev(Overall) 0.00833809 StDev(Within) 0.0084882 Overall Capability Pp 4.00 PPL 3.94 PPU 4.05 Ppk 3.94 Cpm * Potential (Within) Capability Cp 3.93 CPL 3.87 CPU 3.98 Cpk 3.87
NO. 10	NO. 11	NO. 12
 Process Capability Report for Drawing NO.10 Process Data LSL 37.45 Target * USL 37.75 Sample Mean 37.65 Sample N 15 StDev(Overall) 0.0164751 StDev(Within) 0.0167717 Overall Capability Pp 3.03 PPL 4.05 PPU 2.02 Ppk 2.02 Cpm * Potential (Within) Capability Cp 2.98 CPL 3.97 CPU 1.99 Cpk 1.99 	 Process Capability Report for Drawing NO. 11 Process Data LSL 7.9 Target * USL 8.1 Sample Mean 7.99333 Sample N 15 StDev(Overall) 0.009759 StDev(Within) 0.00993468 Overall Capability Pp 3.42 PPL 3.19 PPU 3.64 Ppk 3.19 Cpm * Potential (Within) Capability Cp 3.36 CPL 3.13 CPU 3.58 Cpk 3.13 	 Process Capability Report for Drawing NO.12 Process Data LSL 23.65 Target * USL 23.85 Sample Mean 23.74 Sample N 15 StDev(Overall) 0.02 StDev(Within) 0.02036 Overall Capability Pp 1.67 PPL 1.50 PPU 1.83 Ppk 1.50 Cpm * Potential (Within) Capability Cp 1.64 CPL 1.47 CPU 1.80 Cpk 1.47
NO. 13	NO. 14	NO. 15
 Process Capability Report for Drawing NO. 13 Process Data LSL 27.97 Target * USL 27.98 Sample Mean 27.9753 Sample N 15 StDev(Overall) 0.0009759 StDev(Within) 0.000993468 Overall Capability Pp 1.71 PPL 1.82 PPU 1.59 Ppk 1.59 Cpm * Potential (Within) Capability Cp 1.68 CPL 1.79 CPU 1.57 Cpk 1.57 	 Process Capability Report for Drawing NO. 14 Process Data LSL 32.81 Target * USL 33.11 Sample Mean 32.968 Sample N 15 StDev(Overall) 0.0101419 StDev(Within) 0.0103244 Overall Capability Pp 4.93 PPL 5.19 PPU 4.67 Ppk 4.67 Cpm * Potential (Within) Capability Cp 4.84 CPL 5.10 CPU 4.58 Cpk 4.58 	 Process Capability Report for Drawing NO. 15 Process Data LSL 70 Target * USL 70.15 Sample Mean 70.0827 Sample N 15 StDev(Overall) 0.0116292 StDev(Within) 0.0118385 Overall Capability Pp 2.15 PPL 2.37 PPU 1.93 Ppk 1.93 Cpm * Potential (Within) Capability Cp 2.11 CPL 2.33 CPU 1.90 Cpk 1.90

Table 11
Cpk summary.

	No.	Cp	Ca	Cpk	Target	ADV
Unit: mm	1	10.73	0.0022	10.68	100.000	100.001
	2	3.62	0.0288	3.41	67.900	67.908
	3	6.61	−0.0155	6.40	59.820	59.815
	4	3.36	0.0333	3.13	3.350	3.353
	5	6.67	0.0200	6.40	38.100	38.106
	6	5.89	0.0177	5.68	82.100	82.105
	7	4.01	0.0333	3.74	28.600	28.606
	8	2.01	−0.5333	1.87	27.975	27.974
	9	3.93	−0.0067	3.87	8.000	7.998
	10	2.98	0.1666	1.99	37.600	37.650
	11	3.36	−0.0333	3.13	8.000	7.993
	12	1.64	0.0366	1.47	23.85	23.74
	13	1.68	−0.4666	1.57	27.975	27.975
	14	4.84	0.0266	4.58	32.960	32.968
	15	2.11	0.5511	1.90	70.000	70.08

Subsequently, utilizing the tolerance standards in Table 7 and the measurement standards and specifications in Table 8, we conducted a random inspection of 15 improved products. The measurement results are presented in Table 9.

Finally, the measurement results in Table 9 were imported into Minitab for the calculation of Cpk. The results are presented in Table 10. Concurrently, the results from Table 10 were compiled into Table 11.

5. Conclusions

Wheelchair components, though seemingly unassuming, play an indispensable role in ensuring user safety. Defects in these parts pose a significant risk of secondary injuries to users. This study is dedicated to the implementation of the Six Sigma methodology to stabilize the product yield rate at above 3.5 sigma (99.97%), thereby enhancing overall product reliability and market performance.

By integrating methodologies such as Six Sigma, QFD, manufacturing flowcharts, control plans, cpk, and FMEA, we investigated the production parts approval process. The primary objectives were to optimize manufacturing efficiency, elevate product quality, and mitigate risks to the greatest extent possible. Through the strategic application of a comprehensive suite of risk assessment and quality management tools, we aimed to preclude the need for reactive learning from accidents or failures, thus preventing substantial financial losses. Moreover, the deployment of these quality tools is expected to enhance customer satisfaction and strengthen product competitiveness.

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