A DMAIC Approach to Defect Reduction in Electrical Control Panel Production (ACFA 7003)

Module – Masters Project

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Abstract

This report presents a comprehensive quality improvement initiative undertaken within control panel manufacturing, guided by the Define, Measure, Analyse, Improve, Control (DMAIC) framework. The aim was to systematically reduce the rate of defects, enhance operational efficiency, and embed sustainable processes to achieve long-term quality excellence.

During the Define phase, key challenges were identified which included recurring defects such as incorrect wiring, missing labels, and poor assembly. Engagement with key stakeholders ensured the alignment of objectives and laid the groundwork for targeted interventions. The Measure phase focused on collecting and analysing defect data which enabled the prioritisation of the most critical issues through tools like Pareto analysis and structured defect logging. The Analyse phase employed root cause analysis techniques, such as the 5 Whys and Failure Modes and Effects Analysis, to uncover underlying process weaknesses such as inconsistencies in design reviews, inadequate quality checks, and interdepartmental communication gaps. Insights from this phase informed the development of solutions during the Improve phase, including the implementation of enhanced quality checklists, defect tracking mechanisms, and regular quality meetings to encourage collaboration and accountability, this led to a measurable reduction in defect rates. The Control phase ensured the sustainability of improvements by updating Standard Operating Procedures, incorporating quality checklists into the Integrated Management System, and introducing Key Performance Indicators to monitor performance. Control charts were established to track trends in defect rates, while periodic audits and stakeholder engagement reinforced adherence to the updated processes.

While significant progress was achieved, challenges remain, such as residual defects, employee adoption of new processes, and data reliability. Recommendations for future work include leveraging automated defect tracking systems, investing in employee training, exploring innovations like IoT and AI technologies, fostering a culture of quality, and conducting detailed defect analyses to address residual issues.

This project demonstrated the effectiveness of the DMAIC framework in achieving immediate quality improvements and established a strong foundation for ongoing innovation and operational excellence. By addressing limitations and leveraging emerging opportunities, the organisation is well-positioned to sustain improvements and foster a culture of continuous improvement.

Abbreviations

Design, Measure, Analyse, Improve, Control (DMAIC)

Motor Control Centres (MCC)

Programmable Logic Controller (PLC)

Variable Speed Drivers (VSD)

Human Machine Interface (HMI)

Plan-Do-Check-Act (PDCA)

Key Performance Indicator (KPI)

Standard Operating Procedures (SOPs)

Statistical Process Control (SPC)

Critical to Quality (CTQ)

Defect Per Opportunity (DPO)

Defects per Million Opportunities (DPMO).

Suppliers-Inputs-Process-Outputs-Customers (SIPOC)

Failure Mode and Effects Analysis (FMEA)

Functional Acceptance Test (FAT)

Original Equipment Manufacturers (OEMs)

Root Cause Analysis (RCA)

Integrated Management System (IMS)

Internet of Things (IoT)

Artificial Intelligence (AI)

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Introduction

Hornbill Engineering was established in 1989, through the years Hornbill grew into a well-established full turnkey solution contractor in the UK for electrical, instrumentation, control and automation. Hornbill offers services such as low and high voltage installation and maintenance, instrumentation, control panel manufacturing, systems design, commissioning, hazardous area inspections and remedials, civils engineering, personnel hire, and training. Their expertise spans across a wide range of industries including clean and wastewater, oil and gas, cryogenics, metal industries, and many more.

Hornbill Engineering was acquired by OCU Group in July 2023, the company has now re-branded as OCU Hornbill, a sub company of OCU Group Services. The acquisition saw Hornbills already wide range of services expand further into areas such as horizontal directional drilling, overhead lines, and more. OCU Group is dedicated to pioneering advancements in utilities and energy transition contracting, with a mission to innovate and promote sustainability. Their commitment to tackling complex challenges drives new levels of growth in both their employees and their capabilities.

OCU Hornbill operates a facility specialised in the design, manufacturing, and automation services for electrical control panels to clients' exact specifications. The control panels range from Form 4 Motor Control Centres (MCC), Programmable Logic Controller (PLC) and Human Machine Interface (HMI) control panels, Variable Speed Drives (VSD) panels, Distribution Boards, and so on. Figure 1 is an example of an MCC designed, manufactured, installed, and commissioned by OCU Hornbill for a nickel refinery in the South Wales region. This panel was required to control the conveyor and elevator system to transport raw material across site. Figure 2 is an example of a Form 2 Mixing Vessel panel, which has been designed, manufactured, and commissioned by OCU Hornbill for a long-term customer. This panel is offered to manufacturers that require evaluation of membrane filtration to become more cost-effective in their process, in addition it can be used for pilot trials to ensure accurate representation when scaling up the processes. This is the most reliable method to verify separation performance, process feasibility, system parameters of membrane filtration.

Figure 1 - Form 4 Motor Control Centre

Figure 2 - Mixing Vessel Panel

The company has, and is, going through major changes since OCU Group acquired Hornbill Engineering. A result of the changes has meant that the defects have increased within the manufacturing facility. Although the exact reasons are currently unknown, this could have been due to the changes in company structure, management, processes, and the workforce. Addressing the defects is critical to maintaining the quality of the products. The bespoke nature of each control panel build introduces variability and complexity, making it challenging to maintain consistent quality. The project will aim to standardise quality management across varied designs to attempt to reduce variability and therefore defects. Defects in control panels can lead to significant operational disruptions for customers, resulting in dissatisfaction, loss of trust, and potential damage to OCU Hornbill's reputation. Defects also lead to increased costs due to rework, waste, and potential penalties or loss of future business. Quantifying and reducing defects are crucial for enhancing customer satisfaction, loyalty, and improving profitability (Antony & Banuelas, 2012).

Design, Measure, Analyse, Improve, Control (DMAIC) is a data-driven, structured problem-solving methodology widely used in projects to systematically enhance processes by reducing defects, improving quality, and increasing efficiency. Each phase of DMAIC, represented by its acronym, plays a critical role in guiding teams through the stages of problem identification, solution development, and long-term success (Eshraghi & Eneyo, 2021).

The Define phase is pivotal as it sets the foundation for the entire project. It involves clearly identifying the problem at hand, determining the scope of the project, and aligning the teams' efforts with the overall objectives. In the Measure phase, the focus shifts to gather relevant data to understand the current state of the process through measuring key metrics and identifying process variables. This phase ensures that the data is accurate to make informed decisions in subsequent phases. The Analyse phase involves examining the data collected to identify the root causes of problems. This is one of the most critical stages, as it will go beyond identifying symptoms and seeks to uncover the underlying causes that contribute to inefficiencies or defects. In the Improve phase, solutions are developed based on the insights gained from the Analyse phase. It focuses on testing and implementing changes that will lead to improvements in the process. Whether it is through process redesign, automation, or eliminating waste, the goal is to optimise performance and resolve the root causes of the problems. Finally, the Control phase ensures that the improvements made are sustainable over time, processes must be monitored continuously to ensure that gains are maintained (Ghosh & Maiti, 2014). Additionally, any variation from the process is identified early enough to allow for corrective actions to be taken promptly.

In manufacturing, where precision, consistency, and efficiency are paramount, DMAIC is especially valuable. This structured approach emphasises data and root cause analysis, DMAIC ensures that improvements are grounded in solid evidence, reducing the reliance on trial-and-error methods. For manufacturing processes, particularly in industries that produce complex, bespoke products such as electrical control panels, DMAIC provides a disciplined framework to manage variability and uphold high-quality standards. It empowers manufacturers to continuously improve processes, adapt to changing customer demands, and maintain a competitive edge in the market. Furthermore, the methodology's focus on control ensures that improvements are sustainable, delivering long-term benefits to both the company and its customers (Boon Sin, et al., 2015).

Given the complexity and precision required, adopting a structured approach like DMAIC is essential for identifying and mitigating quality issues. This topic was chosen to address these challenges directly and to implement practical solutions and drive measurable improvements. Streamlining the production process through the DMAIC approach will enhance operational efficiency, reducing production time and increasing throughput. It is vital that employees are involved throughout the process, employees which are being involved in the DMAIC process are likely to engage more, take ownership, whilst also build their morale as they contribute to meaningful improvements in the workplace (Daniyan, et al., 2022). Reducing waste and inefficiencies contributes to the company's sustainability goals, aligning with OCU Group's commitment to innovative and sustainable practices. The improvements and best practices developed through this project can be scaled and applied to other areas of the business, multiplying the benefits across the organisation.

Aim

The primary aim of this project is to systematically reduce the occurrence of defects in the production of bespoke electrical control panels at OCU Hornbill by implementing DMAIC methodology.

Objectives

1. Investigate the current process and the teams understanding of the problem. Define who the customers are along with their needs and expectations.
2. Collect and analyse data on defect rates, types, and their occurrence throughout the production process. Quantify the financial impact of the defects.
3. Conduct a thorough root cause analysis to identify the underlying factors contributing to defects.
4. Develop and implement targeted improvement strategies to address the identified root causes of defects.
5. Pilot process improvements to evaluate their effectiveness, making any necessary adjustments.
6. Measure the effectiveness of the implemented improvements by comparing post-implementation defect rates with baseline data.
7. Establish control mechanisms and standard operating procedures (SOPs) to sustain the improvements achieved.

These aims and objectives provide a structured approach to reducing defects in the production of bespoke electrical control panels, ensuring that the project is focused, measurable, and aligned with OCU Hornbill's strategic goals.

Literature Review

The purpose of the literature review is to gather and integrate existing knowledge on defect reduction, quality improvement methodologies, and the application of the DMAIC process, particularly in manufacturing environments. By exploring relevant research journals, case studies, and best practices, the literature review will provide a strong foundation for better understanding the common challenges, solutions and opportunities specific to defect reduction in bespoke electrical control panel production. This literature review will support the project by identifying proven strategies, highlighting effective approaches and tools used in similar contexts, which can be adapted and applied to this project. It will also assist in guiding process improvements, providing evidence-based recommendations for each phase of DMAIC, ensuring that the project is informed by successful practices. The review will help to set realistic goals and benchmarks by comparing this situation with documented outcomes in the literature.

Six Sigma is a methodology that has been implemented in many industries for over 30 years, initially developed by Motorola. It has contributed towards companies drastically increasing their profit margins by reducing waste and defects, improving quality. The methodology puts an emphasis on listening to the voice of the customer to ensure that the specifications generated are aligned with their needs and requirements. The systematic methodology heavily relies upon statistics to reduce defect rates but is flexible and can be used in each business function such as sales, manufacturing, or even finance (Ansari, et al., 2010). The tools chosen can be one of the most critical factors in the success of Six Sigma. Different tools are used at each stage of DMAIC, for example in the define phase tools such as brainstorming, Critical to Quality (CTQ), and Suppliers-Inputs-Process-Outputs-Customers (SIPOC) are used. In the measure phase, tools and techniques like Pareto chart, data collection plans, along with histograms are used. The analyse phase relies heavily on tools like cause-and-effect diagrams or Failure Mode and Effects Analysis (FMEA). Improvement plans and Design of Experiments (DOE) remain a vital tool during the improve phase. Finally, control plans and control charts in the control phase.

In the context of defect reduction, it is essential for the improvement of efficiency to understand and manage quality costs. The costs of quality can typically be divided into four categories, these are prevention, appraisal, internal failure, and external failure costs (Hakem, et al., 2024). To remain profitable, costs need to be optimised, and waste needs to be reduced, which is what make DMAIC methodology perfect in this situation. To better understand the implications of defect reduction strategies in low-volume, bespoke manufacturing, an analysis of relevant studies and methodologies is essential. A key paper addressing quality inspection effectiveness and cost evaluation in low-volume assembly processes provides valuable insights into how uncertainty in defect prediction can affect quality costs (Galetto, et al., 2020). The paper highlights the importance of designing strategies for quality inspections. In low-volume production, where variability is higher and defects can be more costly, the ability to predict and prevent defects through well-designed inspection strategies reduces the likelihood of costly rework at later stages such as following delivery to the client. The focus of the paper involves evaluating the different inspection strategies effectiveness and cost, this is related to appraisal costs. The methodology helps to balance the costs by identifying optimal inspection strategies. However, an over-reliance on inspection drives up costs which

may be necessary, on the other hand, if inspections are not thorough enough defects can be missed. The paper does not directly address internal or external failure costs, but it touches upon it by understanding and mitigating the uncertainty of defect predictions. Costs are incurred when detecting defects during manufacture as it leads to rework or scrap. The goal of improving quality inspection strategies reduces the chance of defective products reaching the customer.

Building on the understanding of quality costs and their importance in managing defect reduction, a 2017 research study was undertaken which aimed to assess the overall success of Six Sigma within multiple manufacturing industries. The comprehensive analysis reviewed over 100 articles, a key finding was that companies such as Motorola, Honeywell, Dow Chemical, Dell, and many more saved over $1bn. Although cost savings are a huge benefit and are a key performance indicator for the research, other benefits were identified with multiple papers reporting the performance indicators. These included reducing cycle time, defects and rework, lead times, customer complaints, and many more (Patel & Desai, 2018). The improvements stress Six Sigma's broader impact on operational efficiency and quality, rendering it a vital methodology for driving both financial and process-related benefits in manufacturing environments.

In addition to the clear financial and operational benefits demonstrated by Six Sigma methodology, studies have highlighted the importance of building and maintaining strong, collaborative relationships within project teams as a critical factor for successful implementation. These connections play a major role in the depth and durability of the improvements made, effective teamwork promotes mutual understanding and makes it easier to integrate, which is essential for finding and eliminating defects (Jamil, et al., 2020). One study undertaken in a multi-organisational research and development network provides insight into how relationships play a crucial role in determining the success of projects and individual influence within them in particular tie intensities such as collaboration, coordination, and communication (Provan & Lemaire, 2015). Tie intensities reflect the level of commitment, trust built, and interaction frequency between the team. Stronger more intense ties are needed for tasks that are complex to allow for knowledge sharing and collaboration. Lower intensity ties can be adequate for simpler tasks which are less interdependent. The studies finding suggest that not all interactions contribute equally to the project's success. It suggests that coordination ties are key to sustaining a good working relationship without huge commitments unlike full collaboration. Coordination ties seem to strike a balance between high involvement and accessibility, this balance is required in large complex projects to ensure efficiency and knowledge sharing is achieved. Overcommitment could lead to resources being put under strain. The study concluded that knowledge is best shared through intense collaboration ties rather than casual communication. However, as the study is undertaken in a multi-organisational project, it highlights that at time managers might struggle to facilitate meaningful cross-organisational collaboration but suggests it should be encouraged.

Relationships are crucial for project success, projects often rely on knowledge exchange which translates in practical solutions. Coordination ties often connect team members, their relationships assist in defining roles and expectations which allows the team to leverage its resources more effectively to focus on tasks which will add value to the project. Influential team members often play a critical role in decision making which can

drive the projects direction and outcomes (Unegbu, et al., 2021). Managers should intentionally structure relationships to improve the project outcomes by encouraging coordination by assigning clear roles, facilitate access, and informal interactions to foster collaborative ties, and identify and support the influential individuals within the project network as they will act as knowledge hubs to enhance project wide communication.

Change management is vital for organisational transition, especially when implementing process improvements. It ensures that the changes are adopted effectively, minimising resistance. To ensure a smooth transition, all affected stakeholders should be informed about the rationale, benefits, and details of the changes being implemented using multiple communication channels such as team meetings and emails to avoid misunderstandings (Ayhan, et al., 2015). Training sessions should be conducted on any updated standard operating procedures to ensure staff are comfortable with the new processes, particularly around accountability. Support mechanisms should be in place, change champions or process owners should be appointed to support their teams through the changes with feedback mechanisms established to address concerns or make minor adjustments as necessary (Malik, et al., 2021). Ideally, changes implemented should be incremental rather than all at once.

The benefits for good change management practices should be clear enough for all organisations to recognise. Employees are more likely to embrace changes when they are included, well-informed, and are offered support through the transition, improving morale and engagement. Proper training and preparation reduces resistance and downtime during process changes. However, poor change management will have the opposite effects, employees may resist new processes and may perceive changes as burdensome. Lack of training and clarity which can lead to varying levels of adoption, frustration, and a sense of being undervalued which in turn reduces morale (Sung & Kim, 2021). This all can lead to errors, rework, and inefficiencies caused by poor change implementation, which can offset any potential gains.

Change management is a crucial component of the DMAIC framework, particularly during the Improve and Control phases as these phases are where solutions are implemented, and mechanisms are put in place to sustain these improvements long term. During the Improve phase, change management supports the adoption of new strategies, tools, and processes. In the Control phase, change management plays a pivotal role in embedding the improvements into daily operations. While methodologies such as Plan-Do-Check-Act (PDCA) and Kotter’s change model are widely used, this report focuses on incremental changes through the DMAIC approach. Nevertheless, effective change management principles such as stakeholder engagement, communication, and training are common across all frameworks and are essential to sustaining improvements.

DMAIC Case Studies

A study was carried out to enhance part quality in small and medium-sized enterprises in the automative manufacturing industry (Sumasto, et al., 2023). The study aimed at reducing defects but also at improving the quality of the parts moving forward by implementing DMAIC. The cause of the defects was known in the define stage, during the measure stage the data from the field is collected which determined the sigma levels. During the analyse stage, the author used tools such as the fishbone diagram and the 5W + 1H method to describe the causes. The improve stage used the results of the analysis to produce an improvement repair plan for each one of the problems. The author details that in the control stage the sigma level is calculated which shows that the improvements and the study was a success, with a positive impact which supports the approach of using DMAIC to reduce defects. However, the study does not consider any of the views from others within the manufacturing team at any stage which can prove to be vital. It also doesn't make mention to implementing any formal procedures or processes to the quality management system to ensure that the improvements are solidified and enforced moving forward.

A similar study was carried out with the purpose of applying DMAIC methodology to reduce defects experienced when manufacturing doors of a telecommunication cabinet (Abhilash & Thakkar, 2019). The paper recognised that DMAIC methodology is a powerful tool that has been proven to reduce defects along with many other benefits already discussed. This workstream was identified to be researched as it had one of the highest profitable products, but it also had the highest number of rejections and rework cost with the hinges being identified as the main reason for the rejections. Following the measuring phase a pareto chart presented the percentage split for the type of defect, the Defects Per Million Opportunities (DPMO) and sigma level is calculated. In the improve phase a solution was suggested and introduced, the control phase checked the performance by re-calculating the DPMO and sigma level. The sigma level increased from 3.49 to 3.67 following the study, an increase in the sigma level means the process is becoming more dependable, with fewer defects and greater efficiency, leading to better overall performance. Achieving higher sigma levels is a key objective in Six Sigma methodology, aiming for near perfection in quality. Although this seems to be a small improvement, the company are moving closer towards zero defects, which is ultimately the goal. A criticism for the control phase undertaken is that it was not detailed how the improvements made would be sustained over time to prevent regression. It was not detailed if the companies SOPs were updated to include the improvements made. Suggestions should have also been made to further reduce defects following on from this study.

Another report highlights the successful application of Lean Six Sigma and the DMAIC methodology to achieve business transformation goals in defect reduction (Condé, et al., 2023). The structured use of the DMAIC resulted in measurable improvements in defect rates within car parts manufacturing. By achieving and exceeding the project targets outlined in the project charter, the study demonstrates the practical utility of six sigma tools. The report emphasises the importance of the phases such as the Control phase in sustaining achieved gains. These quantifiable improvements, including an increase in sigma levels, further validate the methodology's effectiveness.

The report also highlights its practical and social implications, serving as a guide for practitioners in the automotive sector and other industries, enabling broader adoption of six sigma methodologies. The project selection process, based on the company's internal criteria, also introduces subjectivity, potentially biasing the outcomes. Future studies should explore scientifically validated project selection frameworks to address this limitation. Additionally, the report lacks a detailed comparison between DMAIC and DOE, providing little data or examples to illustrate the limitations of DOE. A more robust comparison could strengthen the argument for DMAIC's superiority. Moreover, while the study focuses heavily on its successes, it does not adequately address the challenges encountered during the implementation. Insight into obstacles and mitigation strategies could provide a more balanced perspective.

Another case study effectively applies the DMAIC methodology to enhance quality and sustainability in additive manufacturing by integrating pre-selected Key Performance Indicators (KPI) with Six Sigma principles, the study a well-structured approach to improve efficiency whilst aligning to the sustainability goals (Rodriguez Delgadillo, et al., 2022). A key strength of this study is its practical implantation which provides valuable insights as well as emphasising the importance of employee training in gaining improved results. The study does have its limitations, such as its reliance on a single case study which limits the findings. The analysis is largely based on data from the company stakeholders, future work could benefit from incorporating quantitative data to enhance accuracy. It also does not consider long term environmental impacts or set goals for waste reduction and energy efficiency.

Defect Reduction in Bespoke Manufacturing versus Mass Production

Defect reduction approaches differ when considering bespoke manufacturing and mass production due to the inherent differences in process complexity, product variability, and workforce involvement.

Bespoke manufacturing produces highly customised, one-off products such as bespoke electrical control panels tailored to client specifications. Standardisation is difficult, there is a high process variability, therefore quality issues are more likely to arise. Defect reduction must account for the variability in design, materials, and processes, making it harder to predict and control sources of defects. Process controls must be adaptable to cope with frequent changes in design. Generally, more skilled labour is required in a bespoke manufacturing environment. However, human error is a frequent source of defects which results in more focus on training (Huang & Strigini, 2023), and workforce engagement in defect reduction efforts. The root causes of defects may differ significantly from one project to another, making it harder to apply standard corrective actions. Defect detection is manual, dependent on in-process inspections. Quality control is often integrated throughout production. Prevention strategies involve close communication with clients, careful management of design changes, and adaptability in the production process. Costs of defects in bespoke manufacturing tend to be higher per unit, due to the customised nature of the products. Customers also expect higher quality as products are tailor-made, even a minor defect leads to dissatisfaction.

However, mass production focuses on producing large volumes of identical products and standardised designs. Once processes are optimised and standardised, improvements can be sustained, leading to fewer defects over time due to consistency. Defect reduction is easier to manage because the product and process remain stable across production cycles. Statistical Process Control (SPC), machine optimisation and automation can be used to monitor and reduce defects systematically rather than human interventions. Mass production defects are detected using automation which makes it more predictable, allowing for systematic and repeatable solutions, such as adjusting machinery or modifying production schedules. Defects can be costly but there is usually a much lower percentage as the defects are spread across a larger production volume.

Identified Gaps in the Literature

Following the literature review, it seems evident that some key themes seem to emerge regarding the importance of quality improvement methods, specifically Six Sigma and the DMAIC process for reduction defects and increasing efficiency across multiple manufacturing environments.

There is a distinct gap in the literature which reveals an opportunity for further study, particularly in relation to the unique challenges of defect reduction in bespoke manufacturing environments. Research on DMAIC and Six Sigma in high volume, mass production manufacturing environments is in abundance, far fewer studies focus on applying these methodologies to bespoke, low volume manufacturing. Due to the inherently more variable and complex nature of bespoke manufacturing, the challenges differ significantly. A standardised tools such as DMAIC is well suited to repeatable processes, it may need to be adapted to handle the unpredictability of bespoke manufacturing. Studies rarely address how to tailor DMAIC phases to handle high variability in designs, and process steps. Further study can be undertaken to investigate how DMAIC tools can be modified or enhanced for use in bespoke manufacturing. Including the development of new metrics, flexible control methods, or adaptable analysis tools that can handle frequent design changes and variability.

A number of studies mentioned the effectiveness of DMAIC in reducing defects, however they often failed to outline mechanisms to sustain the improvements over time, especially within high variability, bespoke manufacturing. A key approach to sustain improvements could be to develop and adapt SOPs, they are the foundations of maintaining quality. The SOPs can even be designed with flexibility to allow for adaption to different customer requirements. Regular internal audits and reviews of the process to ensure they are still appropriate but also are improving. Data can also be collected on defects, quality issues, and any deviations from the process. This data can be used to drive the team to establish feedback loops to capture lesson learned and provide insights into strengths and weaknesses. Further studies should focus on mechanisms for committing to improvements in environments where production processes vary significantly. Research could look to explore how updating SOPs and embedding quality checks into each customised project phase can prevent regression and maintain quality gains.

The available literature emphasises the importance technical tools within DMAIC, such as statistical analysis, control charts, and FMEA. However, only few studies thoroughly explore the role the humans have, including team collaboration, training, and communication All are critical in bespoke manufacturing where skilled labour plays a significant role and is relied upon. Human error remains to be a huge source of defects in bespoke environments, yet the literature lacks a comprehensive examination of how to include training, team coordination, and employee engagement strategies into DMAIC for sustaining quality improvement. Further research could magnify on the impact of human factors within defect reduction, particularly within custom manufacturing. Investigating how training, communication, and collaboration can affect defect rates and how to integrate these factors into the DMAIC process would provide valuable insights.

This report will aim to fill some of these gaps by applying DMAIC within a bespoke electrical control panel manufacturing setting, with a focus on adapting the methodology to

handle high variability and customisation. By studying this unique application of DMAIC, the research will contribute new insights into how each phase of DMAIC can be tailored for bespoke production environments. Additionally, the study will address the issue of sustaining improvements, potentially by integrating adaptive SOPs and flexible quality control measures. Furthermore, this research will include the exploration of human factors, particularly focusing on team coordination, training, and client communication as part of defect prevention. By emphasising these human elements alongside technical tools, the research aims to produce a more holistic defect reduction framework for bespoke manufacturing.

Tools and Techniques

By identifying the tools and techniques to be used ahead of time it helps the project team understand the problem-solving framework and ensures there is consistency in data collection, analysis, and improvement. It allows the time to gather resources, software, or expertise that may be needed for data analysis (Sharma, et al., 2022). It also ensures that each phase is aligned with Six Sigma best practices and that the process follows a standardised approach. Also, by pre-selecting tools, it helps guide the team toward specific actions that are suitable for the types of problems and data that are encountered.

Define Phase

During the define phase, the main goal is to clearly understand the problem at hand, to identify the key requirements, and the projects scope.

SIPOC is an important tool, it is a high-level visual tool which assists in mapping out the entire process flow from the suppliers through to the customer. This visual tool helps the team, and stakeholders develop a shared understanding and the key components, preventing miscommunication (Zhang, et al., 2022). It clarifies the process boundaries, defining start and end points of the process being investigated whilst identifying the key elements such as the inputs, outputs, suppliers and customers.

CTQ tree is a tool used to dissect the broad customer needs into specific and measurable requirements which are vital to delivering a quality product or service. This tool helps to prioritise the most critical quality aspects to the customer and ensures the project is focused on the correct elements to increase customer satisfaction (De Koning & De Mast, 2007). VOC data is often a foundation used to build the CTQ tree as it captures the direct input from the client through surveys, interviews, or other forms of feedback to identify specific qualities or outcomes most important to the client. This can be essential in ensuring that the project is solving the critical issues that matter to the client.

Measure Phase

The measure phase aims to gather data on the process in place to help establish a baseline, quantifying the problem and identifying where improvements will be essential.

A data collection plan outlines the data that needs collecting, the ways in which it will be collected, who will be responsible for collecting it, and when it will be collected. Using this tool help identifying the type of data needed to analyse the problem, ensuring only relevant information is collected. Specifying the methods for data collection ensures consistency and accuracy when gathering data which is very important when dealing with complex processes like in this instance of bespoke manufacturing, where variability is high. A well-defined plan assigns roles and responsibilities, so there is no confusion in the team.

A Pareto chart follows the 80/20 rule, it is said that 80% of the problems or issues are most often cause by 20% of the factors. This chart helps the project team focus on tackling the most significant sources of defects by easily showing which issues occur most often in a visual format, enabling the team to decide upon further root-cause-analysis. The Pareto chart instructs to direct attention to the vital few causes rather than addressing all problems equally.

Analyse Phase

In the analyse phase, identifying the root cause of the defects and inefficiencies are the primary objective.

FMEA is a step-by-step approach to identify the potential failure modes or potential ways the process or product may fail, what effect it will have, and what the root causes are. FMEA also aims to evaluate the likelihood, severity, and detectability of each of the failure modes identified, whilst prioritising the most critical ones. This is important for the team working in a bespoke manufacturing environment as they product variability can lead to a wide range of failure modes. Identifying potential failures early is a proactive approach which helps to avoid the need for a trail-and-error approach, reducing risks, and defects in the long term. The team will be forced to examine the process from multiple perspectives, from design, through the manufacture but also by customer requirements, ensuring all possible sources of failure are considered.

Improve Phase

The main goal of this phase is to develop, verify, and implement solutions which directly address the root causes of the defects experienced and identified in the analyse phase. DOE, brainstorming and Kaizen are tools that are essential Tools such as brainstorming, Design of Experiments (DOE), and Kaizen are essential to assist the team in because they help teams creating solutions to optimise the processes through experiments, and continuous improvement.

Group brainstorming creates ideas and potential solutions encourages the team to think outside the box with multiple options being narrowed down to the most feasible and effective. Team members have different perspectives, experience, and knowledge which allows for more comprehensive possible solutions especially in complex processes like bespoke manufacturing. The open collaborative environments lead to higher engagement with both quick fixes and long-term improvements being implemented.

DOE helps to test different inputs to see the effects of process outputs during a controlled manner which allows for identifying which factors greatest impact the reduction of defects. DOE helps in bespoke manufacturing, where each project may have unique variables, each factor can be fine-tuned for optimal performance. This also reduces trial and error, experimenting with changes and confirming their effectiveness before implementation reduces risk of consequences.

Kaizen focuses on small incremental improvements rather than large scale solutions. In bespoke manufacturing, small adjustments can lead to significant improvements over time. Small changes protect from disrupting the entire process if the solution doesn’t work. This philosophy encourages continuous improvement driven by all employees; this is vital to maintain competitive advance especially in bespoke production where the customer need evolves regularly.

Control Phase

The control phase focuses on maintaining the new level of process improvements, preventing a return to previous defects.

Control charts track performance over time through tracking key metrics, detecting any variations that prove to be a problem. The team can take corrective action to ensure quality levels are maintained. Corrections are based upon actual data rather than an assumption.

SOPs provide detailed, instructions informing of the steps for tasks, or processes which ensure compliance with standards and regulatory requirements as well as customer specification. These are important in the control phase to standardise the improved process, ensuring all follow the steps to reduce the risk of regression. In bespoke manufacturing it is particularly important, each project is different but having consistency in the process is critical. New employees can often introduce new defects but having SOPs in place can give those employees a reference and serve as essential training.

Define Phase

Project Charter

Problem Statement

The production of bespoke electrical control panels is prone to quality inconsistencies and defects due to its nature. This leads to increased costs, delays, and reduced customer satisfaction. Traditional quality control methods are less effective due to the high variability inherent in low volume, custom production. This project aims to systematically measure, identify, analyse, and reduce defects in this setting through a structured DMAIC approach, ultimately improving quality, reducing waste, and optimising costs.

The Goal Statement

The goal is to reduce defect rates in the production of bespoke electrical control panels by 25% over the next few months. This will be achieved by implementing the DMAIC methodology to measure defects, identify root causes of defects, streamline quality control processes, and enhance production standards. The focus will be on improving functional reliability, build quality, and compliance with specifications, ultimately enhancing customer satisfaction and reducing rework costs.

Business Case

Defects are costly for the organisation, it leads to an increase in rework, scrap, potential warranty claims, which all impact profit margins and ultimately lead to a decrease in customer satisfaction and future sales. Each panel is tailor made to client's requirements, given this nature, defects are particularly disruptive, errors have a high risk of affecting functionality, compliance and delivery times.

Improving defect rates by 25% will decrease direct costs associated with errors during design and production as well as strengthening OCU Hornbills reputation for quality, reliability, and providing solutions to customer problems. Addressing root causes of defects enables more efficient production workflows, enhancing quality control processes. The organisation's commitment to this project will foster continuous improvement, which positions us competitively within the industry, and set a foundation for further advancements in manufacturing excellence opening potential for future growth within the market.

Scope Statement

The scope includes all stages of the panel production process, from initial design, component selection, through to assembly, and final inspection. This project will address issues such as design inconsistencies, material defects, and assembly errors that contribute to quality issues.

Some of the inclusions are:

- Evaluation of the current process and defect rates.
- Implementation of quality improvement tools, including SIPOC, CTQ, and FMEA, within the DMAIC framework.
- Training for staff on defect prevention methods and quality control.

- Data collection and analysis on defect types, and frequencies.
- Development of enhanced inspection and quality control procedures.

Some of the exclusions are:

- Altering any customer specific design requirements, unless those changes are directly related to reducing defects.
- Any adjustments in the process outside the production area, such as sales or maintenance.
- Major capital investments, such as new machinery purchases, which are outside of process adjustments or incremental quality improvements.

Project Milestones

1. Define phase completion – the key activities to achieve this is to finalise a project charter, identify stakeholders, undertake a SIPOC diagram, and develop a CTQ tree.
2. Measure phase completion – the key activities of this are to develop and implement a data collection plan and complete a process flow chart.
3. Analyse phase completion – the key activities are to conduct root cause analysis using tools like FMEA and to identify key defect drivers.
4. Improve phase completion – the key activities are to brainstorm and implement solutions, test process changes through design of experiments and refining solutions for defect reduction.
5. Control phase completion – the key activities are to implement control measures, establishing control charts, finalising SOPs, and possibly conducting training sessions.
6. Project closeout and final review – the key activities are to submit the final report and present the project outcomes.

Stakeholders

The project stakeholders can be categorised into either internal or external to OCU Hornbill.

Internal Stakeholders

- Operations Manager (Project Sponsor). Whose role is to oversee the DMAIC project, driving efficiency and ensuring defect reduction in the production processes through regular briefings and weekly reports. The operations manager provides the team with clarification of the objectives, the current organisational process, clarification of each stakeholders' role. The team are given empowerment to make decisions and communicate to each other often.
- Quality Control Team. Whose role is to monitor and inspect the control panels throughout the production process to ensure quality standards are being met. They collaborate on defect data collection and root cause analysis, sharing findings to ensure alignment on the impact of defects. This project aligns with their interests, high product quality is achieved by reducing defect rates to a minimum.

- Production Team (Panel Builders). Whose role is directly involved in the manufacturing and assembly of electrical control panels. Daily stand-up meetings are held to discuss defects found during production and how to improve the assembly process. The production team will be motivated towards this project as this is aiming to reduce rework for them and improving efficiency. However, it could potentially lead to an increase in quality control work for them.
- Design and Engineering Team. Whose role is to provide technical designs and specifications for the control panels, holding review sessions to ensure design changes are aligned with defect reduction goals. Again, this project should be of high interest, it will ensure designs are feasible and minimise design-related defects.
- Procurement Team. Whose role is to source materials and components required for the production of the control panels. Monthly supplier quality reviews to monitor performance and the quality of materials and components being delivered.
- Finance Team. Whose role is to oversee budgeting and financial impacts. Reducing the financial costs associated with defects and rework.

External Stakeholders

- Customers/end-users. These are the businesses purchasing the bespoke electrical control panels for their needs and requirements. Customers should be engaged to gather feedback through surveys on delivered panels to assess customer satisfaction and identify any areas for improvement. Receiving defect-free, high-quality products that meet their specifications and requirements is key to them.
- Suppliers. These provide the materials, components, and parts for manufacture. Suppliers should be engaged quarterly to discuss any defects caused by supplied materials and how to improve the supply chain quality control.
- OCU Group Management. As the parent company, OCU Group oversee broader business operations and strategic initiatives. It is in their interest to ensuring that the project aligns with company goals, particularly in efficiency and customer satisfaction. Overall progress of the project will be needed to highlight success in defect reduction, cost savings, and customer satisfaction improvements.

The process was observed and understood, it is understood that multiple types of defects are experienced at different stages of the process. The SIPOC diagram shown in Table 1 is a visual representation of OCU Hornbill manufacturing process in a table form. Figure 3 is a visual representation of the process in a flow chart form. The SIPOC diagram has helped to clearly define the customers. OCU Hornbill have a wide range of customers, a group discussion was held within the panel engineering office on what the team felt the key needs of their customers were. The included the below:

- Customisation, mostly all require tailor made solutions which is specific to their operational processes, system interfaces and their environmental conditions.
- Reliability, that the finished panel is built to be able to be operate in the environment it was intended for. For example, a pumping station for a treatment works may require the panel to be manufactured in stainless steel with a high ingress protection.

- Safety, control panels are designed and manufactured to the safety integrity levels set out prior to work commencing following risk assessment.
- Compliance, the panel must meet all the relevant industry standards.
- Easily operated, designed for straightforward human operation by both physical pushbuttons/selector switches but also HMIs.
- Maintenance and support, offered as part of the full turnkey services OCU Hornbill provide which is crucial to minimising downtime.
- Cost efficiency, this is very important to customers whilst also still meeting potentially high-performance standards.
- Lead time, customers often place orders for panels just-in-time. It is important to meet the delivery requirements to ensure the project is fulfilled on time.
- Clear communications, customers require clear and regular communication during a project to prevent misinterpretations or errors.

S Suppliers	I Inputs	P Process	O Outputs	C Customer
<u>External</u> Component Suppliers Automation System Suppliers Test Equipment Suppliers Logistics Providers Tools & Equipment Suppliers <u>Internal</u> Panel Designers Panel Builders Quality Assurance Team Procurement Team Accounting Team Automation Engineers	Components Automation System Consumables Tools & Test Equipment Technical Drawings Customer Specifications Industry Regulatory standards (IEC, ATEX, etc) Software Packages Workforce (panel builders, designers, software engineers, quality assurance) Processes & Procedures Documentation for Compliance Safety Certifications Customer Feedback	Design & Specification Component Selection & Procurement Panel Assembly Programming & Configuration Testing & Quality Control Documentation & Compliance Delivery & Installation	Completed Electrical Control Panel Technical Documentation Compliance Certifications Test and Inspection Results Installation & Commissioning Support Maintenance Support Customer Feedback Sign Off	Industrial End-Users (Oil & Gas, Metals, Water Treatment, etc) System Integrators Original Equipment Manufacturers (OEMs) Consulting Firms Internal Stakeholders –as part of their installation packages

Table 1 – SIPOC Diagram

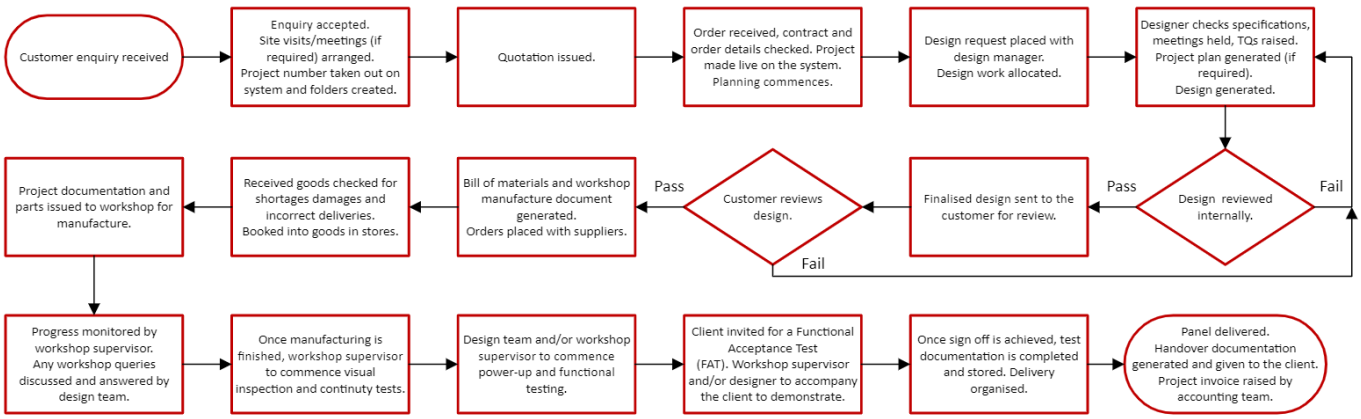

Figure 3 - Manufacturing Process Flow Chart

The VOC was identified by sending out surveys through Microsoft forms to multiple clients. All those who answered remain anonymous to ensure that their true thoughts are submitted. The survey was designed to be mostly multiple choice to take a maximum of 2 minutes to answer to ensure more customers return the form. The overall need was to receive defect-free, high quality electrical control panels. The CTQ tree shown in Figure 4 highlights the key quality drivers that can be addressed to reduce defects and improve overall customer satisfaction with bespoke electrical control panels. These drivers can be achieved by meeting the requirements listed for each driver, measures can be put in place.

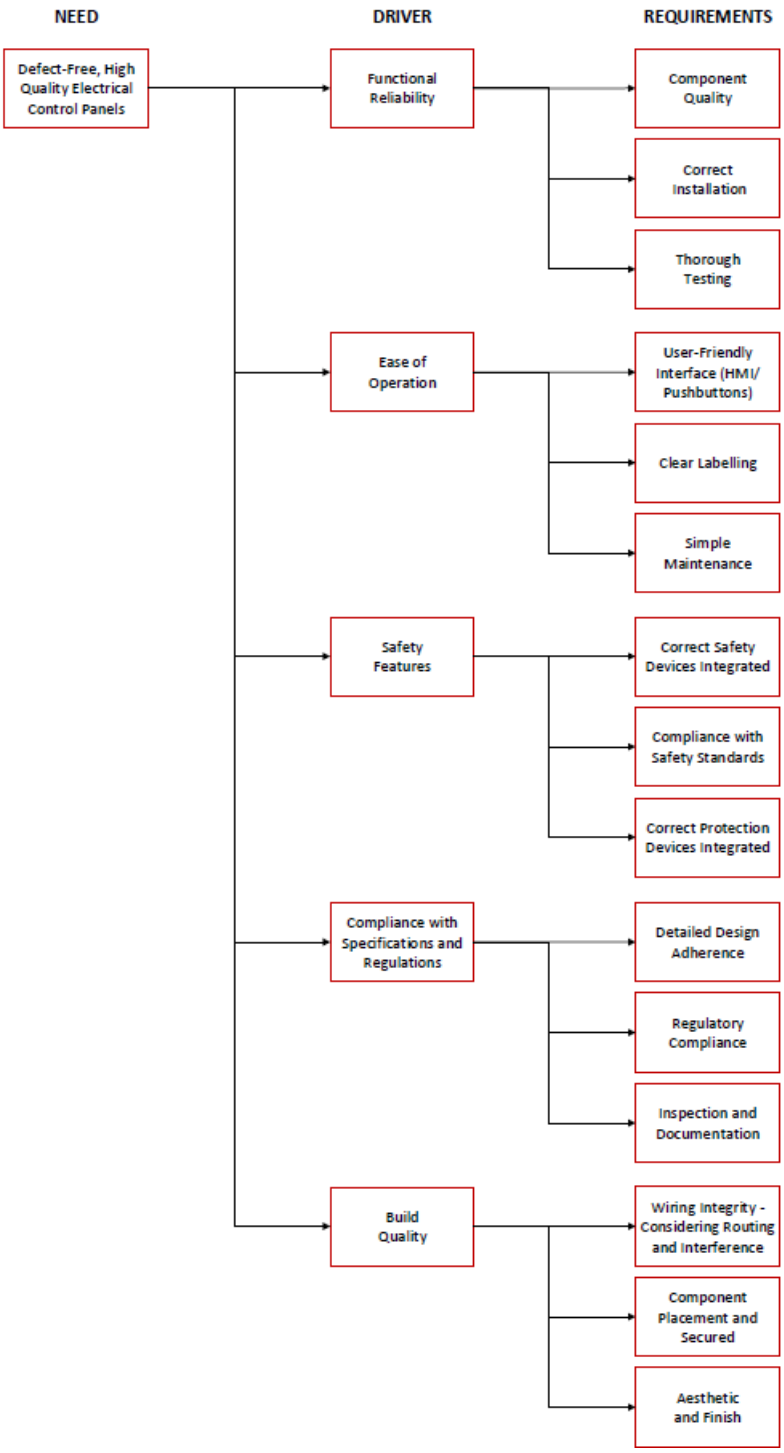

Figure 4 - CTQ Tree

Measure Phase

Following on from the Define phase, variability within the process is identified and presented.

Following the generation of the design, it will progress through two reviews. The first is an internal one, reviewed by a member of the design team, usually a senior member. The second is an external review conducted by the client. The variation that can occur here is that the ability and understanding of the individual reviewing the design is unknown whether internal or external. Some individuals may pick up potential issues or defects whereas others may not. Another potential variation is during ordering, receiving and inspection of delivered goods. The variation occurs if goods are delayed due to shortages or damaged items which can disrupt the schedule. Another variation occurs during the manufacture stage as each panel builder builds to a different standard due to the variance of their experience and knowledge. Further variations include delay and/or rework if quality issues are detected during inspection or functional tests as well as additional FAT sessions if the client is not satisfied during the initial demonstration. More variations occur during the final documentation stage if there are delays in completing documentation which can affect invoicing and the delivery timeline. Addressing these issues might involve implementing strategies, forms, or process updates for more effective design feedback loops, supplier management, quality checks, and process standardisation.

During this phase, a data collection plan is utilised to gather accurate and relevant data which is related to defects in the production process for the control panels. The data is used as a tool to identify and categorise the most common defects experienced whilst also quantifying the frequency and severity of them. It helps to gain an understanding of the impact of the defects and provide a basis for root cause analysis during the analyse phase. Another objective is to track key performance metrics from the CTQ tree, including functional test failures, and compliance with specifications.

Data Category	Description	Metric	Source of Data	Collection Method
Defect Type	Types of defects	Defect Classification	Inspection and/or testing records	Manual logging by workshop supervisor/QA team/ engineers
Defect Frequency	Number of defects per panel	Defect Rate	Inspection and/or testing records	Manual logging by workshop supervisor/QA team/ engineers
Customer Satisfaction	Feedback on built control panels	Satisfaction Score (1-5)	Customer feedback survey	Survey forms or digital surveys
Rework Time	Time spent on fixing defects	Rework Time (hours)	Production logs	Manual time-tracking
Safety Incident Reports	Number of safety-related defects reported	Incident Reports	Incident reports	Manual reports from safety team

Table 2 - Data to be collected

The stage in which the defect occurs will also be logged, as well as whether it was found internally or externally. The rework cost of the defects will also be recorded, in both materials and labour costs. The data will be collected weekly, and logged at the beginning of each week, the data will be collected for around of 6 months. Although OCU Hornbill does log defects when testing, sometimes these defects are corrected during manufacture or testing without being properly logged. The whole team will be briefed of the importance of logging each defect during the whole project lifecycle. Regular data validation checks will be implemented to ensure data accuracy as well as cross-verification if critical data points such as test failures and inspections. The collection method will be during quality control checks and testing results, this will be collected by the workshop supervisor, design engineers, automation engineers, and test engineers. The roles and responsibilities of each team member will be discussed with them individually, these were already set out during the define stage. Data will be presented using a Pareto chart to identify the most frequent defects and prioritise efforts on high-impact issues. It will then be analysed using tools such as FMEA to understand the underlying causes of the most frequent defects.

Collecting this data does come with some challenges and risks. There could be a portion of incomplete or inaccurate data so regular audits of data collection practices will be conducted with the team to ensure accuracy and consistency. There may also be resistance from staff, they may be hesitant to report defects. However, a no-blame culture will be encouraged to focus on improvement, not punishment. The data collected is shown in Figure 5 which is inclusive of all the panels manufactured, descriptions, defect types, stages of failure, and quality costs.

Job Number & Panel Number	Panel Description	Entry Date	Defect Type	Internal/ External	Stage of Failure	Total Material Cost of Rectification	Estimated Hours to Rectify	Total Quality Cost
23.JR.729-100	Picton SPS Pump Panel	08/01/2024	Foreign objects inside panel	Internal	Manufacture	£0.00	0.5	£11.50
23.JR.729-100	Picton SPS Pump Panel	08/01/2024	Missing labelling	Internal	Manufacture	£0.00	2	£46.00
23.JR.729-100	Picton SPS Pump Panel	08/01/2024	Missing components	Internal	Manufacture	£0.00	2	£46.00
23.JR.921-100	Freshwater East Pump Panel 1	16/01/2024	Missing components	Internal	Manufacture	£12.00	3	£81.00
23.JR.921-100	Freshwater East Pump Panel 1	16/01/2024	Missing labelling	Internal	Manufacture	£9.00	1	£32.00
23.JR.921-200	Freshwater East Pump Panel 2	16/01/2024	Missing components	Internal	Manufacture	£12.00	3	£81.00
23.JR.921-200	Freshwater East Pump Panel 2	16/01/2024	Missing labelling	Internal	Manufacture	£9.00	1	£32.00
24.IH.056-100	Instrument JB 1	13/02/2024						£0.00
24.IH.056-200	Instrument JB 2	13/02/2024						£0.00
24.IH.056-300	Instrument JB 3	13/02/2024						£0.00
24.IH.056-400	Instrument JB 4	13/02/2024						£0.00
24.IH.056-500	Instrument JB 5	13/02/2024						£0.00
24.IH.056-600	Instrument JB 6	13/02/2024						£0.00
23.JR.878-100	Stove Dome Booster Panel	12/03/2024	Incorrect wiring	Internal	Design	£0.00	4	£120.00
23.JR.878-100	Stove Dome Booster Panel	12/03/2024	Wrong labelling	Internal	Design	£4.50	2	£64.50
23.JR.642-100	CDA Drier Panel 1	18/03/2024	Missing labelling	Internal	Manufacture	£9.00	1	£32.00
23.JR.642-200	CDA Drier Panel 2	18/03/2024	Missing labelling	Internal	Manufacture	£9.00	1	£32.00
24.IH.029-100	Freeze Dryer HMI Panel	19/03/2024	Foreign objects inside panel	Internal	Manufacture	£0.00	0.5	£11.50
24.IH.029-100	Freeze Dryer HMI Panel	19/03/2024	Loose connection	Internal	Manufacture	£0.00	0.5	£11.50
24.IH.029-100	Freeze Dryer HMI Panel	19/03/2024	Missing labelling	Internal	Manufacture	£4.50	2	£50.50
24.IH.029-100	Freeze Dryer HMI Panel	19/03/2024	Missing components	Internal	Manufacture	£3.50	6	£141.50
24.IH.029-100	Freeze Dryer HMI Panel	19/03/2024	Incorrect wiring	Internal	Manufacture	£0.00	2	£46.00
24.IH.029-200	Main PLC Panel	19/03/2024	Incorrect wiring	Internal	Design	£0.00	4	£120.00
24.IH.029-300	Remote IO Panel	19/03/2024						£0.00
23.JR.755-100	RIO Panel	22/03/2024	Missing labelling	Internal	Manufacture	£4.50	1	£27.50
23.JR.1094-100	Air Compressor MCC Panel	11/04/2024	Missing labelling	Internal	Manufacture	£4.50	1	£27.50
23.JR.1094-100	Air Compressor MCC Panel	11/04/2024	Incorrect wiring	Internal	Manufacture	£0.00	2	£46.00
23.JR.1094-100	Air Compressor MCC Panel	11/04/2024	Non-compliant with specification	Internal	Design	£0.00	8	£240.00
23.JR.1094-100	Air Compressor MCC Panel	11/04/2024	Failed functional test	Internal	Testing	£0.00	8	£184.00
24.IH.177-100	Llangennech Instrument Panel	15/04/2024						£0.00
24.IH.313-100	Lee Mill Cloth Filter STW Panels	17/04/2024	Missing labelling	Internal	Manufacture	£4.50	2	£50.50
24.IH.313-100	Lee Mill Cloth Filter STW Panels	17/04/2024	Failed functional test	Internal	Testing	£115.00	8	£299.00
24.IH.179-100	Brynmawr Instrument Panel	18/04/2024						£0.00
24.IH.019-100	Lamphey SPS Pump Panel	06/05/2024	Incorrect wiring	Internal	Manufacture	£0.00	2	£46.00
24.IH.019-100	Lamphey SPS Pump Panel	06/05/2024	Missing labelling	Internal	Manufacture	£4.50	1.5	£39.00
23.JR.1414-100	Drill Rig Changeover Panel	28/05/2024	Loose connection	Internal	Manufacture	£0.00	0.5	£11.50
23.JR.1414-100	Drill Rig Changeover Panel	28/05/2024	Incorrect wiring	Internal	Manufacture	£0.00	2	£46.00
23.JR.1414-100	Drill Rig Changeover Panel	28/05/2024	Improper component installation	Internal	Manufacture	£0.00	2	£46.00
24.IH.271-100	Tongs Test Panel	12/06/2024	Missing labelling	Internal	Manufacture	£4.50	1	£27.50
24.IH.100-100	Cefn Onn Instrument Panel	19/06/2024						£0.00
24.IH.561-100	Pump Panel	24/06/2024	Incorrect component specification	Internal	Design	£542.00	4	£662.00
24.IH.561-100	Pump Panel	24/06/2024	Incorrect wiring	Internal	Manufacture	£0.00	2	£46.00
24.IH.561-100	Pump Panel	24/06/2024	Missing components	Internal	Manufacture	£0.00	2	£46.00
24.IH.561-100	Pump Panel	24/06/2024	Poor or wrong enclosure assembly	Internal	Manufacture	£0.00	6	£138.00
24.IH.561-100	Pump Panel	24/06/2024	Missing labelling	Internal	Manufacture	£4.50	1.5	£39.00
24.IH.279-100	Mixing Vessel Panel	28/06/2024	Missing labelling	Internal	Manufacture	£4.50	1	£27.50
24.IH.279-100	Mixing Vessel Panel	28/06/2024	Wrong components installed	External	Design	£10.42	8	£250.42
24.IH.410-100	Catsash PRS Panel	03/07/2024						£0.00
23.JR.1286-100	Machynlleth Instrument Plate	03/07/2024						£0.00
23.JR.1287-100	Rhayader Instrument Plate	03/07/2024						£0.00
24.IH.118-100	ESD Control Panel	06/07/2024	Faulty components	Internal	Material Supply	£10.42	1	£33.42
24.IH.535-100	Brinsworth MCC	15/07/2024	Missing components	Internal	Manufacture	£12.00	3	£81.00
24.IH.535-100	Brinsworth MCC	15/07/2024	Wrong labelling	Internal	Manufacture	£0.00	2	£46.00
24.IH.535-100	Brinsworth MCC	15/07/2024	Incorrect wiring	Internal	Manufacture	£0.00	3	£69.00
24.IH.535-100	Brinsworth MCC	15/07/2024	Loose connection	Internal	Manufacture	£0.00	0.5	£11.50

Figure 5 - Dataset

The data is categorised and listed in order of frequency, from highest to lowest. This helps to show which defects are the most common, and potentially, the most important to address. There was a total of 31 control panels that were monitored and logged with 18 of them being reported with defects, giving an overall percentage of 58% of all the panels manufactured during this period having at least one defect. The cumulative frequency and percentage for each defect type is then calculated. The cumulative percentage shows the proportion of the total defects each defect type accounts for. This is explained using Equation 1, calculated by dividing the defect frequency by the cumulative frequency, and multiplying by 100 to give the percentage.

$$\frac{Frequency}{Cumulative\ Frequency} \times 100$$

Equation 1 - Cumulative Percentage Equation

Defect Type	Frequency	Cumulative Frequency	Cumulative Percentage
Missing labelling	13	13	30.95%
Incorrect wiring	8	21	50.00%
Missing components	6	27	64.29%
Loose connection	3	30	71.43%
Foreign objects inside panel	2	32	76.19%
Wrong labelling	2	34	80.95%
Failed functional test	2	36	85.71%
Faulty components	1	37	88.10%
Wrong components installed	1	38	90.48%
Incorrect component specification	1	39	92.86%
Poor or wrong enclosure assembly	1	40	95.24%
Non-compliant with specification	1	41	97.62%
Improper component installation	1	42	100%

Table 3 - Pareto Analysis Table

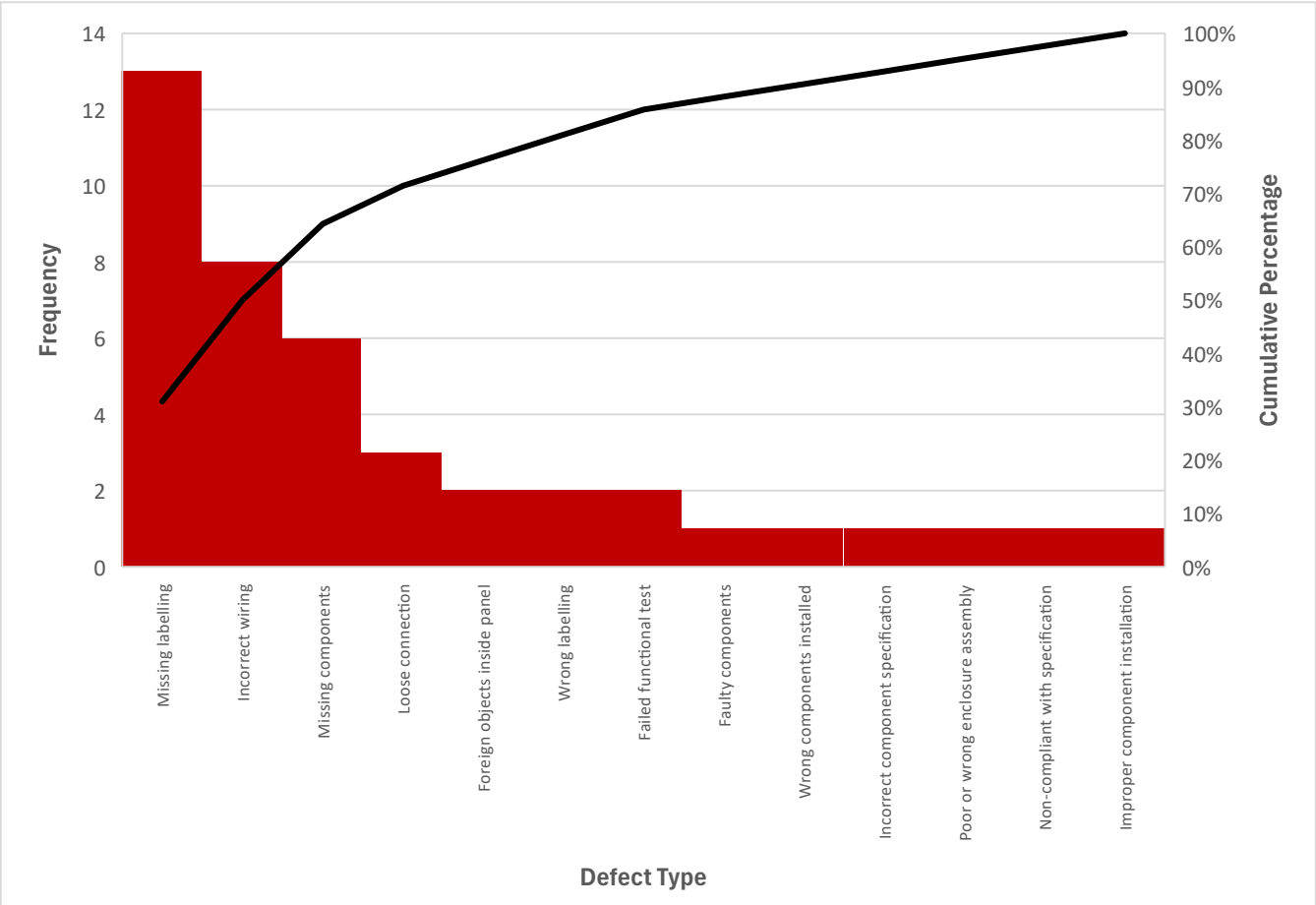

Figure 6 - Pareto Chart

Based on the measured data, the Sigma level can be calculated as a baseline. The equations to reach the Sigma level are shown in Equation 2, which is the Defect Per Opportunity (DPO) and Equation 3, which is the Defects per Million Opportunities (DPMO).

$$DPO = \frac{Number\ of\ defects}{Number\ of\ units\ \times\ Opportunities\ per\ unit}$$

Equation 2 - DPO Equation

$$DPMO = DPO\ \times 1{,}000{,}000$$

Equation 3 - DPMO Equation

The number of units produced is 31, the number of defects found are 31, the opportunities per unit is 4. The opportunities per unit is worked out as the stages at which a defect can occur, this is during design, manufacture, testing, or delivery. Using a Sigma conversion table with a 1.5 sigma shift, a DPMO of 338,710 corresponds to a Sigma level of approximately 1.9. This is high and shows there is significant room for improvement but as previously mentioned in bespoke manufacturing there is higher variability leading to higher defects.

Analyse Phase

Based on the Pareto chart generated from the research undertaken of the defects experienced within the manufacturing section. The Pareto chart shown in Figure 6 visually demonstrates that there are few defect types which contribute to the majority of defects, following the Pareto 80/20 rule (Nwajana, et al., 2024). The Pareto chart has served as a tool to help in prioritising the quality improvement efforts on the high frequency defects which is clearly targeting the missing labelling and incorrect wiring defect types. Corrective actions and training will help to reduce the overall defect rates.

The most frequent defect types are missing labelling and incorrect wiring, which is the bulk of the defects which together, accounts for more than half of the total defects, indicating that focusing on these areas could return the most significant quality improvements. There are also other secondary defect types, such as missing components and loose connections, which also contribute notably but are far less frequent. Defects such as improper component installation, non-compliance with specification, and poor or wrong enclosure assembly appear less frequently, with minimal impact on the cumulative defect rate.

The dataset shown in Figure 5 has a total cost of quality defects of £3,499.34. Each defect type has a total quality cost, this includes the labour hours, and any material costs needed for rectification. The most frequent defect type has been identified as missing labelling which has a total quality costs per instance of £27.50 to £50.50. To rectify this defect type it takes between 1 and 2 hours. There is a low material cost and rework time, but the frequency occurrences show that these add up quickly. Incorrect wiring and missing components, the next most frequent defect types, require substantial rectification and in some cases a lot higher material costs in some cases. The highest individual quality costs occur with the “Pump Panel” on project 24.IH.561-100, this is due to an “Incorrect component specification” at £662.00 which occurred in the design phase. However, most defects occur during the manufacture stage, followed by the design phase, there are very minimal during other phases. Defects occurring in the design phase ultimately incur significant cost per defect in comparison to defects in the manufacture phase. A positive which is clear following the data measured if that only one defect was reported external, following delivery to the client, almost all defects are internal. The labour cost to rectify the defects accounts for the bulk of the total quality costs.

The dataset reflects that while defects such as missing labelling have low individual costs, their frequency makes them notable contributors to the total quality cost. In contrast, defects such as incorrect wiring are less frequent but have a higher cost impact per occurrence. The data collected only considers direct costs such as the material and labour costs to undertake the rework. It does not consider indirect costs such as admin costs for re-work such as the re-ordering or booking in of materials. It also does not consider the cost of the time that the employee should be on other work generating income for the company instead of resolving defects. Given that missing labelling and missing components are common issues, implementing a checklist during and/or directly after manufacturing can help identify these defects earlier. As incorrect wiring occurs frequently, enhanced training for the panel builders as well as standardised wiring protocols could reduce this defect type.

FMEA

Process Step	Function	Failure mode	Effect(s) of potential failure	Severity	Potential causes of failure	Occurrence likelihood	Current design controls (detection)	Effectiveness of best method of detection control	RPN (Risk priority no.)	Recommended action(s)	Responsible
Design	Develop comprehensive technical drawings and documentation incorporating industry standards and regulations. Facilitate collaboration among teams.	Misunderstanding of customer specifications.	Poor functionality, customer dissatisfaction.	8	Lack of clarity in specifications, oversight.	6	Encouraged to attend site visit and hold meetings with the client.	5	240	Checklist to discuss with client. Set up regular communication channels. Incorporate milestone reviews/sign off.	Design Manager & QA Team
		Incomplete documentation.	Confusion during assembly, increased assembly time.	6	Time constraints, lack of process adherence.	7	SOPs in place. Time allocated for documentation.	4	168	Implement a checklist for required documentation for each phase.	Design Manager & QA Team
		Overlooked regulatory requirements.	Legal non-compliance, project delays, possible safety concerns.	10	Insufficient knowledge of regulations, neglect.	4	Training given and designs reviewed to ensure compliance.	4	160	Provide further training. Incorporate regulatroy compliance checks in the design review process.	Design Manager
		Design reviews not undertaken or poorly undertaken.	Increased risk of errors going unnoticed.	7	No structured review process.	7	SOPs in place.	7	343	Implement common check lists for design reviews. Document issues and follow up on actions from the review.	Design Manager & QA Team
		Miscommunication among team members.	Inconsistent design interpretations, errors.	8	Poor communication practices, unclear roles.	5	All design team in same room.	7	280	Establish regular meetings to discuss progress and issues. Define roles and responsibilities to avoid confusion.	Project Manager
Component Selection	To identify, evaluate, and choose specific parts, materials, and components that meet the technical, quality, cost, and regulatory requirements of the project.	Selecting components that don't meet specification.	Performance issues, customer satisfaction, safety hazards, warranty claims.	10	Pressure to reduce costs, insufficient understanding of specifications.	5	Design reviews undertaken, approved vendor lists in place.	4	200	Improve detail in specification documents.	Design Team
		Selecting components that are at end of lifecycle.	Production delays, increased maintenance costs.	6	Supplier communication gaps, rushed selection process.	4	Good supplier relationships who give updates on lifecycle changes.	3	72	Conduct annual lifecycle audits.	Procurement Team
		Selecting components that are difficult to source.	Long lead times, possible production stops, increasing costs.	7	Not considering availability when designing, specialised equipment required.	6	Multiple suppliers in place.	4	168	Focus of building relationships, select components that are widely available.	Procurement Team & Design Team
		Selecting components with unreliable documentation.	Risk of failure, assumption design errors, compliance issues.	6	Outdated datasheets, using documentation from one source.	4	Reputable suppliers used that keep documentation up to date.	5	120	Develop a supplier documentation standard.	QA Team & Design Team
		Selecting components without considering long-term support.	Increased maintenance costs, additional upgrade costs.	5	No agreements for long-term support, no end of life process in place.	4	Support contracts in place with main automation suppliers.	3	60	Formalise component replacement procedures.	Operations Team
Manufacture/ Assembly	Assemble all components into a finished product.	Incorrect assembly/wiring.	Possible safety risk, damage to components, product not functioning correctly.	9	Unclear instructions, lack of quality checks, rushing work, insufficient training.	5	Standardised work instructions, training provided, inspections and supervision provided.	6	270	More frequent training, team breifings with lessons learnt.	Workshop Supervisor
		Missing or wrong components, labels, etc	Improper operation, causing functional or safety issues, customer dissatisfaction.	7	Documentation errors, mislabeling during assembly, inadequate verification steps.	4	Inventory managed, components verified in design review.	5	140	Provide checklists to verify component selection, visual checks at end of build prior to testing.	Design Manager & Workshop Supervisor
		Damage during build.	Rework, increased costs, risk of early failure, higher warranty claims, customer dissatisfaction.	7	Poor workmanship (distractions), inadequate training, poor handling procedures.	6	Designated storage areas, training provided.	6	252	Improved workspace layout, implement procedures on higher risk activities such asenclosure modifications.	Workshop Supervisor
		Build not compliant to specification.	Rework, increased costs, safety risk, higher warranty claims, customer dissatisfaction.	9	Incomplete documentation, misinterpretation of specifications, inadequate training on standards.	4	Regulation training, approved documentation provided.	5	180	Team briefings each week, constant communication through build.	Workshop Supervisor
Inspection & Testing	The purpose of inspection and testing is to verify that the assembled product meets all specified requirements, is free of defects, and functions correctly before it reaches the customer.	Incomplete inspection/testing.	Defects may pass undetected, customer dissatisfaction, increased warranty claims.	8	Insufficient test coverage, lack of test instruction, inadequate training of staff, time constraints.	4	Standardised test procedures, training on inspection process.	5	160	Implement quality audits on spection process.	QA Team
		Incorrect test results.	Products may pass as acceptable (false negatives), or acceptable products may be rejected (false positives), leading to increased rework, delays, and costs.	8	Calibration errors in testing equipment, human error, improper test setups.	5	Equipment calibration, training on testing equipment use.	4	160	Increase calibration frequency, automate data recording to minimise human error, conduct root cause analysis on incorrect test results	QA Team
		Inadequate function testing.	Functional defects may not be detected, customer complaints, and increased field failures.	8	Llack of understanding of functional requirements, insufficient time allocated for functional testing.	3	Standard functional test procedures.	4	96	Design engineers to write individual function test procedures to ensure functional tests meet product requirements, allocate more testing time.	Design Manager, Team & Workshop Supervisor
		Failure to record and address defects.	Recurring issues, poor quality control, missed opportunities for process improvement.	7	Inadequate documentation processes, lack of feedback loop, failure to act on recorded defects.	7	Snagging lists and standard test procedures.	6	294	Implement defect logs and quality review meetings.	QA Team & Workshop Supervisor
Delivery	The purpose of the delivery process is to ensure that the final product is safely, promptly, and accurately delivered to the customer.	Delayed delivery.	Customer dissatisfaction, lost future business, harm to reputation.	8	Supply chain disruptions, lack of contingency plans	4	Logistic partners used.	6	192	Establish contingency plans for high priority deliveries, diversify partners.	Project Manager
		Damage during transit.	Unusable condition, customer dissatisfaction, increased costs, rework.	9	Inadequate packaging, poorly handled udring transit, improper loading.	4	Employees trained to package panels earlier, selection of reputable couriers.	4	144	Improve packaging materials, audit couriers.	Project Manager & Workshop Supervisor
		Incorrect delivery address.	Delivery to wrong location, delays, increased costs, customer dissatisfaction.	7	Data entry errors, unclear address information from the customer, lack of verification process.	3	Address verification in order processing, double-checking customer provided information.	4	84	Create checklist before shipping, provide a final confirmation email to the customer confirming delivery details.	Procurement Team
		Insufficient communication with customer.	Customer is unaware of delivery status, decreased satisfaction, potential failure of delivery.	6	Failure to notify customer of delays or changes, lack of automated communication system.	4	Email updates	6	144	Set up automated notifications, provide tracking information.	Project Manager

Figure 7 - FMEA

Root Cause Analysis

Based upon the FMEA in Figure 7, several failures will be focused on which have the highest risk priority numbers. A Root Cause Analysis (RCA) using the "5 Whys" methodology is to be undertaken.

- Failure mode: Design reviews not undertaken or poorly undertaken
    - RPN: 343
    - Effect: Increased risk of errors going unnoticed.

1. Why was the design review not conducted or done poorly?
    a. There is no standardised design reviewal process.
2. Why is there not a standardised design review process?
    a. The importance of standardising reviews has not been emphasised in the workflow.
3. Why has standardisation not been emphasised?
    a. As each panel is bespoke it has been assumed that each review is bespoke as well as management have not recognised the risk with unstructured reviews until now.
4. Why did management fail to recognise the risk?
    a. There have been no major incidents which has highlighted this previously which is showing that a proactive approach has not been taken previously.
5. Why were previous errors not considered serious enough to prompt action?
    a. They were not documented adequately or were not reviewed in a feedback loop.

The recommended action here is to implement a structured checklist for design reviews, document issues systematically, and set up follow up actions for unresolved issues. This will reduce variability by creating a checklist that covers critical design aspects, regulatory compliance, and client specifications, ensuring that all relevant areas are reviewed consistently. Members could also be trained on how to effectively conduct thorough design reviews which will help reduce oversight. Another additional recommendation is to involve peer review in the process where someone from the production team reviews the design to give an external perspective, which can help catch overlooked issues and bring in new insights.

- Failure mode: Failure to record and address defects
    - RPN: 294
    - Effect: Recurring defects, missed quality improvement opportunities.

1. Why were defects not recorded or addressed?
    a. There was an inadequate documentation process.
2. Why was the documentation process inadequate?
    a. There was no standardised defect logging system.
3. Why is there no standardised defect logging system?
    Defects have mostly been addressed on an ad-hoc basis, depending on severity.

4. Why were only severe defects given priority for recording?
    a. Minor issues were assumed to be inconsequential without proper analysis.
5. Why was there no analysis to identify the impact of minor issues?
    a. Feedback loops between the workshop, quality control, and design team were weak.

The recommended action is to implement a defect log system and hold regular quality review meetings to ensure all defects are recorded and reviewed continuously.

- Failure mode: Miscommunication among team members
    - RPN: 280
    - Effect: Inconsistent design interpretations, errors in design and/or production, potential rework.

1. Why was there miscommunication among team members?
    a. Information was not being shared effectively between departments or individuals.
2. Why was information not shared effectively?
    a. There was no structured communication protocol or regular meeting schedules.
3. Why is there no standardised defect logging system?
    a. It was assumed that informal or ad-hoc updates were sufficient for sharing information.
4. Why did team members rely on informal communication?
    a. Formal communication practices, such as regular meetings, were not consistently implemented.
5. Why were formal practices not implemented consistently?
    a. Lack of emphasis on the importance of standardised communication process for teamwork.

The recommended action is to establish a structured communication protocol which includes regular team meetings, and that management reinforces the importance of all members attending the meetings.

- Failure mode: Incorrect assembly/wiring
    - RPN: 270
    - Effect: Possible safety risks, product malfunction, customer dissatisfaction, and increased rework costs.

1. Why did incorrect assembly or wiring occur?
    a. Team members misunderstood or did not follow the instructions accurately.
2. Why did team members misunderstand or not follow the instructions accurately?
    a. Communication of assembly requirements was inadequate, some staff members lacked the necessary training to interpret and implement the instructions correctly.
3. Why was communication of assembly requirements inadequate, and why did staff lack training?

   a. Assembly instructions were not clearly documented, and training was informal, relying heavily on verbal guidance rather than standardised written documentation or visual aids.
4. Why were the assembly instructions not clearly documented, and why was training informal?
   a. There was no standardised procedure or communication protocol in place to ensure that instructions were detailed, accurate, and accessible to all team members, leading to gaps in knowledge sharing and a lack of structured training.
5. Why was there no standardised communication protocol or structured training for assembly instructions?
   a. Past practices prioritised other elements of the manufacturing process over comprehensive documentation and formal training, and resources were often allocated toward meeting production targets rather than investing in communication and training improvements.

The recommended action is to develop clear visually supported assembly instructions where possible which reduces reliance on verbal instruction. Clear communication protocols should be implemented such as periodic briefings and shared communication platforms to ensure all the team are informed. A further recommendation is to implement a structured training program for team members which includes hands-on practices.

Summary of Recommendations

Based on the Pareto analysis undertaken, it is evident that the defect types that need to be addressed are the missing labelling and incorrect wiring. These are priority areas which can be improved by introducing another quality check within the SOPs. For example, quality check can be introduced that requires the panel builder to undertake a 5–10-minute inspection when they complete the build. It can require the panel builder to fill out a checklist to ensure that their panel is ready to be tested. Additionally, some training can be undertaken to ensure that the panel builder understands the drawings and documentation that is being issued to them.

Another recommendation following the FMEA, and the root causes identified through the 5 Whys analysis is to establish a detailed, standardised checklist for design reviews to ensure consistency of critical aspects such as the client's specifications and regulatory compliance. The reviews should document issues found during the review which can be used for creating feedback loops for tracking issues. On top of this peer review should be added into the process where someone from the production team reviews the designs to add another perspective.

A further recommendation is to hold frequent quality meetings, ideally weekly, to review all recorded defects, and address defects issues. This will also improve the communication between the workshop, quality control, and design team to ensure that all defects are evaluated for their potential impact and address them proactively through implementing addition steps or undertake training. Additionally, schedule and emphasise the important of attending consistent meetings between the design and production team to improve communication channels.

The final recommendation on top of the previous few is to develop standardised assembly instructions, possibly with visual aids where possible, to reduce the reliance on giving verbal explanations. This should improve accuracy in assembly. The team can be briefed on these and shared during the regular team meetings that are going to be implemented. Formal training programs can be implemented to ensure staff can accurately follow the assembly instructions.

Improve Phase

Prior to implementation of any improvements, it is crucial to incorporate change management strategies to ensure that the changes are successful. Change management involves planning, communicating, and supporting the transition process for all stakeholders affected by the improvements. The key stakeholders are engaged early to share the rationale behind each change, emphasising the benefits which is the reduce defects, improve efficiency, and compliance. These stakeholders consist of the quality control team, production team, and design team. Involving the team encourages their buy-in and ownership, however they may have some concerns such as employee resistance to change, employees struggling to understand or execute new quality checks, implementing multiple changes simultaneously which may overwhelm employees, or short-term productivity dips. However, these concerns will be addressed by proactive actions such as regular meetings or workshops to provide updates on progress, address concerns, gather feedback, and share success stories to build confidence. How the changes benefit employees directly will be highlighted, such as by increasing skill development opportunities. Training can also be provided to ensure that each of the employee involved in the process feel confident in their tasks. Implementing many changes at once has been considered but some changes bare no difference to specific teams. For example, implementing checklists for design reviews doesn't impact the production team.

The Pareto analysis undertaken focuses on high impact areas to achieve significant quality improvements by addressing the most frequent defects. The defects being targeted are types such as missing labelling, missing components, and loose connections. The improvement action to be undertaken is to integrate a quality check step requiring a 5–10-minute inspection by the panel builder following the completion of each build. A checklist will be used to ensure all connections are not loose, components, labels, and wiring are present and accurate. Additional training will be provided to ensure panel builders understand and can accurately interpret all design documentation, reducing errors due to misunderstanding.

Table 4 has been taken from the internal request for test checklist that was created for the panel builders to complete prior to any testing taking place. Along with this checklist the panel builder must also fill in the relevant information for the project and panel such as project code, serial number, as well as sign and date the document. Signing to take responsibility for the tasks, verifying the tests were conducted thoroughly will reduce the likelihood of cutting corners but also helps for tracking issues later.

GENERAL CHECK PRIOR TO INTERNAL TESTING This document should be completed by the panel builder.			
CHECKLIST	**COMMENTS / OBSERVATIONS**	**N/A**	**YES**
Enclosure is clean and free from damage, litter, and swarf		☐	☐
Wall brackets or lifting eyes fitted		☐	☐
Adequately earth bonded		☐	☐
All components fitted and are the correct type and rating		☐	☐
Enclosure, equipment, and terminals correctly labelled		☐	☐
Trunking lids fitted		☐	☐
Ferrule numbers applied to all cables		☐	☐
All terminations tight and as per schematic drawing - ***check 10-20% of terminations***		☐	☐
Network cables tested and labelled		☐	☐
Fuses fitted and correct		☐	☐
Drawings marked up for any changes made		☐	☐
Materials left over together ready to hand over to engineering team		☐	☐

Table 4 - Request for test checklist

The recommendation of creating a comprehensive defect log, a system has been implemented to include all defect types, regardless of severity. This recommendation is justified because it establishes a proactive and systematic approach to defect management, ensuring continuous quality improvement. This approach ensures that even minor issues, which may indicate broader process weaknesses, are identified and addressed accordingly. The defect log has been extended from the initial investigation undertaken at the beginning of this report and now includes categorisation of defects by type, frequency, and severity. Additionally, feedback loops have been established to communicate defect data back to the relevant teams, fostering continuous learning and improvement. Bi-weekly quality meetings have been formalised and are now held with key stakeholders, including representatives from the workshop, quality control, and design teams. These meetings follow a structured agenda to maximise their effectiveness. The agenda includes reviewing defect logs, discussing root causes and corrective actions, analysing unresolved or recurring issues, and sharing lessons learned to prevent similar problems in the future. Clear action items are assigned to team members with defined timelines, ensuring accountability and follow-through. Meeting outcomes, including decisions, actions, and follow-ups, are documented and shared with all stakeholders to maintain transparency and alignment across teams.

The FMEA and 5 Whys Analysis emphasises for the standardisation and improvement of the design review process. This will aim to reduce variability and oversight in design reviews, preventing defects due to design errors. A comprehensive checklist will be established which covers the critical design aspects such as regulatory compliance, client specifications, and potential risks. Any issues found during reviews are to be documented to create a feedback loop. Finally, the addition of a peer review step where a production team member evaluates the design. This external perspective helps identify potential issues and brings fresh insights. The design team should also undergo regular training as well as training on conducting thorough and structured design reviews, ensuring that they understand both the process and the importance of consistency in each review.

Whilst creating a design review checklist, it became evident that a designer checklist that the designer can use must be in place first as the two together would serve distinct complementary purposes in the design process. The designers' checklist acts as a tool for the designer to address all key aspects of the design during and after the creation process as well as proactively preventing errors, or oversights. This checklist, shown in Table 5, enables the designer to self-verify their work, reducing the likelihood of fundamental errors being passed through into the review stage, making the process smoother and more focused on validating higher level compliance rather than fixing basic issues such as details being incorrect on the title block or poor cross referencing between sheets. The same checklist will be used by the reviewer to ensure that both reviews, done by the designer and the reviewer, align completely.

GENERAL REQUIREMENTS	N/A	Designer	Reviewer
Define the purpose, system requirements, and user specifications.	☐	☐	☐
Confirm applicable standards (e.g., BS 60204, BS 7671, BS 61439).	☐	☐	☐
Assess operating conditions such as temperature, humidity, dust, and vibrations.	☐	☐	☐
Document input voltage, frequency, and power requirements.	☐	☐	☐
COMPONENT SELECTION	**N/A**	**Designer**	**Reviewer**
Confirm voltage and current ratings match the application requirements.	☐	☐	☐
Choose components that fit within the panel while maintaining required clearances.	☐	☐	☐
Ensure device compatibility (e.g., contactors and overloads, communication protocols).	☐	☐	☐
Verify the specification of safety components, such as interlocks and E-stops.	☐	☐	☐
Verify that circuit breakers, fuses, or protection devices are properly specified and rated to calculated short-circuit current.	☐	☐	☐
Check wire types, sizes, and insulation meet design requirements.	☐	☐	☐
Design for anti-condensation heating or cooling as required.	☐	☐	☐
Design for ventilation or forced cooling if required.	☐	☐	☐
Include surge protection devices if necessary.	☐	☐	☐
Ensure proper control voltage and ratings for contactors, relays, and all other components.	☐	☐	☐
Verify the accuracy of control logic, interlocks, and operational sequences.	☐	☐	☐
Verify that control panels and PLC inputs/outputs are labelled consistently with associated devices.	☐	☐	☐
Ensure safety circuits (e.g., emergency stops, safety relays) are included in the drawings and logically connected.	☐	☐	☐
Ensure that grounding points are indicated and appropriately referenced to terminal blocks.	☐	☐	☐
Ensure standardised symbols are used consistently throughout the schematic.	☐	☐	☐
Ensure that all external equipment within the design is detailed including terminations, location, and tag number.	☐	☐	☐
Confirm accurate representation of power sources with ratings and polarity clearly shown.	☐	☐	☐
Confirm that all external references (e.g., to related manuals, or standards) are valid and up to date.	☐	☐	☐
Confirm that part numbers or catalogue details are included where procurement information is necessary.	☐	☐	☐
Confirm that all components, IDs, connections, and wire numbers are present, clear, consistent.	☐	☐	☐
Confirm all components are correctly identified with unique reference designations.	☐	☐	☐
Calculate total power consumption and ensure panel supply meets or exceeds demand.	☐	☐	☐
Ensure compliance with applicable safety standards (e.g., BS EN 60204-1).	☐	☐	☐
Verify that the schematic is legible (appropriate font size, line thickness, scale, and spacing).	☐	☐	☐
DRAWING LAYOUT	**N/A**	**Designer**	**Reviewer**
Ensure the title block includes all required details	☐	☐	☐
Ensure the drawing follows an industry-standard logical flow (e.g., left-to-right, top-to-bottom).	☐	☐	☐
Verify proper sheet numbering and cross-references between sheets.	☐	☐	☐
Key included for symbols and wire colours, adhering to customer specifications.	☐	☐	☐
Group terminal blocks, junctions, and connectors logically.	☐	☐	☐
Ensure the layout is uncluttered, easy to navigate, and legible.	☐	☐	☐
PANEL LAYOUT AND MECHANICAL DESIGN	**N/A**	**Designer**	**Reviewer**
Choose the correct enclosure type based on environment, space, and form of separation.	☐	☐	☐
Heating and cooling components strategically arranged to ensure optimal performance.	☐	☐	☐
Components arranged for logical wiring and segregation of power/control circuits. *Include adequate trunking and correctly segregate IS, power, and control circuits.*	☐	☐	☐
Verify that dimensions and positions of mounting holes, brackets, and other hardware are clearly specified.	☐	☐	☐
Verify that labels correctly correspond to the intended components and equipment.	☐	☐	☐
VERIFICATION AND DOCUMENTATION	**N/A**	**Designer**	**Reviewer**
Ensure the revision history table is complete and accurate.	☐	☐	☐
Ensure the drawing aligns with the project's design intent, technical specifications, and customer requirements.	☐	☐	☐
Confirm that the drawing is ready for approval.	☐	☐	☐
Internal review and approval by a competent person within the workshop team. ***Ensure each revision is documented.***	☐	☐	☐
Develop a test procedure for validating panel functionality.	☐	☐	☐

Table 5 – Designers & Reviewer Checklist

Establishing structured communication protocols is essential to address miscommunication and ensure consistent, clear information sharing among team members. This improvement is justified because it will help minimise misinterpretations, errors, and the need for rework, ultimately improving overall workflow efficiency. A consistent meeting schedule has been introduced to facilitate discussions on critical areas such as design updates, production issues, and progress on ongoing quality initiatives. The meetings emphasise the importance of attendance and active participation, fostering accountability and collaboration across teams. By providing a regular platform for sharing information, addressing challenges, and aligning on priorities, communication gaps are reduced, and team cohesion is strengthened.

Dataset Following Improvements

The data collected is shown in Figure 8 which is inclusive of all the panels manufactured, descriptions, defect types, stages of failure, and quality costs. This dataset was taken following the improvements made. However, this data was collected over a 6-week period.

Job Number & Panel Number	Panel Description	Entry Date	Defect Type	Internal/ External	Stage of Failure	Total Material Cost of Rectification	Estimated Hours to Rectify	Total Quality Cost
24.IH.526-100	Tenby Saltern Sands Pump 1 Plate	11/11/2024						£0.00
24.IH.526-200	Tenby Saltern Sands Pump 2 Plate	11/11/2024						£0.00
24.IH.526-300	Tenby Saltern Sands Pump 3 Plate	11/11/2024						£0.00
24.IH.813-100	Condensate Return Panel 1	13/11/2024	Incorrect wiring	Internal	Manufacture		1	£23.00
24.IH.813-200	Condensate Return Panel 2	13/11/2024						£0.00
24.IH.1062-100	Rxi Upgrade Panel	04/12/2024	Wrong labelling	Internal	Manufacture		1	£23.00
24.IH.892-100	Ethanol Transfer Remote Panel	02/12/2024						£0.00
24.IH.894-100	Changeover Panel	10/12/2024						£0.00
24.IH.894-200	Temporary LV CB Panel	10/12/2024	Poor or wrong enclosure assembly	Internal	Design	£220.00	4	£312.00

Figure 8 - Improved Dataset

Again, the data is categorised and listed in order of frequency, from highest to lowest. This helps to show which defects are the most common following the improvements made so far. There was a total of 9 control panels that were monitored and logged with 3 of them being reported with defects, giving an overall percentage of 30% of all the panels manufactured during this period having at least one defect. Again, the cumulative frequency and percentage for each defect type is then calculated.

Defect Type	Frequency	Cumulative Frequency	Cumulative Percentage
Wrong labelling	1	1	33.33%
Incorrect wiring	1	2	50.00%
Poor or wrong enclosure assembly	1	3	100.00%
Loose connection	0	3	
Foreign objects inside panel	0	3	
Missing labelling	0	3	
Failed functional test	0	3	
Faulty components	0	3	
Wrong components installed	0	3	
Incorrect component specification	0	3	
Missing components	0	3	
Non-compliant with specification	0	3	
Improper component installation	0	3	

Table 6 - Improved Pareto Analysis Table

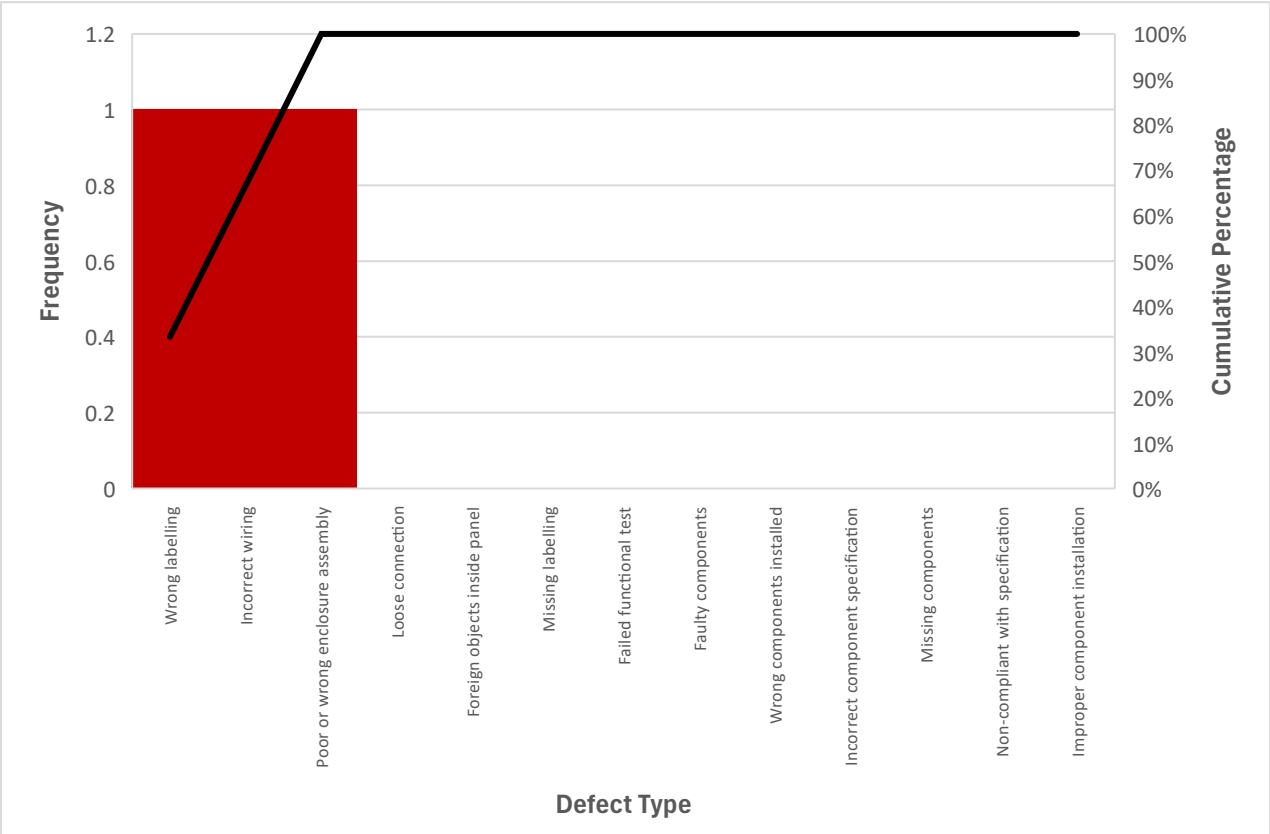

Figure 9 - Improved Pareto Chart

Based on the improved measured data, the new Sigma level can be calculated to see if there has been any improvement. The same equations are used for the Sigma level. The new number of units produced is 9, the number of defects found are 3, the opportunities per unit is 4. Using the same conversion table, a DPMO of 83,333 corresponds to a Sigma level of approximately 2.88. This indicates moderate performance but still room for improvement.

The initial data for the Pareto analysis, shown in Figure 6, was monitored over a six-month period. It identified significant defects impacting quality in the manufacturing process, with the majority of defects concentrated in a few key areas. "Missing labelling" (13 occurrences, 30.95%) and "Incorrect wiring" (8 occurrences, 50.00% cumulative) were the most frequent defects, contributing to half of all reported issues. These were followed by "Missing components" (6 occurrences, 64.29% cumulative) and "Loose connections" (3 occurrences, 71.43% cumulative), indicating areas for targeted quality improvement efforts. Other defects such as "Foreign objects inside panels" and "Wrong labelling" contributed minimally to the cumulative percentage.

After implementing process improvements, due to the analysis undertaken in the previous stage, a follow-up Pareto analysis, shown in Figure 9, was conducted over a six-week period. It revealed a significant reduction in the frequency and types of defects. The defects identified were limited to just three occurrences: "Wrong labelling," "Incorrect wiring," and "Poor or wrong enclosure assembly," each occurring only once. The improvements effectively eliminated the previously high-frequency defects, such as "Missing labelling" and "Incorrect wiring," which no longer appear as dominant issues. This reduction

in defect occurrences demonstrates the effectiveness of the corrective actions and quality initiatives, such as enhanced communication protocols, comprehensive defect logging, and structured quality meetings, in addressing the root causes and improving overall manufacturing quality within a shorter timeframe. The six-week timeframe in the improved dataset demonstrates rapid progress, highlighting the effectiveness of the implemented measures within a relatively short period. The focus on high-priority defects, such as "Missing labelling" and "Incorrect wiring," appears to have yielded significant results, validating the Pareto-driven approach. Addressing these defects first likely had a cascading effect, reducing related issues. The ability to maintain low defect occurrences during the short period suggests that key improvements were effectively implemented. However, further monitoring is required to ensure these improvements are embedded into routine operations and are not one-time interventions.

However, despite the improvements, three defect types still appear. Whilst these could be isolated incidents, their continued presence indicates that some residual process weaknesses remain, requiring further investigation and refinement. The elimination of defects across many categories may raise concerns about whether the dataset represents a complete and accurate record of issues. There is a possibility of underreporting due to time constraints, oversight, or over-reliance on temporary fixes which should be considered. It could also be due to the six-week period, which may not fully reflect long-term trends, variability in production, or the consistency of implemented changes. A longer observation period is necessary to validate the improvements and ensure sustained quality. Also, a large amount of time during the timeframe that the data was taken was spent working on a large project which is not yet manufactured or tested. More defects may have been recorded following the completion of this project.

The following is a brief summary of how the PDCA methodology was used in the Improve phase. During the Plan stage, the Pareto analysis ensured the focus was on the most frequent defects such as missing labelling, missing components, and loose connections, these were targeted for improvement. Integrating a quality check step with a detailed checklist, additional training for panel builders, and establishing a defect log system were planned and designed to ensure comprehensive coverage of potential issues. The Do stage, saw the implementation of new quality check inspections both for the design team and the manufacturing team requiring sign off, training sessions for panel builders to improve understanding of design documentation and reduce errors caused by misinterpretation as well as defect log systems and structured communication protocols were implemented, ensuring detailed tracking and reporting of issues. The Check phase followed up with another Pareto analysis which showed a significant reduction in defect occurrences. During the Act phase, adjustments were made to the process based on monitoring outcomes, such as ensuring bi-weekly quality meetings continued to address residual issues.

Control Phase

This phase will ensure that the improvements made during the improve phase are sustained over the long term to prevent regressions to the previous processes and ensuring consistent quality outcomes. To achieve this, a number of actions will need to be implanted to maintain and monitor the changes introduced.

The first control change which is essential is for the SOPs to be updated to reflect the new quality checks and design reviews. Periodic reviews of the SOPs and checklists will be undertaken to ensure the company is keeping up with changes in technology, customer requirements, and regulatory standards. The new "Request for test checklist" shown in Table 4, and the "Designer & Reviewer Checklist" shown in Table 5 is finalised and added into the company Integrated Management System (IMS). The IMS is a combination of multiple management systems such as quality, environmental, health and safety, asset management, and many more. These checklists are easily accessible for all teams through the company intranet. Along with the additional quality documents, the manufacturing flow chart is also updated from the original shown in Figure 3. The updated is shown in Figure 10, each of the processes and decisions from the flow chart which are highlighted in yellow have been updated to utilise the additional quality checklists, as well as ensuring now that all defects are logged. Following feedback from the team, an additional document will now be required with all control panels that require testing. The designer will need to generate a test procedure which details what is required during the functional test, whoever is functionally testing the panel will know exactly what the design was intended to do.

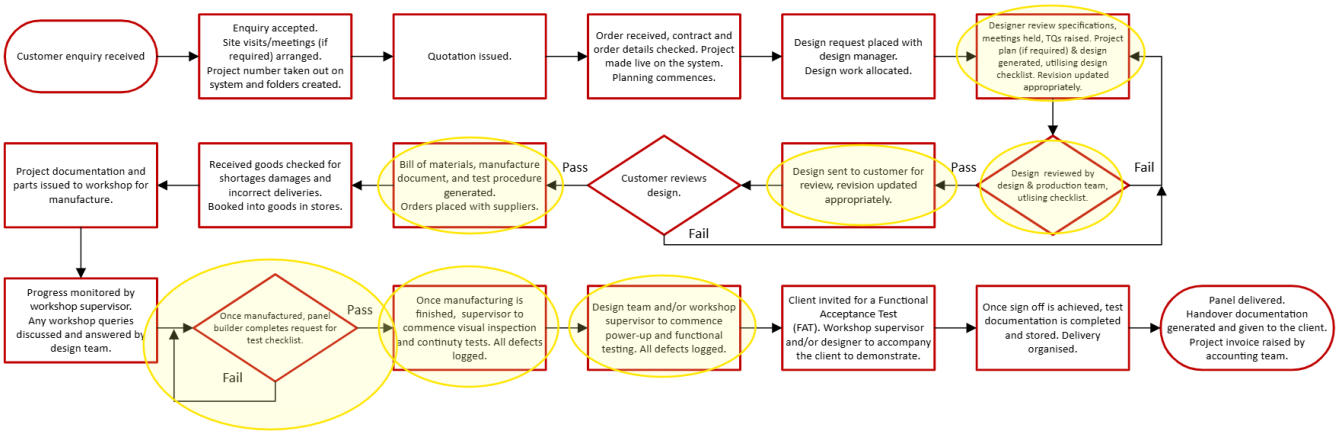

Figure 10 - Updated manufacturing flow chart

Another control change added is to hold employees accountable by designate process owners for key areas. For example, the design review will ideally be undertaken by the design manager, defect logging will be undertaken by the quality assurance lead but will require continual communication between the lead and the production and design teams. The individuals will be held responsible and accountable for each of these areas for maintaining adherence to the updated processes and to monitor outcomes. Another way to promote accountability is to ensure that all the quality checklists require employee sign off or defect resolutions to reinforce ownership of their work.

A further control is to monitor key metrics by defining and tracking key performance indicators. The tracked metrics include defect rates, recorded and completed checklist rates,

quality meeting attendance, and number of design revisions required for both internal review and customer review approvals. Trends will be monitored in recurring defects to identify early signs of process drifts. Trends on how many revisions of designs are required to achieve sign off will also give insight into if some designers may need additional training. These KPIs will be reviewed each month by the operations manager. Figure 11 is an example of a control chart to be used for the number of defects. This data is taken form the dataset shown in Figure 5, Table 7 is a breakdown showing the number of defects per month. From this, the average, shown in Equation 1 was calculated, along with the standard deviation, upper control limit and the lower control limit.

Month	Number of Defects
January	7.0
February	0.0
March	11.0
April	6.0
May	5.0
June	8.0
July	5.0

Table 7 - Number of defects per month

$$Average = \frac{Total\ number\ of\ defects}{Data\ set\ values}$$

Equation 4 - Average

$$Standard\ Deviation = \sqrt{\frac{\sum (X - X^{-})\,2}{(n-1)}}$$

Equation 5 - Standard Deviation

$$Upper\ Control\ Limit = \bar{x} + (3 * \sqrt{\bar{x}})$$

Equation 6 - Upper Control Limit

$$Lower\ Control\ Limit = \bar{x} - (3 * \sqrt{\bar{x}})$$

Equation 7 - Lower Control Limit

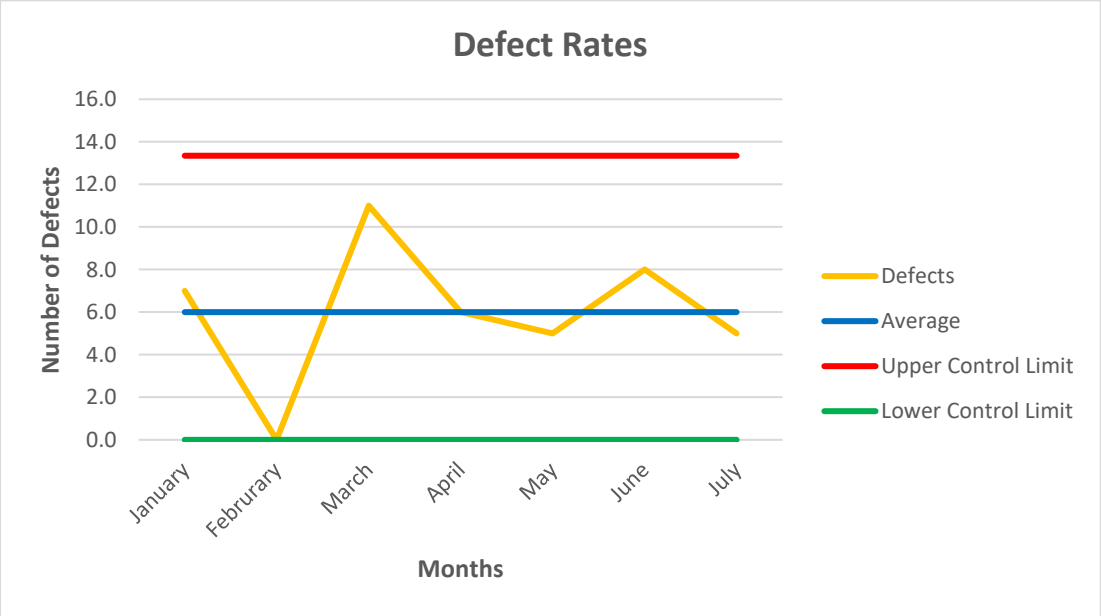

Figure 11 - Defect rates control chart

To ensure compliance to the changes, periodic audits will be conducted which includes random inspections of defect logs, design reviews, and assembly outputs to verify adherence to improvements. The bi-weekly quality meetings will be continued to review metrics, discuss any recurring issues, and refine the processes, as necessary.

Change Management

The PDCA cycle has been selected for implementing changes due to its simplicity, alignment with DMAIC, scalability for incremental change, resource efficiency, and continuous improvement mindset.

During the Plan Phase the problem was identified, a Pareto analysis is to be used to identify high-impact defect types with efforts focused on these areas to address root causes effectively. Interventions are to be designed to add a 5–10-minute inspection quality check by the panel builder as well as developing and formalising checklists (e.g., "Request for Test Checklist" and "Designer & Reviewer Checklist") to standardise procedures. Training is developed and scheduled for panel builders and designers to ensure accurate interpretation of design and quality documents. Structured communication protocols are established to facilitate information flow between teams. A comprehensive defect log system is planned to track defect types, frequency, and severity, ensuring proactive defect management.

The Do Phase focused on implantation and execution of the improvement actions planned with the introduction of the new quality checks, defect logging processes, and structured communication protocols. Deploying the “Request for Test Checklist” and “Designer & Reviewer Checklist” across teams standardises quality checks and ensure consistency. Bi-weekly quality meetings formalised with stakeholders from workshops, quality control, and design teams to review defect data and drive accountability. Training undertaken with teams on conducting structured design reviews, including peer evaluations, and ensure consistency in compliance with regulatory and customer requirements.

During the Check phase, data collection saw the monitoring of defects over defined periods of six months before improvements, six weeks after implementation. Pareto analysis on post-implementation data evaluated the effectiveness of corrective actions with a comparison of defect types and rates before and after improvements to assess impact.

Finally, the Act phase led to updating SOPs and integrating new checklists into the company’s IMS, ensuring accessibility and adherence across teams. Designation of process owners for key areas (e.g., design review by design manager, defect logging by quality assurance lead), reinforcing ownership with required signoffs on quality documents. The use of KPIs tracks long-term performance as well as periodic audits and random inspections to ensure adherence to changes. Bi-weekly quality meetings are continued to discuss unresolved issues, refine processes, and communicate lessons learned to address any emerging trends or process deviations promptly.

Conclusion

This report outlines a comprehensive approach to improving the current integrated management system by adding value to the quality process in the control panel manufacturing section of the company. By applying the DMAIC framework, a structured path was followed which aided in identifying the root causes of defects, the implementation of targeted improvements, and ensured the sustainability of these changes over the long term to prevent regress. The report's findings and the improvements made have demonstrated the significant progress toward achieving higher quality standards, greater operational efficiency, and enhanced stakeholder engagement, which all adds to the company reputation and profitability.

The project charter provided a clear framework, aligning problem identification, solution implementation, and outcome evaluation to ensure focused and impactful efforts. The problem statement highlighted challenges in managing high variability and ineffective traditional quality controls. The goal statement set a target of reducing defect rates by 25%, full evaluation will require long term monitoring, however significant progress has been achieved with updated SOPs, enhanced controls, and measurable quality improvements. The business case emphasised the financial and reputational benefits of defect reduction. This project mitigated risks by implementing targeted solutions, improving efficiency, reducing rework, and will enhance customer satisfaction. The scope statement ensured that improvements focused on production processes, with tools like SIPOC, CTQ, and FMEA enabling systematic and feasible enhancements. Key milestones across DMAIC phases were completed successfully.

The overall aim of the project set out at the beginning was achieved as improvements were implemented, which led to a measurable reduction in defects. Again, all objectives were achieved. Objective 1 as an evaluation of the process was conducted using SIPOC and CTQ tools, ensuring clarity of customer needs and team understanding of quality expectations. Objective 2 by data on defect rates and types systematically collected and analysed. Financial impacts were considered in the business case, emphasising cost reductions through defect minimisation. Objective 3 by completing RCA using FMEA to identify key defect drivers to guide targeted improvements. Objective 4 by developing and implementing targeted strategies such as the new quality checklists and defect tracking. Objective 5 by implementing and monitoring process improvements. Objective 6 by ongoing monitoring and control charts being established to track progress. Objective 7 by updating SOPs, control charts, and accountability measures being implemented to ensure sustainability.

In the Define phase, the critical issues which are affecting product quality were identified, with a focus on high frequency defects such as missing labelling, incorrect wiring, and poor assembly. These defects were found to be recurring and impactful, making it essential that immediate action is taken to rectify them. Engaging key stakeholders, including the quality control, production, and design teams, from the outset helped ensure that all parties were aligned in the shared goal of reducing defect and improving product quality. Their support and involvement were vital in both the identification of issues and the implementation of solutions, encouraging buy-in and promoting a sense of ownership over the process.

During the Measure phase, data collection and analysis revealed key areas for intervention. The introduction of a system to log each defect allowed for a structured approach to identify, categorise, and track defects. A detailed Pareto analysis was conducted, confirming that a significant portion of defects could be attributed to a few key issues. This data-driven approach helped prioritise interventions that would have the most immediate and significant impact on reducing defects.

The Analyse phase enabled a deeper understanding of the root causes of defects, such as inconsistencies in design generation and reviews, inadequate quality checks, and communication issues between departments. Tools such as the 5 Whys and FMEA aided and facilitated a thorough investigation of underlying process weaknesses. This analysis highlighted the need for standardised procedures, improved cross department communication, and enhanced training for employees involved within the design and assembly processes.

In the Improve phase, several key actions were taken to address the identified issues from the analysis phase. These included the development and implementation of comprehensive checklists for the designer during design generation which followed through into the design reviews, mentioned previously as the “Designer & Reviewer Checklist.” As well as an additional checklist following the assembly process, mentioned previously as the “Request for Test Checklist.” These tools ensured that critical design aspects and quality checks were systematically addressed, reducing errors and increasing consistency in the finishing control panels. Additionally, a more robust defect tracking and feedback system was established, including bi-weekly quality meetings to foster collaboration and continuous improvement. The changes made during this phase led to a reduction in defects within a short period, demonstrating the effectiveness of the interventions.

The Control phase outlined the strategies necessary to maintain and monitor these improvements over the long term to prevent regress. Key measures, such as the integration of updated checklists and processes into the company’s IMS, were implemented to ensure the consistency of the changes. Process owners were designated to maintain accountability, ensuring that specific areas, such as design reviews and defect logging, continued to adhere to the updated quality standards. The introduction of KPIs allowed for ongoing monitoring of critical metrics, such as defect rates, the number of completed checklists, and the number of internal and external design revisions. Control charts, such as the one for defect rates shown in Figure 11, were put in place to track trends over time which will enable early identification of any process drifts. Periodic audits and random inspections are introduced to further ensure compliance with the updated processes, while the continued engagement of key stakeholders in bi-weekly meetings provides a platform for addressing any emerging or ongoing issues.

Despite the significant improvements, there are challenges that still remain, which indicates that further monitoring is required. Although the defect rates have substantially reduced following the improvements made, the persistence of specific defects, such as incorrect wiring and enclosure assembly indicates that residual process weaknesses may still exist. These lingering issues may reflect areas where further refinement is needed or where additional training could be beneficial. However, these could be isolated events which are difficult to prevent even with further measures in place. Moreover, whilst the six-week monitoring period showed promising results, longer term observation is essential to validate

whether these improvements are in fact sustainable over time and to confirm that new defects do not arise.

It is vital to highlight the potential limitations to help identify areas for future refinement. The data reliability and completeness are the first to mention as the accuracy of the conclusions drawn is heavily dependent on the reliability and completeness of the data collected during the Measure phase. If defect logs were inconsistently maintained or if the data was incomplete, it might have led to underestimation or overestimation of the problems scale. The interventions, such as the updated checklists and enhanced review processes are tailored to the manufacturing department, there solutions may not be applicable in other departments. Despite process improvements and assigning accountability, achieving consistent adoption of the changes by the employees can be challenging. The effectiveness of the changes can be limited by the employee's resistance to change, their varying levels of engagement and differing skill levels. Current resources are in place to maintain the changes, however if there was a constraint in areas such as resource, time, or financial, it could hinder the full realisation of the project's benefits. Another limitation is the department could become over reliant on checklists. Whilst they improve consistency, employees may end up completing them as a formality without fully engaging with the intent behind each item, limiting its effectiveness. Finally, despite control measures being put in place, processes may drift over time due to unforeseen challenges, such as staff turnover, or changing customer requirements. These changes could introduce new quality risks that were not anticipated during the project.

In conclusion, the process improvements, led by the DMAIC approach, has proven to be instrumental to notable gains in quality and efficiency, with defects being reduced and overall operational performance improving. Each phase provided clear deliverables and insights which ensured that interventions were well targeted and impactful. By embedding the principles of DMAIC into the organisation moving forward, the company is better positioned to maintain high quality standards, to respond effectively to new challenges, and to foster a culture of ongoing innovation and excellence. The success of this project lies in the systematic application of quality improvement tools, the active involvement of key stakeholders, and the establishment of robust processes and metrics for ongoing monitoring and control. However, continued focus on monitoring, training, and refinement will be critical to maintaining these improvements and further enhancing the processes, and the quality of the control panels. This project has not only resulted in immediate benefits but has also set the foundation for a culture of continuous improvement and quality excellence that will support long term success.

Recommendations for Future Work

The improvements implemented during this project have laid a strong foundation for enhanced quality management and operational efficiency. However, as with any dynamic system, continuous refinement and proactive measures are essential to sustain and build upon these gains. This section outlines recommendations for future work, focusing on addressing identified limitations, leveraging emerging opportunities, and ensuring the long-term success of the initiatives undertaken.

To improve the robustness of the insights derived during the project, future work should prioritise the introduction of an automated system to collect real time data of defects, and other process elements. OCU Group have also acquired Insiris, they are a leader in workforce management and automation software. Insiris could aid in developing software to automate the process. This would reduce the likelihood of errors and inconsistencies in data entry. The system can use predictive analytics to identify patterns and trends in defect rates and quality issues. This will help to anticipate process drifts before they become severe. Data from suppliers and customers should be included, supplier quality and the view of the customer, this will help gain a holistic view of factors influencing quality outcomes. However, there would be high initial costs associated with the development, maintenance, and implementation for software development hardware acquisition but also additional training for employees.

Another critical recommendation to sustain improvements is investing in the workforce by developing a comprehensive training program which is focused on quality management principles, to identify defects and resolve them using different techniques. To start this process a skill gap analysis can be conducted regularly to identify areas where employees may require additional support or training, particularly in design and review processes. This will ensure that a culture of ownership and accountability is fostered where employees are rewarded and recognised for their contributions to maintaining standards. However, to implement this there could be resource constraints, developing and implementing a comprehensive training program will require significant financial, time, and human resources. The program will be at risk of becoming outdated without continual updates to training materials and the program.

A recommendation for future work could lie in the exploration of innovations and technology such as the use of digital simulations to test and refine manufacturing processes before implementation. Internet of Things (IoT) enabled sensors could be integrated into the manufacturing, for example using machine to allow for more accurate cutting, drilling, and assembly, or IoT enabled torque wrenches to log tightening data for quality assurance. Artificial intelligence (AI) can be explored to see what AI-driven tools for defect detection, predictive maintenance, and quality assurance. However, the implementation of technologies such as AI systems or IoT-enabled sensors will involve significant costs for hardware, software and training. The integration into the existing manufacturing processes can be complex and time-consuming, particularly if legacy systems are still in use. There may also be a possibility of data security or privacy concerns as AI systems often rely on extensive data collection. The return on investment may be uncertain, a further analysis would be required before implementing these systems.

Broader cultural and organisational initiatives is another recommendation, leveraging the position as an operations manager a mindset that prioritises quality at all organisational levels can be promoted. Ensuring that leadership is actively engaged in and visibly supportive of quality initiatives whilst also fostering collaboration between departments and ensuring a shared ownership of the outcomes. However, as the improvements are rolled out across the organisation there would be more resistance to change. There may also be inconsistencies in support from leadership across all levels as some managers may prioritise other metrics such as cost or speed over quality.

Focusing on each defect in more detail moving forward as well as addressing residual defects is another recommendation for future work. By analysing defects comprehensively, it can be pinpointed to specific issues, then targeted corrective actions can be implemented, and it can uncover specific training needs to address skill gaps. This approach also enables better resource allocation, supports data driven decision making, and will ultimately enhance customer satisfaction by improving product reliability. However, the approach is not without limitations as detailed defect analysis can be time consuming and resource intensive which can lead to production delays and lower profit margins, striking the correct balance would be essential. Not all defects have a significant impact on quality, overanalysing minor issues might divert attention from more critical problems. The cost and effort of investigating certain defects may outweigh the benefits of resolving them. Employees may feel burdened overtime, especially if it leads to additional tasks or stricter oversight which can result in decreased morale.

By addressing these areas, future efforts can build on the successes of this project and further embed a culture of excellence within the organisation, providing a roadmap for sustained improvement.

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