ENHANCING QUALITY MANAGEMENT THROUGH SEMI-AUTOMATION AND DIGITAL INTEGRATION FOR SOLAR ENERGY SOLUTIONS

by

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DECLARATION

I, Robyn Cornelius, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed RCornelius **Date** 20 November 2025

ABSTRACT

This study investigates how semi-automation and digital integration can strengthen quality management within a start-up battery manufacturing environment producing lithium-ion battery packs for solar energy systems. Start-up manufacturers often rely heavily on manual processes, which increases variability, defect risk, and inefficiencies. The research therefore examines whether introducing semi-automated welding and digital integration tools can meaningfully improve product quality, process consistency, and operational efficiency.

A mixed-methods design was adopted, combining quantitative production data from torqued (manual) and welded (semi-automated) assembly lines with qualitative insights from audit reports, observation logs, and internal quality documentation. The quantitative findings show that semi-automation significantly enhanced process stability. Although welded packs recorded more defects in absolute numbers, they represented far lower defect rates when normalised to output. Variability in electrical performance decreased markedly, with statistically significant improvements across discharge, charge, and final-charge voltage stages. Real-time monitoring data further indicated narrow voltage spreads and low internal-resistance variation, demonstrating equipment stability and consistent weld integrity.

Operational efficiency also improved. First Pass Yield for welded packs stabilised close to 100%, while the manual line continued to fluctuate. Throughput on the welded line exceeded 350 packs per month compared to fewer than 100 on the manual line. Time-study results confirmed an overall 14% reduction in assembly time, with the greatest savings achieved in joining stages where laser welding replaced labour-intensive manual operations. Although scrap costs were initially higher for welded packs due to early learning-curve defects, machine-driven faults were more systematic and easier to eliminate than persistent human-error variation.

Qualitative findings supported these results by highlighting how semi-automation reduced reliance on operator skill, improved traceability, and strengthened process control in a context where documentation consistency, training gaps, and fragmented data previously hindered quality performance.

Overall, the study demonstrates that semi-automation and digital integration substantially enhance quality management in start-up battery assembly environments. Improvements in process stability, defect predictability, throughput, and real-time monitoring show that even under resource constraints, digital and semi-automated systems offer a practical and scalable pathway toward higher quality and operational excellence.

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GLOSSARY

Terms/Acronyms/Abbreviations	**Definition/Explanation**
Assembly Method – Torqued	Manual joining method using torque tools to join busbars to cell terminals.
Assembly Method – Welded	Semi-automated laser-welding joining method to join busbars to cell terminals.
ATP	Acceptance Test Procedure
CAPA	Corrective and Preventive Action
FPY	First Pass Yield
Inline Monitoring	Real-time monitoring of voltage & IR during production
Internal Resistance (IR)	Electrical resistance within the battery.
Laser Welding	Precision joining technique used in semi-automation.
LCL / UCL	Lower / Upper Control Limits.
Millivolt Spread (mV Spread)	Difference between highest and lowest cell voltage.
mV	Millivolt (cell voltage difference)
Pp / Ppk	Process Performance Indices
Process Capability	Statistical measure of process performance (Cp/Cpk)
Process Variation	Inconsistencies in output between manual and welded processes.
QC	Quality Control
QMS	Quality Management System
RCA	Root Cause Analysis
Rework	Products requiring correction or repeat testing during production.
Scrap Cost	Cost associated with failed or defective packs.
Semi-Automation	Combination of human operations, oversight and automated welding.
SPC	Statistical Process Control
Temperature Stability / Thermal Behaviour	Temperature performance across charge/discharge cycles.
Temperature Uniformity	Consistency of temperature across a pack.
Traceability	Tracking components, defects, and production flow.
Voltage Stability	Stability across discharge, charge, and final charge cycles.

CHAPTER ONE: SCOPE OF THE STUDY

1.1 Introduction

The fast-growing renewable energy sector has brought a strong focus on building efficient solar energy systems. The battery packs are at the heart of these systems. The way these batteries are assembled has a direct impact on how well the system performs and how long it lasts. Start-up companies in this sector, often constrained by limited resources and under pressure to maintain a competitive edge, face particular challenges in ensuring the quality of their products. This study, titled "Enhancing Quality Management through Semi-Automation and Digital Integration in Battery Assembly Lines for Solar Energy Solutions at a Start-up Company," addresses the important issues surrounding quality management in this niche. The research has explored the impact of semi-automation and digital integration on quality management in battery assembly lines, with a focus on start-up environments.

1.2 Background of the Study

The rapid expansion of the renewable energy sector, particularly solar energy, has intensified the demand for high-performance and reliable energy storage solutions. Batteries play a critical role in solar energy systems by storing excess energy generated during peak sunlight hours and supplying it during periods of low or no sunlight. This function highlights how crucial quality management is in battery assembly, since the performance and lifespan of these batteries directly influence the efficiency and reliability of solar energy systems (Aneke & Wang, 2016).

Traditional battery assembly lines often rely heavily on manual inspection and quality control procedures, which introduce a high risk of human error and inconsistency. This not only affects product reliability but also slows production and adds rework costs. Human reliability studies by Torres *et al.* (2021) confirm that tasks such as bracket fastening and cable routing are particularly vulnerable to errors, and that improving inspection methods and worker feedback can significantly reduce variability. In a start-up company, where resources are typically limited, the need for efficient and reliable quality management processes is even more pronounced. Therefore, integrating semi-automation and digital technologies into battery assembly lines presents a promising solution to overcome these challenges. Semi-automation involves using automated systems for repetitive and precision tasks, while still allowing human oversight, thereby reducing errors and improving consistency (Kang *et al.*, 2016).It is expected that semi-automation will effectively resolve problems associated with human error and inefficiencies in processes.

Digital integration, including the use of the IoT, machine learning, and data analytics, further improves quality management by enabling real-time monitoring, predictive maintenance, and data-driven decision-making (Lee *et al.*, 2015). It is anticipated that these technologies will enable the development of more robust and efficient quality management systems that support real-time monitoring and predictive maintenance. Moreover, modern data-driven technologies can aggregate and analyse large volumes of production and sensor data in near real-time, enabling manufacturers to detect anomalies before defects manifest and proactively optimise production. For start-up companies in rapidly evolving sectors, these capabilities provide a competitive advantage by enhancing product quality, lowering costs, and boosting operational efficiency (Bag *et al.*, 2020).

Based on the above considerations, it is vital for this study to explore the implementation of semi-automation and digital integration in battery assembly lines, with a particular focus on their impact on quality management within a start-up manufacturing environment.

1.3 Problem Statement

The increasing demand for renewable energy solutions has placed solar energy at the forefront of sustainable power generation. Central to the efficiency and reliability of solar energy systems is the quality of battery packs used for energy storage. In start-up companies, where resource constraints and competitive pressures are significant, maintaining high standards of quality management in battery assembly lines is crucial (Schlemitz & Mezhuyev, 2024).Traditional quality control processes in battery manufacturing, which rely heavily on manual inspection and testing, are prone to human error, inefficiencies, and inconsistencies, leading to potential defects, safety risks, and increased production cost (Wang *et al.*, 2019).

The adoption of semi-automation and digital integration technologies presents a promising solution to these challenges. Semi-automation can enhance precision and consistency in battery assembly by automating repetitive and precision tasks, thereby reducing human error (Calvo & Gil, 2022).Meanwhile, digital technologies such as the IoT, machine learning, and data analytics enable RTM and predictive maintenance, facilitating more efficient and reliable quality management processes (Lee *et al.*, 2015). However, the implementation of these technologies in start-up environments poses unique challenges, including high initial investment costs, the need for technical expertise, and integration with existing manufacturing systems (Wang *et al.*, 2022). Furthermore, despite the potential benefits, there is a lack of comprehensive studies addressing the specific impact of semi-automation and digital integration on quality management in battery assembly lines within start-up companies. This gap in the literature highlights the need for empirical studies to assess how these technologies contribute to improving product quality, lowering operational costs, and boosting production efficiency, particularly within start-up environments. Addressing this gap will provide valuable insights for start-up companies in the renewable energy sector, helping them to adopt advanced manufacturing technologies to remain competitive and sustainable.

1.4 Research Rationale and Significance

The renewable energy sector in South Africa is expanding rapidly as the country seeks to reduce its reliance on non-renewable sources and align with global sustainability goals. Studies show that solar and wind energy are key drivers in achieving a low-carbon energy future for Southern Africa, with the potential to meet 100% of electricity demand by 2050 (Wu *et al.*, 2024)However, the pace of progress has been uneven. Regulatory challenges, skills shortages, and inconsistent policy implementation continue to slow the growth of renewable energy manufacturing and limit its contribution to industrial development (Ukoba *et al.*, 2025 ; Oladejo *et al.*, 2025).

Within this context, manufacturing start-ups in the renewable energy space face unique challenges. Many operate under tight resource constraints and must balance rapid production demands with maintaining quality and reliability. The local supply chain also presents ongoing risks, with long lead times, import dependency, and logistical inefficiencies affecting production stability and cost control (Tshifhumulo *et al.*, 2025). These realities make it difficult for emerging companies to implement structured quality systems while adapting to the demands of a growing and increasingly technology-driven market.

This study is important because it examines how quality management can be effectively built into such start-up environments - where semi-automation, digital monitoring, and human input still coexist. It addresses an academic gap by exploring how Quality Management Systems can be integrated into semi-automated contexts, bridging the divide between manual and fully automated production. The study also offers practical insights for industry, showing how data, process feedback, and real-time monitoring can improve consistency and efficiency even when resources are limited.

Beyond its technical and operational focus, the research contributes to South Africa's broader renewable energy agenda by highlighting the everyday realities faced by local manufacturers. The findings aim to support both policy and practice - helping strengthen localisation, promote quality-driven innovation, and guide future strategies for sustainable manufacturing in developing economies.

1.5 Research Aim and Objectives

The aim of this study is to investigate the impact of semi-automation and digital integration on quality management in battery assembly lines for solar energy solutions. This investigation seeks to understand how emerging technologies can enhance quality performance, operational efficiency, and sustainability within the context of a start-up in the renewable energy sector.

To achieve this aim, the study is guided by the following specific objectives to:

i. establish the essential components of an effective QMS for a start-up in the energy sector.
ii. determine the effect of semi-automation on product quality and production efficiency in battery assembly lines.
iii. determine the effectiveness of real-time monitoring in the early detection and resolution of quality issues.
iv. develop strategies for integrating and automating quality processes, and to assess their anticipated impacts on the company's operations.

1.6 Research Questions

The primary research question of this study is the following:
How is quality management enhanced through semi-automation and digital integration?

To answer the primary research question, the following investigative research questions were formulated:

i. What are the essential components of an effective QMS for a start up in the energy sector?
ii. How does semi-automation of the battery assembly line affect product quality and production efficiency?
iii. How effective is real-time monitoring in the early detection and resolution of quality issues?
iv. What strategies can be employed to integrate and automate quality processes, and what are their anticipated impacts on the company's operations?

1.7 Delimitations and Limitations of the Study

While this study aims to generate insights into the intersection of semi-automation, digital integration, and quality management within a start-up manufacturing context, certain limitations and delimitations must be acknowledged. These boundaries define the scope of the investigation, shape the interpretation of results, and inform the extent to which conclusions may be generalised.

1.7.1 Delimitations

To ensure focus and feasibility, this study has been deliberately delimited in scope. These delimitations establish the boundaries of inquiry and define what is intentionally excluded from the research to maintain conceptual and methodological clarity.

- Product Design Analysis: While battery design plays a critical role in performance and reliability, this research does not focus on evaluating or optimising design modifications. Instead, it examines how semi-automation and digital integration impact manufacturing quality within existing design variations.
- Industry Scope: The research is limited to the manufacturing of battery packs for solar energy applications and does not extend to other energy storage systems or industries.
- Quality Metrics: The study assesses quality based on defect rates, rework occurrences, and efficiency improvements but does not include lifecycle performance testing or reliability assessments beyond manufacturing.
- Implementation Scale: The research focuses on semi-automation and digital integration within a single manufacturing facility, and findings may not be directly applicable to other facilities with different operational structures.

1.7.2 Limitations

The following limitations highlight potential challenges and contextual constraints that may influence the study’s outcomes and interpretation:

- Generalisability: The findings of this study may be context-specific and may not be generalizable to all manufacturing sectors. Variations in industry practices, organisational cultures, and regulatory environments may limit the applicability of the findings beyond the study context (Trydegård & Blide, 2020)
- Potential for Measurement Error: Despite efforts to develop valid and reliable measurement instruments, there is a risk of measurement error inherent in real-time data collection and qualitative interpretation. Variability in data

interpretation, especially when using semi-automated or operator-driven systems, may introduce inaccuracies (Christler *et al.*, 2020).

- Financial Constraints: Funding limitations typical of start-ups may restrict access to advanced technologies and automation tools, potentially limiting the extent of digital integration and process optimisation (Duffner *et al.*, 2021).
- Lack of Processes and Systems: The absence of standardised procedures in young companies can hinder the implementation and evaluation of formal quality management systems (Löfgren, 2012)
- Workforce: Human resource challenges, including limited expertise in automation and quality management systems, can pose significant barriers to technological adoption in start-ups (Sudha & Kolla, 2016)
- Changing Environment: The dynamic and evolving nature of the start-up ecosystem and the solar energy industry may shift organisational priorities and affect the continuity of quality initiatives (Patat & Jayaprakash, 2018)
- Data Availability: Start-ups may lack extensive historical data for analysis, making them reliant on real-time and short-term data streams, which may impact the depth and reliability of quality insights (Stock *et al.*, 2021)

This research will be conducted at a manufacturing plant located in the Western Cape specializing in battery production and system integration assembly.

1.8 Research Assumptions

In conducting this research, several assumptions are made to facilitate data interpretation and methodological consistency. These assumptions form the basis for the research design and analysis, though any deviation from them could affect the study’s validity.

- Process Consistency: It is assumed that the semi-automated processes under study remain consistent throughout the data collection period, with no major changes in operational procedures.
- Data Accuracy: The research assumes that the historical production and quality data used for analysis are accurate and reflective of actual manufacturing conditions.
- Equipment Functionality: It is assumed that all digital integration tools and monitoring systems used in the study function correctly and provide reliable data.

1.9 Research Design and Methodology

Research methodology refers to the systematic approach used to solve a research problem. It involves understanding the scientific methods and logic behind how research is conducted. Within this, the research design serves as a blueprint, outlining how data will be collected, measured, and analysed to ensure relevance to the research purpose while maintaining practicality. It defines the overall structure of the study - from framing the hypothesis to final data analysis (Kothari C.R., 2004, pp. 8, 31).

The proposed research has adopted a mixed methods approach to investigate the enhancement of quality management in manufacturing through semi-automation and digital integration. This approach allows for the integration of both quantitative and qualitative data, providing a comprehensive understanding of the research problem (Guetterman *et al.*, 2023).

Adopting a mixed methods approach for this study allows for a thorough investigation of the enhancement of quality management in manufacturing through semi-automation and digital integration. By leveraging both quantitative and qualitative data, the research can provide a comprehensive, validated, and contextually rich understanding of the impact and effectiveness of these technological advancements.

Data collection was carried out using direct observations, document analysis and production data. Observations was conducted on-site to understand the existing workflows, identify bottlenecks, and assess the current state of quality management practices. Additionally, company documents such as quality reports, production logs, and maintenance records were analysed to gather quantitative data on performance metrics and quality control issues. This triangulation of data sources will ensure a robust and comprehensive data set for analysis (Yin, 2018).

1.10 Ethical Considerations

The study followed ethical considerations by obtaining a letter of permission from the company where the study was conducted, confirming that all research activities were authorised. The identity of the organisation will remain anonymous, and all information provided will be treated with strict confidentiality. Data collected during the study will be securely stored on a password-protected computer, accessible only to authorised personnel. The information will be used solely for the purposes of this research and will not be shared or applied elsewhere without explicit consent. All findings will be reported transparently and accurately to maintain the integrity and credibility of the research process.

1.11 Organisation of the Thesis

- Chapter 1: Scope of the study

  This chapter outlined the extent of the research endeavour. It elucidated the core research problems, which form the foundation of the study, and establish the context for the research. The chapter delved into the research questions, objectives, methodology, and design, providing a comprehensive overview of the research process. Additionally, it discussed the underlying assumptions and the significance of the research. Essentially providing an overview of the thesis structure.

- Chapter 2: Holistic overview of the research environment

  This chapter aimed to offer readers a glimpse into the research context by outlining the location where the study took place and explained the reasons for choosing this setting for the research undertaking.

- Chapter 3: Literature review

  In this chapter, a comprehensive review of the academic literature relevant to the research study was undertaken to provide a solid foundation for the investigation. Furthermore, the literature review offered an academic framework for the unique aspects that addressed the research problem.

- Chapter 4: Research Methodology

  The Research Methodology chapter provided a comprehensive overview of the approach employed in the study. It began with an explanation of the chosen research paradigm and justified its selection based on the research questions and objectives. The chapter outlined the research design and rationalised its suitability for the study's goals. It then delved into the data collection methods, sampling strategy, and data analysis techniques, and elucidated their alignment with the research objectives. Ethical considerations as well as limitations of the methodology was discussed.

- Chapter 5: Data Analysis and Discussion

  The data analysis and discussion chapter offered a comprehensive exploration of the findings obtained through the collected data. It began with an overview of the data analysis techniques employed and the results thereof. The chapter presented the findings and related them back to the research questions and objectives. Furthermore, the implications of the findings was discussed. Any unexpected or contradictory results was addressed, and possible explanations provided. Finally, the chapter provided a discussion that integrated the findings with relevant theoretical frameworks, drew conclusions and offered recommendations for future research.

- Chapter 6: Recommendations and Conclusion

  The recommendations and conclusion chapter offered insights derived from the study's findings and provided guidance for future research or practical applications. It began with a synthesis of the important findings, the chapter highlighted significant patterns, trends, or implications observed in the data. Furthermore, the chapter reflected on the study's contributions to the existing literature and its implications for theory or practice. The chapter concluded with a summary of the study's significance, reaffirming its importance and potential impact on the field, and offered closing remarks to encapsulate the research journey.

1.12 Summary of the Chapter

This chapter of the research provided an introduction and overview of enhancing quality management systems through semi-automation and digital integration. The chapter also detailed the research problem, which forms the heart of the research study, and laid the way for the research. Aspects pertaining to the research process, investigative questions, research objectives, research design and methodology, assumptions and significance of the research, were also elaborated upon. The next chapter will provide further information and expand on the relevant areas to clearly state the context, environment and background to the research problem statement.

CHAPTER TWO: HOLISTIC OVERVIEW OF THE RESEARCH ENVIRONMENT

2.1 Introduction

This chapter discusses the research environment and provides further context on the research setting. This chapter provides an overview of the company and explains why the study is taking place at this company.

2.2 Research Location

The research was conducted at a start-up company in the Western Cape, South Africa, specialising in the production and assembly of battery packs for solar energy solutions. The Western Cape is a hub for renewable energy initiatives, with both government and private sector investments aimed at reducing reliance on non-renewable resources (the Western Cape captures 70 % of the country's renewable energy component manufacturing - a central role in South Africa's clean-tech industry) (Western Cape Government, 2025).

2.3 Company Profile

The company, while still in its infancy, is making strides in the solar energy sector, specifically in producing high-quality batteries used for energy storage in solar systems. The battery packs manufactured by this company are critical to the functionality of solar energy systems, as they store energy generated during peak sunlight hours for use during periods when sunlight is insufficient. The quality and reliability of these batteries directly affect the efficiency and sustainability of solar installations, making quality management in this context a matter of utmost importance.

Being a start-up, the company operates with limited resources, both in terms of finances and personnel. Like many young enterprises, it faces challenges such as limited production capacity, competitive market pressures, and the need to maintain high standards of quality. The company's approach to quality management is crucial for its long-term success and competitiveness in a market where reliability and product longevity are primary factors.

2.4 The Manufacturing Process: Challenges and Opportunities

The company's manufacturing process is a focal point of this research, as it directly relates to the quality management issues that the study aims to address. The battery assembly process was largely manual, with human workers responsible for critical quality control stages. These manual processes, while cost-effective in the short term, are prone to human error, which can result in inconsistencies in product quality, increased production costs, and a higher likelihood of defects.

The company has four different production lines which focuses on different assembly processes. All these lines are mostly manual driven. The battery assembly line is the first of its kind at the company for semi-automation and digital integration.

2.4.1 Manual Processes and Human Error

At present, the quality control process within the company involves a series of inspections at various stages of the battery assembly line. Workers are tasked with visually inspecting components, testing battery performance, and identifying any defects before the products are packaged for distribution. While these manual inspections are standard practice in many start-up manufacturing environments, they present several challenges.

Human error is one of the primary concerns associated with manual quality control processes. Studies have shown that manual inspections, no matter how thorough, are limited by the cognitive and physical capacities of workers. Fatigue, distractions, and varying levels of experience among workers can all contribute to errors during the inspection process, leading to defects that may not be caught before the product reaches the customer (Löfgren, 2012). In a highly competitive market such as renewable energy, these errors can damage a company’s reputation and erode customer trust.

Furthermore, the reliance on human inspectors can lead to inconsistencies in quality management (Kang *et al.*, 2018). Even when following standardised procedures, different workers may interpret guidelines or inspection criteria in varying ways, leading to variations in product quality. This is particularly problematic in battery production, where even minor defects can lead to significant performance issues or safety concerns, such as overheating or short-circuiting (Du *et al.*, 2024; Zhao *et al.*, 2024).

2.4.2 The Need for Semi-Automation and digitalisation

To address these challenges, the company is exploring the potential of semi-automation in its battery assembly line. Semi-automation refers to the integration of automated systems to perform repetitive and precision-based tasks, while still allowing human workers to oversee and manage the process (Langer & Söffker, 2015; Christler *et al.*, 2020). This hybrid approach is particularly suitable for start-ups, as it balances the need for improved precision and efficiency with the flexibility that small-scale operations require (Tejaningrum, 2022).

Semi-automation offers several benefits for quality management. Automated systems can perform inspections with a higher degree of accuracy and consistency than human workers, thereby reducing the likelihood of defects (Christler *et al.*, 2020; Kahveci *et al.*, 2022). Moreover, automated systems are less prone to fatigue and can operate continuously without the need for breaks, increasing overall production efficiency (Burdo & Bolotov, 2024).

For a start-up like the one in this study, semi-automation provides a cost-effective solution to scaling production while maintaining high standards of quality. It allows the company to gradually automate crucial aspects of the assembly line without requiring a full-scale investment in automation technology, which may be beyond the company's current financial capacity (Tejaningrum, 2022).

2.4.3 The Role of Digital Integration

In addition to semi-automation, the company is also looking into digital integration as a means of enhancing its quality management processes. Digital technologies, such as the IoT, machine learning, and data analytics, offer new opportunities for real-time monitoring and predictive maintenance (Kahveci *et al.*, 2022; Narahari *et al.*, 2023; Liu *et al.*, 2023).

By incorporating IoT devices into the assembly line, the company can monitor critical performance metrics such as temperature, voltage, and charge capacity in real-time (Schlemitz & Mezhuyev, 2024). These sensors can detect anomalies in the manufacturing process, allowing the company to identify potential defects early and take corrective action before the product moves further along the assembly line. This capability is particularly important in battery production, where minor deviations from the ideal specifications can lead to significant quality issues (Wolniak & Grebski, 2023; Kahveci *et al.*, 2022).

2.5 Rationale for Selecting the Research Environment

As a start-up in the renewable energy sector, the company faces specific challenges that make it an ideal case study for this research. Start-ups in this sector are under constant pressure to innovate while operating with limited resources (Fraihat *et al.*, 2023). The need to balance cost-efficiency with high-quality standards is a significant challenge, especially when dealing with products as complex and safety-critical as battery packs (Saiful Izwaan Saadon, 2023).

The renewable energy market, and specifically the battery manufacturing sector, is highly competitive. Customers expect products that are reliable, long-lasting, and safe. Defects or inconsistencies in battery quality can lead to performance issues, safety concerns, and ultimately, reputational damage (Wolniak & Grebski, 2023). In this context, improving quality management through semi-automation and digital integration offers the company a potential competitive advantage (Liu *et al.*, 2023).

2.6 Contextual Challenges in the South African Renewable Energy Manufacturing Sector

South Africa’s renewable energy manufacturing sector, particularly battery assembly and solar component production, operates under a complex set of structural and systemic constraints. First among these is energy reliability. According to (Ukoba *et al.*, 2025) frequent load-shedding and voltage instability interrupt industrial operations which in turn increases risks to production scheduling and process stability. These disruptions force manufacturers to either invest in costly backup systems or suffer unplanned downtime. This is especially burdensome for start-ups with limited capital and funding.

Further adding to the burden, are supply chain and logistics constraints. Import dependency for critical components, long lead times, high freight costs, and customs delays erode responsiveness and raise material costs (ManufacturingEzyFind, 2025). For a developing local battery assembler competing in a global market, delays in sourcing cell tabs, printed circuit boards, or electronic control units can derail production runs and reduce yield margins. Often, parts cannot be sourced locally due to either their high cost or availability (Tshifhumulo *et al.*, 2025).

The renewable energy manufacturing sector is specialised industry requiring skilled professionals. Although South Africa hosts capable engineers, few possess hands-on experience in battery manufacturing, semi-automation integration, or high-precision quality control in renewable-energy systems (Oladejo *et al.*, 2025).These skills shortages and technical capacity gaps compound the challenges faced in this sector. In an industry evolving rapidly in technology, recruiting and retaining personnel who can operate, maintain, and interpret data from semi-automated systems is a recurring struggle.

South Africa’s transforming energy sector has become a focal point for extensive academic research. Several studies have explored the feasibility of attaining 100 %

renewable electricity by 2050,with solar PV and wind energy as critical enablers of this transition (Wu *et al.*, 2024). However, despite this potential. the country’s progress toward large-scale renewable adoption has been constrained by regulatory challenges and inconsistent policy execution *(Ukoba et al., 2025)*.

2.7 Link Between the Research Environment and Study Objectives

The selection of this start-up battery assembly facility as the research site was deliberate, as it serves as a living testbed through which each of the study’s objectives can be examined within a real-world, resource-constrained environment. The setting is characterised by evolving production scales, intermittent process interruptions, and limited resources - factors that reflect the operational realities of many emerging renewable energy manufacturers in South Africa.

The first objective, which focuses on identifying the essential components of a QMS suitable for a start-up, is inherently grounded in this context. Within such an environment, traditional, rigid QMS structures often prove impractical. Instead, this research setting enables a practical exploration of which elements - such as traceability mechanisms, competence management, and feedback loops - are both feasible and critical to maintaining quality in a growing, capacity-limited organisation.

The second objective, which examines the effect of semi-automation on product quality and production efficiency, is directly observable at this facility. The transition from manual torquing to semi-automated laser welding on one assembly line provides a natural comparative framework under consistent supply chain and energy constraints. This real-time shift offers measurable insights into how semi-automation influences production outcomes without the confounding influence of external environmental differences.

The third objective - evaluating the effectiveness of real-time monitoring systems - gains depth in this setting precisely because of its inherent instability. Operational disturbances such as load-shedding, delayed material supply, and human variability create the ideal conditions to test how resilient and responsive real-time quality monitoring can be when exposed to genuine manufacturing challenges. The data gathered from this environment reflect realistic, not idealised, operational conditions, enhancing the robustness of the findings.

Finally, the fourth objective, which aims to develop integration and automation strategies for quality improvement, gains unique relevance in a context where infrastructural limitations, fragmented data systems, and skill shortages persist. Solutions that prove successful under these constraints are more likely to demonstrate resilience and applicability across similar emerging-market or start-up manufacturing environments.

In essence, this research environment - defined by its constraints, transitions, and evolving scale - is not a limitation but a methodological strength. It compels the evaluation of quality management, automation, and monitoring systems under practical conditions, ensuring that the study's conclusions are not theoretical abstractions but grounded, transferable insights applicable to other renewable energy start-ups operating in comparable contexts.

2.8 Summary of the Chapter

This chapter established the foundation for the research by outlining the context in which the study takes place. It introduced the start-up renewable energy company that serves as the research site, described its operations, and positioned it within South Africa's growing clean-energy manufacturing landscape. The chapter also discussed the broader environmental, economic, and infrastructural realities that shape manufacturing performance in this sector, including resource limitations, supply chain constraints, and the transitional nature of production systems in emerging enterprises. The unique conditions of this start-up environment make it a fitting platform for examining how semi-automation, real-time monitoring, and integrated quality processes can enhance manufacturing outcomes. The company's small scale and evolving processes allow for the observation of change as it happens, providing insight into both the opportunities and the challenges faced by renewable-energy manufacturers in developing contexts.

In linking the research environment to the study's objectives, the chapter demonstrated how each aim - defining key QMS components, assessing the impact of semi-automation, evaluating real-time monitoring, and developing integration strategies - is embedded within the organisation's operational reality. Rather than serving as limitations, these contextual constraints strengthen the study's validity by ensuring that findings are practical, applicable, and relevant to similar start-up settings within South Africa's renewable-energy industry.

CHAPTER THREE: LITERATURE REVIEW

3.1 Introduction

This chapter reviews existing theories and studies on quality management, semi-automation, and digital integration in manufacturing. The aim is to build the theoretical foundation for the study and link these concepts to the research objectives.

Quality management has evolved from basic inspection and control to integrated systems that emphasise process consistency, leadership, and continual improvement. With the rise of Industry 4.0, quality is increasingly shaped by automation, data connectivity, and real-time monitoring. These developments are particularly relevant for start-up manufacturers, where limited resources and growing production demands require adaptable quality systems.

The literature review aligns with the research aim - to explore how quality management can be improved through semi-automation and digital integration in a start-up battery assembly environment

3.2 Conceptual Overview of Quality Management in Manufacturing

Quality Management encompasses the organisational processes designed to ensure outputs consistently meet specified requirements and fitness-for-use standards. The concept of quality has evolved through multiple definitions, from Juran's "fitness for use" to Crosby's "conformance to requirements" (Narahari *et al.*, 2023). The contemporary ISO 9001 standard defines quality as the "degree to which a set of inherent characteristics fulfils requirements" (International Organization for Standardization, 2015).

The evolution of quality practice, in manufacturing, has progressed through distinct chronological phases. Initial inspection-based methods focused on detecting defects in finished products. This gave way to statistical quality control, utilizing process data to monitor and control variation (Wolniak & Grebski, 2023). See Figure 3.1. The development of Total Quality Management introduced a holistic philosophy emphasizing organization-wide commitment and continuous improvement (Sader *et al.*, 2019). The current paradigm, Quality 4.0, leverages Industry 4.0 technologies like IoT and big data analytics to enable predictive quality and real-time decision-making (Liu *et al.*, 2023).

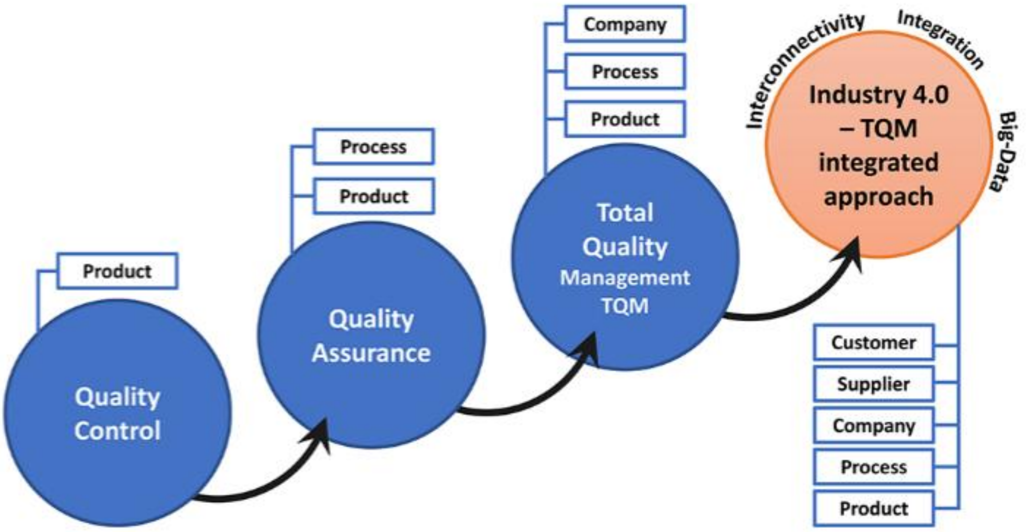

Figure 3.1: the development of quality management in manufacturing overtime (source: (Sader *et al.*, 2019))

A Quality Management System formalizes these principles through documented structures and procedures. Modern QMS frameworks prioritize evidence-based decision making, increasingly enabled by data analytics and digital platforms that facilitate traceability and closed-loop quality control (Filz *et al.*, 2024). However, QMS implementation in start-ups and SMEs faces particular challenges, including resource scarcity, lack of standardized processes, and cultural resistance to formal systems (Oommen & Vinayagam, 2024; Nunes *et al.*, 2022). This context necessitates pragmatic approaches to quality management that balance rigor with operational flexibility.

This foundation in quality principles provides the basis for examining how semi-automation enables their practical implementation in manufacturing environments.

3.3 Semi-Automation in Manufacturing Systems

Semi-automation represents a pivotal strategy in modern manufacturing, deliberately blending human cognitive flexibility with machine precision to create robust and adaptable production systems (Langer & Söffker, 2015; Christler *et al.*, 2020). This hybrid approach is particularly critical for complex, high-value assembly processes - such as those found in battery manufacturing - where the inflexibility of full automation is prohibitive, yet the consistency demands exceed what is sustainable through purely manual methods (Burdo & Bolotov, 2024; Wolniak & Grebski, 2023). It serves as a practical pathway for organisations to systematically enhance quality, throughput, and process control.

3.3.1 Definition and Levels of Automation

Automation in manufacturing is not a binary state but a continuum. Semi-automation occupies a crucial position on this spectrum, characterised by a deliberate division of labour. In this configuration, machinery executes specific, repetitive, or high-precision sub-tasks - such as applying a consistent torque to a fastener or performing a laser weld - while the human operator provides the overarching cognitive framework. This includes system supervision, complex problem-solving, quality verification, and managing unforeseen exceptions (Langer & Söffker, 2015). The rise of collaborative robots epitomises this model, designed to work in close proximity to humans, taking over ergonomically challenging or monotonous duties, thereby freeing operators for higher-value tasks that require judgment and adaptability (Calvo & Gil, 2022). Selecting the optimal level of automation is therefore a strategic calculation, balancing factors like product variability, capital investment, and the desired balance between efficiency and operational resilience.

3.3.2 Benefits and Limitations of Semi-Automation

The advantages of a well-implemented semi-automated system are tangible and multifaceted. By automating process steps most susceptible to human variability, manufacturers can achieve a significant reduction in defects and enhanced product uniformity. For example, Christler *et al.* (2020) demonstrated that semi-automating laboratory analytics drastically reduced inter-operator variability, leading to more reliable and reproducible results - a principle that translates directly to production quality control. Furthermore, collaborative robots can generate substantial process time savings and improve ergonomics, as quantified in assembly use cases by Calvo & Gil (2022). However, these gains are not without their costs. The initial capital outlay for robotics, sensing, and control systems can be substantial, creating a significant barrier for small and medium enterprises (Duffner *et al.*, 2021). Beyond acquisition, these hybrid systems demand new maintenance competencies and necessitate a workforce skilled in both traditional manufacturing and mechatronics, presenting a persistent challenge in workforce development.

3.3.3 Semi-Automation in Battery Assembly Lines

Within the rapidly scaling battery manufacturing sector, semi-automation has become a dominant operational model, adeptly addressing the industry's twin demands of extreme precision and configurational flexibility. The assembly of battery packs for electric vehicles involves a intricate sequence of processes - from sensitive cell handling and precise module stacking to critical electrical connections and final sealing. Many of these tasks are ideally suited for a hybrid approach. Automated systems may perform highly repeatable tasks like plasma cleaning or adhesive dispensing with unwavering consistency, while human technicians oversee the process, conduct tactile and visual inspections of weld quality, and manage the intricate final wiring harnesses that defy easy automation (Stavropoulos *et al.*, 2024). This synergy ensures that critical safety parameters are met with machine-like repeatability, while retaining the human intelligence necessary to adapt to variations in components and to diagnose subtle, non-conforming conditions.

This strategic fusion of human and machine capabilities does more than just improve the immediate process; it creates a foundational data-generating layer. The sensors and control systems inherent in semi-automated equipment produce a continuous stream of operational data, providing the essential feedstock for the digital quality management and real-time monitoring systems that form the core of the next section's discussion.

3.4 Digital Integration and Industry 4.0 in Quality Management

The convergence of operational technology with information technology, encapsulated by the Industry 4.0 paradigm, is fundamentally reshaping quality management. Digital integration creates a connected ecosystem where machines, sensors, and enterprise systems communicate seamlessly, transforming quality from a standalone function into an embedded, real-time characteristic of the manufacturing process.

3.4.1 Digital Integration Concepts

Digital integration within Industry 4.0 is built upon a foundation of interconnected cyber-physical systems. These systems bridge the physical factory floor and the digital computational space, enabling real-time data exchange and decentralized control (Lee *et al.*, 2015). Key enabling technologies include the Industrial IoT, which provides the sensor network for data acquisition; cloud computing, which offers scalable data storage and processing power; and artificial intelligence, which facilitates advanced analytics and predictive capabilities (Vaidya *et al.*, 2018). This technological framework allows for the creation of digital twins - virtual replicas of physical assets - that can simulate, predict, and optimize processes before implementation on the factory floor, thereby pre-emptively addressing potential quality issues.

3.4.2 Quality 4.0: The Digital Evolution of QMS

Quality 4.0 represents the maturation of traditional quality management principles through digital enablers. While the core objectives of customer focus, continuous improvement, and defect reduction remain, the methodologies have evolved dramatically. Traditional statistical process control is being augmented with real-time statistical analytics that can process vast datasets from production lines, identifying subtle patterns and correlations beyond human perception (Wolniak & Grebski, 2023). According to Liu *et al.* (2023), Quality 4.0 shifts the quality function from reactive and preventive to truly predictive, leveraging machine learning algorithms to forecast potential failures and prescribe corrective actions before defects occur. This represents a fundamental transformation from quality control to predictive quality assurance. Figure 3.2, below, shows the evolution of quality over time.

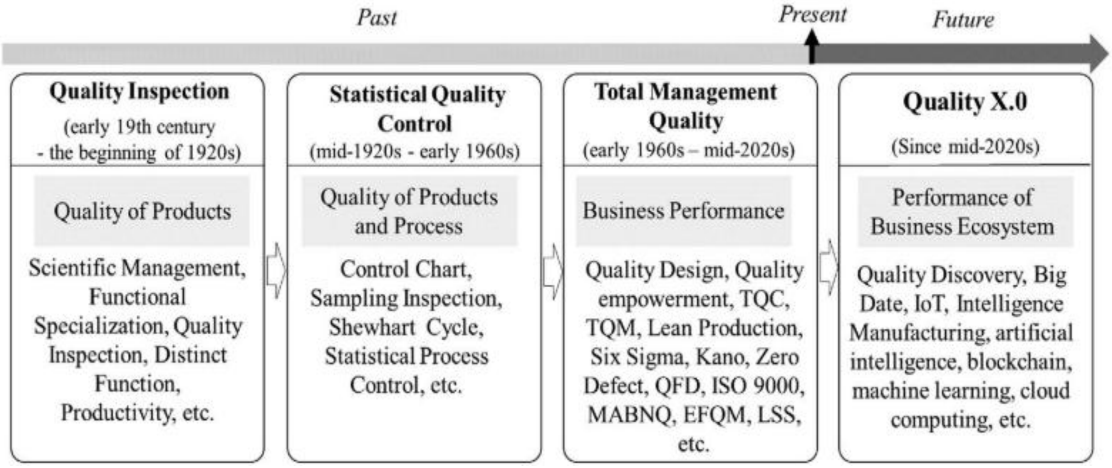

Figure 3.2: Evolution of Quality *Source: (Wen et al., 2022)*

3.4.3 Real-Time Monitoring and Data Analytics in Manufacturing Quality

The implementation of real-time monitoring systems has become a cornerstone of modern quality management. In practice, networks of sensors continuously collect data on critical process parameters - such as temperature, pressure, and vibration - during manufacturing operations. This data is streamed to analytics platforms where it is processed and visualized through dashboards, providing immediate insight into process stability (Filz *et al.*, 2024). The benefits are substantial, including dramatic reductions in defect rates through early anomaly detection, minimized unplanned downtime via predictive maintenance, and improved traceability for root cause analysis. For instance, in battery manufacturing, real-time monitoring of welding parameters and subsequent automated visual inspection can instantly flag anomalies in cell interconnections, preventing the propagation of defects downstream (Wang *et al.*, 2023). However, organizations face significant challenges in managing the resulting data deluge and ensuring cybersecurity across increasingly connected industrial networks.

The deep integration of digital technologies creates a data-rich environment that is particularly relevant for specialized manufacturing sectors.

3.5 Quality Management in the Renewable Energy Manufacturing Sector

The renewable energy manufacturing sector, particularly battery and solar component production, operates under exceptionally stringent quality requirements due to the critical safety, longevity, and performance demands of its end products. Effective quality management in this sector is not merely a competitive advantage but a fundamental prerequisite for market acceptance and operational safety.

3.5.1 Overview of Quality Requirements in Solar Energy and Battery Manufacturing

In lithium-ion battery manufacturing, quality parameters are exceptionally rigorous, focusing on electrical performance, cycle life, and, most critically, safety. Defects such as microscopic metallic particles, improper electrode alignment, or substandard sealing can lead to internal short circuits, potentially resulting in thermal runaway - a dangerous condition of uncontrolled self-heating (Wang *et al.*, 2019). Consequently, process stability and full traceability are paramount. Similarly, in solar PV manufacturing, quality is measured by cell efficiency, durability against environmental degradation, and long-term performance consistency (Aneke & Wang, 2016).Both sectors require a zero-defect mindset, as product failures can have significant safety implications and erode confidence in clean energy technologies.

3.5.2 Challenges of Quality Management in Emerging Economies

Manufacturing in emerging economies, such as those in Sub-Saharan Africa, faces contextual barriers that complicate the implementation of robust quality management. Unstable supply chains can lead to inconsistencies in raw material quality, directly impacting final product reliability (Tshifhumulo *et al.*, 2025). Limited digital infrastructure hinders the real-time data collection and analysis central to modern Quality 4.0 approaches. Furthermore, financial constraints often restrict investments in advanced metrology equipment and comprehensive quality assurance personnel, forcing manufacturers to make strategic compromises (Ukoba *et al.*, 2025). These challenges are acutely felt by start-ups and SMEs attempting to establish a foothold in the global renewable energy market while competing with established international players.

3.5.3 Benchmark Practices and International Standards

Adherence to internationally recognized standards provides a critical framework for achieving and demonstrating quality. The ISO 9001 standard forms the foundational QMS, while ISO 14001 addresses environmental management, which is particularly relevant for the sustainability claims of renewable products. For battery manufacturers supplying the automotive industry, IATF 16949 imposes additional stringent requirements for continuous improvement and defect prevention. However, the applicability of these comprehensive standards to small-scale renewable energy start-ups can be challenging. The resource-intensive nature of achieving and maintaining certification may necessitate a phased or tailored implementation approach, focusing initially on the most critical processes that impact safety and core performance (Patat & Jayaprakash, 2018).

The stringent quality demands and unique challenges of the renewable energy sector create a complex environment for manufacturing start-ups. These organisations must balance rapid innovation and cost constraints with the need to establish robust quality controls that ensure product reliability and regulatory compliance. As a result, pragmatic and scalable quality management approaches are often required to support sustainable growth without overburdening limited organisational resources.

3.6 The Start-Up Context: Constraints and Opportunities for Digital Quality Integration

Navigating the path to manufacturing excellence presents a unique set of challenges and strategic considerations for start-up enterprises. Characterised by inherent resource constraints yet driven by innovation and agility, these organisations must adopt pragmatic approaches to quality management that differ significantly from established industrial players.

3.6.1 Organisational Characteristics of Start-Ups

Start-up manufacturing ventures are typically defined by a high degree of operational agility, a strong orientation toward rapid innovation, and severe resource scarcity. Unlike mature corporations, they operate with lean organisational structures, evolving business processes, and a pressing need to demonstrate market viability quickly

(Nunes *et al.*, 2022). This environment presents a fundamental tension: the need to implement structured, reliable quality systems clashes with the imperative to remain flexible and capital-efficient. Financial constraints further intensify this challenge, as limited access to capital often restricts investment in advanced quality infrastructure, skilled personnel, and long-term system development (Liu *et al.*, 2023). The absence of legacy systems can be an advantage, allowing for the adoption of modern digital tools from the outset, but the lack of standardised procedures and quality culture poses a significant risk to consistent output (Patat & Jayaprakash, 2018).

3.6.2 Barriers to Technology Adoption in Start-Ups

The adoption of sophisticated digital quality technologies faces substantial headwinds in the start-up context. The most pronounced barrier is financial; the significant capital expenditure required for Industry IoT sensors, analytics software, and automation hardware is often prohibitive (Kayser *et al.*, 2023). This is compounded by a frequent scarcity of in-house technical expertise required to implement and maintain these systems effectively. Furthermore, there is often internal resistance to formalised processes, as early-stage teams may perceive structured quality management as bureaucratic overhead that stifles the agility and speed central to the start-up ethos (Alawamleh *et al.*, 2023). Workforce readiness is therefore a dual challenge, requiring both technical upskilling and a cultural shift toward data-driven, disciplined manufacturing.

3.6.3 Opportunities for Incremental Automation and Learning

Despite these constraints, start-ups possess unique opportunities to leverage technology strategically. Semi-automation serves as a powerful transitional strategy, allowing for a phased capital investment while building foundational data streams and operational discipline (Langer & Söffker, 2015). A start-up might begin with a single collaborative robot for a critical, high-variation task, using the operational data generated to justify further automation. This incremental approach facilitates organisational learning, enabling the team to develop the necessary technical competencies and a quality-centric culture in a manageable, scalable way. By focusing on targeted technology adoption that addresses their most critical quality pain points, start-ups can build a foundation for gradual digital transformation without the overwhelming risk of a full-scale, simultaneous implementation.

The distinct challenges and strategic imperatives of the start-up context underscore the need for a tailored conceptual framework.

3.7 Theoretical and Conceptual Framework

This study is grounded in an integrated theoretical foundation that connects technological implementation with organisational outcomes. The research synthesises principles from Quality Management Theory, Socio-Technical Systems Theory, and the Technology-Organisation-Environment framework to explain how manufacturing start-ups can effectively leverage digital tools for quality excellence.

Quality Management Theory provides the foundational premise that a structured, process-oriented approach is essential for achieving consistent output and customer satisfaction. The core principles of customer focus, evidence-based decision making, and continual improvement, as enshrined in ISO 9001 (International Organization for Standardization, 2015), remain paramount. This is complemented by Socio-Technical Systems Theory, which posits that optimal performance is achieved through the joint optimisation of both the social (people, culture, skills) and technical (machines, processes, software) subsystems of an organisation. STS theory explains why the mere introduction of semi-automation or data analytics - the technical component - is insufficient without concurrent development of workforce skills and adaptive organisational structures - the social component. Finally, the TOE framework contextualises this integration within the start-up environment, analysing how the technological characteristics, organisational resources, and external market pressures influence the adoption and effectiveness of digital quality solutions.

Based on this theoretical triangulation, the conceptual framework for this research is presented in Figure 3.3. It proposes that the strategic implementation of semi-automation acts as a key enabling factor, generating the structured operational data necessary for Digital Integration, specifically through real-time monitoring and data analytics. This digital integration directly enhances quality performance by enabling early defect detection, predictive interventions, and improved process control. The framework further posits that this entire pathway is moderated by the start-up context, where factors such as resource scarcity, technical expertise, and organisational agility either constrain or amplify the effectiveness of the technological implementation. The ultimate outcome is improved Operational Efficiency, manifested as reduced scrap, lower rework costs, and increased throughput.

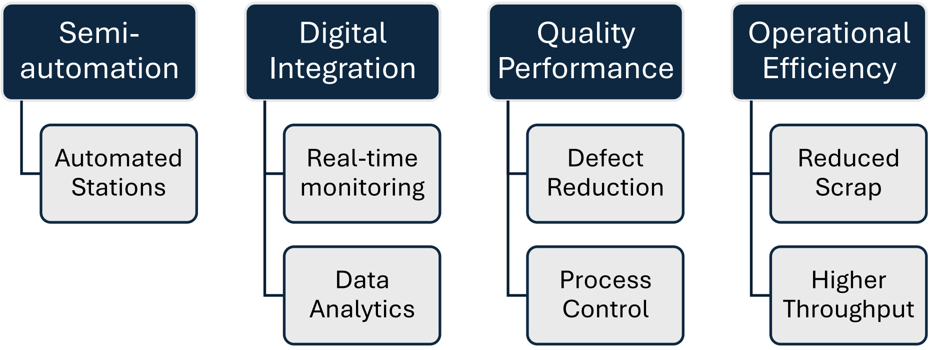

Figure 3.3: Conceptual framework - the interrelationship between semi-automation and digital integration within the start-up context (source: self-developed)

This framework directly links the literature reviewed in the preceding sections and provides a structured model for investigating the research questions. It positions semi-automation not as an end in itself, but as a critical catalyst that, when integrated with digital tools and adapted to the organisational context, drives a virtuous cycle of quality and efficiency improvement. The following chapter on methodology will detail how these constructs are operationalised and measured to empirically test the proposed relationships.

3.8 Literature Gap and Research Justification

This literature review has synthesised current knowledge across three interconnected domains: the principles of quality management, the role of semi-automation as an enabler, and the transformative potential of digital integration, all within the distinct context of start-up manufacturing. While the individual components are well-researched, their synergistic interaction in specific, high-stakes industrial settings remains underexplored.

A significant gap exists in empirical research focused on the integrated implementation of semi-automation and real-time digital monitoring within small-scale or start-up battery assembly contexts. While studies like those of Stavropoulos *et al.,* (2024) detail welding challenges and Filz *et al.,* (2024)propose data-driven platforms, there is a lack of applied research examining how these technologies are pragmatically adopted and scaled by resource-constrained enterprises. The literature extensively covers QMS frameworks for large corporations but offers limited guidance on tailored, lean QMS frameworks that can evolve with a growing start-up in the renewable energy sector, which faces acute pressure for both safety and rapid scalability (Nunes *et al.*, 2022; Oommen & Vinayagam, 2024).

Furthermore, the specific challenges of integrating these systems within the context of emerging economies, such as South Africa, are often overlooked. The compounding effect of unstable infrastructure, supply chain inconsistencies, and skills shortages on digital quality initiatives is not sufficiently detailed in the mainstream literature (Ukoba *et al.*, 2025; Tshifhumulo *et al.*, 2025). Consequently, there is a clear need for research that investigates how semi-automation can be leveraged as a foundational step to generate data, which in turn fuels a incremental and affordable digital quality transformation.

This research is justified as it seeks to address these gaps by providing an empirical case study. It will investigate the practical integration pathway of semi-automation and digital monitoring in a battery manufacturing start-up, proposing a adaptable model for quality management that aligns with the constraints and opportunities inherent to such environments. The findings aim to offer both academic and practical contributions by illustrating how a phased, socio-technical approach can build a robust quality foundation, thereby supporting the growth and reliability of the clean energy manufacturing ecosystem.

3.9 Chapter Summary

This chapter has presented a comprehensive review of the literature relevant to this study, establishing the foundational concepts and identifying the critical gap this research aims to fill. The review began with a conceptual overview of Quality Management, tracing its chronological evolution from inspection-based methods to the predictive, data-driven paradigm of Quality 4.0. It then examined the role of semi-automation as a strategic hybrid approach that enhances quality and consistency while maintaining operational flexibility, with specific applications in complex domains like battery assembly.

The discussion progressed to the transformative impact of digital integration and Industry 4.0 technologies, highlighting how real-time monitoring and data analytics are reshaping quality management into a proactive function. The unique challenges and stringent requirements of the renewable energy manufacturing sector were analysed, underscoring the critical need for robust quality systems in this field. The distinct context of start-up enterprises was then explored, detailing the characteristic constraints of resource scarcity and agility, and the opportunities for incremental technological adoption and organisational learning.

Synthesising these themes, a conceptual framework was proposed, illustrating the theorised relationships between semi-automation, digital integration, quality performance, and operational efficiency, all moderated by the start-up context. This framework directly informed the identification of a clear literature gap: the lack of empirical research on integrated, practical digital quality management pathways tailored for start-ups in high-stakes manufacturing sectors like battery production, particularly within emerging economy contexts.

The insights from this chapter have directly shaped the research design. The following chapter, Methodology, will detail the operationalisation of this framework, describing the specific research philosophy, design, data collection methods, and analysis techniques employed to investigate these relationships and address the identified gap.

CHAPTER FOUR: RESEARCH METHODOLOGY

4.1 Introduction

This chapter outlines the research methodology adopted to achieve the objectives of this study. The chapter explains the philosophical foundation, research design, data collection, and analytical techniques used to investigate how quality management can be enhanced through semi-automation and digital integration in a start-up battery production environment. The methodology provides a structured and transparent approach to ensure that the study's findings are valid, reliable, and aligned with the research problem and objectives.

The study aims to determine how quality management can be strengthened through the integration of semi-automated systems and digital monitoring within a small-scale manufacturing context. To achieve this aim, four key objectives were formulated:

i. To determine the essential components of an effective Quality Management System for a start-up.
ii. To evaluate the effect of semi-automation on product quality and production efficiency.
iii. To assess the effectiveness of real-time monitoring in the early detection and resolution of quality issues.
iv. To develop integration strategies that combine quality processes with automation for improved performance.

This research adopts a mixed-methods approach that integrates both quantitative and qualitative methods. Quantitative data were used to analyse measurable aspects such as defect rates, process efficiency, and production variability, while qualitative insights were drawn from observations, process documentation, and internal quality reports to provide contextual understanding. The integration of both forms of data allows for a comprehensive interpretation of the research problem - providing both breadth through statistical analysis and depth through contextual interpretation.

4.2 Research Philosophy and Paradigm

The research philosophy defines the worldview and underlying assumptions that shape how knowledge is created, interpreted, and applied within a study. This research is grounded in the pragmatic paradigm, which supports the integration of both quantitative and qualitative approaches to address complex, real-world problems (Saunders *et al.*, 2007). Pragmatism views knowledge as something that gains meaning through its practical application, aligning well with the study's aim to improve operational and quality performance within a start-up manufacturing environment through semi-automation and digital integration (Creswell, 2009).

The pragmatic paradigm combines the strengths of positivism and interpretivism, allowing the researcher to use both objective data and contextual understanding (Saunders *et al.*, 2007). The positivist strand supports the collection and analysis of measurable data - such as defect rates, throughput, and efficiency - to evaluate the performance impact of semi-automation and digital systems (Kothari C.R., 2004). Meanwhile, the interpretivist element allows the study to consider qualitative insights drawn from document analysis, production observations, and contextual factors influencing implementation outcomes (Creswell, 2009). This combination ensures that findings are both empirically grounded and contextually meaningful, offering a holistic understanding of how digital and semi-automated systems affect quality performance in a dynamic production environment (Creswell, 2009).

Pragmatism is particularly suitable for applied engineering management studies where the goal is not only to understand phenomena but to improve them through actionable solutions (Saunders *et al.*, 2007). The manufacturing environment at the company operates under real constraints such as limited resources, skill shortages, and evolving automation systems. These practical realities require a flexible and outcome-oriented research philosophy that bridges theoretical understanding and practical improvement (Saunders *et al.*, 2007). The pragmatic paradigm supports this by prioritising the most effective methods to answer the research questions rather than adhering strictly to a single worldview (Creswell, 2009).

In essence, the pragmatic paradigm provides the philosophical foundation that enables this research to integrate both quantitative evidence and qualitative insight. It allows the methodology to remain adaptable, focusing on generating solutions that are not only valid in theory but also applicable in practice - advancing both academic knowledge and industrial capability in quality management under semi-automated and digitally integrated conditions (Guetterman *et al.*, 2023).

4.3 Research Approach

The research approach defines the logical process through which theory and data interact to address the research problem. This study adopts an abductive research approach, which combines both deductive and inductive reasoning to provide a comprehensive understanding of how semi-automation and digital integration influence quality management within a start-up manufacturing environment (Saunders *et al.*, 2007).

The deductive element of the study is based on existing theories and frameworks of quality management and automation. Foundational principles such as process control, data-driven decision-making, and continuous improvement - as reflected in Quality Management System models and Industry 4.0 literature - provide the theoretical grounding for evaluating semi-automation and digital integration within the company context (Kothari C.R., 2004). These theories informed the development of research objectives, which guided the collection and analysis of quantitative data such as defect rates, efficiency trends, and real-time monitoring outcomes.

Simultaneously, the inductive component emerged from the analysis of observed operational data, production documents, and contextual conditions within the start-up environment. This allowed the research to identify patterns, limitations, and improvement opportunities that were not fully explained by existing theory (Creswell, 2009). For example, the interaction between semi-automated welding processes and production variability revealed practical challenges that extend beyond theoretical expectations, offering new insights relevant to small-scale renewable energy manufacturers.

By combining both deductive and inductive reasoning, the abductive approach supports iterative reasoning - moving between theory and empirical evidence (Guetterman *et al.*, 2023). This enabled the study to test existing concepts while generating context-specific strategies for quality improvement. Abduction is particularly well suited to applied engineering studies, where the objective is not only to confirm theoretical relationships but also to develop practical solutions grounded in real operational data (Saunders *et al.*, 2007).

Thus, the abductive approach provided the flexibility required to explore how semi-automation and digital systems reshape quality control processes in a start-up manufacturing context. It ensured that findings were both theoretically informed and empirically validated, producing actionable insights that bridge academic research and industrial application (Creswell, 2009).

4.4 Research Design

The research design provides the overall structure that links the study's objectives, data collection, and analysis procedures into a coherent framework. This study employs a mixed-methods design, integrating both quantitative and qualitative components to provide a comprehensive understanding of how semi-automation and digital integration enhance quality management within a start-up manufacturing environment (Creswell & Clark, 2017). The combination of numerical performance data and contextual insights allows for a richer and more balanced interpretation of findings than would be possible using a single approach (Saunders *et al.*, 2007).

The quantitative strand of the study focuses on measurable production outcomes such as defect rates, throughput, and process variation obtained from semi-automated battery assembly lines. This data provided objective evidence of the operational effects of automation and digital integration (Kothari C.R., 2004). The qualitative strand complements this by analysing contextual information drawn from process documentation, standard operating procedures, and observational notes from production and quality activities (Creswell, 2009). Together, these data sources enabled the study to capture both the technical outcomes and the organisational realities that influence quality performance.

The adoption of a mixed-methods approach was driven by the need to achieve triangulation - using multiple forms of evidence to validate results and strengthen the credibility of interpretations (Creswell & Clark, 2017). Quantitative data offered the statistical basis for assessing trends, while qualitative findings provided explanations for why such trends occurred within the practical constraints of a start-up environment (Guetterman *et al.*, 2023). This integration allowed the study to identify not only measurable improvements but also underlying factors such as workflow disruptions, documentation gaps, and operator adaptability that influence system effectiveness.

A concurrent triangulation design was applied, meaning that both quantitative and qualitative data were collected and analysed during overlapping time frames (Creswell & Clark, 2017). This design ensured that the interpretation of results reflected a real-time understanding of operations rather than a sequential or retrospective view. The concurrent approach was particularly suitable for this study because production processes at the organisation operate continuously, allowing quantitative data from automated systems and qualitative observations from the same period to be compared directly (Saunders *et al.*, 2007). The integration of these findings during interpretation strengthened the validity of conclusions and ensured that both dimensions of quality performance - statistical outcomes and contextual factors - were considered equally (Creswell & Clark, 2017).

The mixed-methods design provided a balanced and systematic means to explore the research problem from multiple perspectives. It enabled the study to quantify the operational impact of semi-automation and digital monitoring while also revealing the contextual challenges and opportunities that shape quality outcomes in a resource-constrained manufacturing start-up (Creswell, 2009).

4.5 Research Setting

The study was conducted at a renewable-energy manufacturing start-up based in the Western Cape, South Africa. The company specialises in the assembly of lithium-ion battery packs designed for solar energy systems. These battery packs are used to provide energy storage solutions for both residential and commercial applications, supporting South Africa's transition toward sustainable energy generation (Keisang *et al.*, 2021). The Western Cape's expanding renewable-energy manufacturing cluster, has become a focal point for innovation and industrial development in clean technology (Nunes *et al.*, 2022).

The company's operations encompass several production lines, including battery assembly, cable manufacturing, and inverter integration, each contributing to complete solar energy storage systems. The battery assembly process involves critical stages such as cell matching, tab welding, module formation, and final testing using automated and semi-automated systems (Wang *et al.*, 2022). A key feature of the production environment is its hybrid configuration - combining manual operations such as component preparation and assembly with semi-automated processes such as laser welding, torque-controlled fastening, and automated testing through Acceptance Test Procedures (Bründl *et al.*, 2024).

As a start-up organisation, the company faces challenges typical of emerging manufacturers, including limited financial and human resources, evolving operational procedures, and the need to balance innovation with production stability (Fraihat *et al.*, 2023). The company is progressively integrating digital systems to improve traceability and data-driven decision-making, such as using real-time monitoring and centralised quality reporting platforms (Wolniak & Grebski, 2023). These initiatives reflect the early stages of a transition toward Industry 4.0 and Quality 4.0 practices, making the facility a suitable environment to explore how semi-automation and digital integration affect quality performance (Liu *et al.*, 2023).

This setting was particularly suitable for the research because it represents the intersection of industrial growth and operational constraint. The company's scale and flexibility allowed close observation of how new technologies are implemented and how digital feedback loops influence process control, defect reduction, and efficiency improvement (Bründl *et al.*, 2024). The combination of manual and semi-automated systems provided an ideal comparative platform for assessing the measurable and qualitative impacts of automation on quality outcomes (Wang *et al.*, 2022). Furthermore, the company's openness to research collaboration ensured access to production data, documentation, and system information necessary to achieve the study's objectives (Narahari *et al.*, 2023).

The company offered a practical and data-rich environment in which to evaluate the effects of semi-automation and digital integration on quality management. Its characteristics as a resource-constrained yet technologically progressive start-up made it an exemplary case for investigating the adaptation of quality principles in emerging renewable-energy manufacturing contexts (Fraihat *et al.*, 2023).

4.6 Population and Sampling

In this study, the concept of population refers not to human participants, but to the production processes and data sources from which information was drawn. The research focused on data and documentation related to battery pack assembly and associated quality management activities within the company. The population therefore comprised all available production records, inspection reports, and real-time system outputs associated with semi-automated and manual assembly operations during the research period.

4.6.1 Target Population

The target population included operational data from the battery assembly line, specifically covering the semi-automated welding process and the manual torquing process used for battery pack assembly. Both processes produce comparable products but differ in their level of automation, allowing for meaningful comparison and evaluation. Supporting quality records - including process control documents, quality checklists, ATP results, and nonconformance reports - formed part of the population examined. These data sources collectively represent the company's operational performance under varying levels of automation and digital integration.

4.6.2 Sampling Technique

Since the study did not involve human participants, purposive sampling was applied to select data sets and documentation that were most relevant to the research objectives (Creswell & Clark, 2017). The sampling process prioritised production periods and process records that reflected both manual and semi-automated operations to enable comparative analysis. Selection criteria included:

- Availability of complete production and testing data;
- Representativeness of the different assembly methods (torqued and welded packs); and
- Presence of digital monitoring or automation elements in the process.

Qualitative data in the form of process documentation, quality manuals, and observational notes were also selected purposively to capture insights into system integration, operational constraints, and procedural standardisation. This approach ensured that both the quantitative and qualitative strands of the study addressed the same operational context, supporting methodological consistency and triangulation.

4.6.3 Sample Size

The sample size for the quantitative analysis was determined by the number of production cycles and test results available within the research timeframe (Creswell & Clark, 2017). Data were collected across multiple production runs to ensure representation of both assembly types - semi-automated (welded) and manual (torqued). The inclusion of multiple units and production shifts provided sufficient variation for meaningful statistical comparison of process performance.

For the qualitative strand, the sample included relevant internal quality documents and process control records, such as inspection logs, ATP summaries, and configuration control reports. The volume of data was sufficient to identify recurring trends, process deviations, and integration patterns without unnecessary redundancy.

The study employed purposive sampling of production data and documentation to ensure the information analysed was directly aligned with the research objectives. This approach provided a balanced dataset that captured both quantitative performance outcomes and qualitative contextual insights, allowing for robust analysis of the impact of semi-automation and digital integration on quality management.

4.7 Data Collection Methods

Data collection in this study followed a mixed-methods approach, combining quantitative production data with qualitative documentation and observation-based insights (Creswell & Clark, 2017). The integration of both forms of data provided a holistic understanding of how semi-automation and digital integration influence product quality and operational efficiency within a start-up manufacturing environment.

4.7.1 Quantitative Data Collection

The quantitative strand of the study focused on production and quality performance data generated during the assembly of lithium-ion battery packs. Data were extracted from multiple sources, including:

- Process tracking systems that record production throughput, defect rates, and rework occurrences;
- The Acceptance Test Procedure system, which captures pass/fail outcomes and voltage consistency; and Aging records of the batteries, which document variation across production cycles (Wolniak & Grebski, 2023).

The quantitative data captured key process parameters such as cycle times, defect frequency, temperature profiles, and output efficiency across both manual (torqued) and semi-automated (welded) assembly methods. The comparison of these datasets enabled an objective assessment of process capability and the influence of automation on quality outcomes (Liu *et al.*, 2023).

Data collection was carried out over multiple production runs to ensure representativeness and account for variability due to shifts, product models, and production conditions. All data were exported into Microsoft Excel and IBM SPSS for cleaning, sorting, and statistical analysis. The structured nature of the data facilitated the application of descriptive and comparative techniques to evaluate the performance effects of semi-automation and digital integration.

4.7.2 Qualitative Data Collection

The qualitative component of the study focused on collecting contextual and process-related information to support and explain quantitative findings. This strand included:

- Document analysis, covering quality procedures, inspection checklists, and audit reports;
- Observation of production activities, particularly the interaction between operators and semi-automated equipment; and

- Review of internal communication records such as deviation logs, maintenance notes, and nonconformance reports.

These qualitative data sources provided insight into operational challenges, process standardisation, and the integration of digital monitoring systems within the production line (Bründl *et al.*, 2024). Observations were documented through detailed field notes recorded during production walkthroughs and routine inspections. No personal identifiers or human-related data were collected, ensuring full compliance with ethical standards.

4.7.3 Data Collection Procedures

Prior to data collection, permission was obtained from the company's management to access production systems, quality records, and process documentation. Data were collected over an extended period to capture normal production variation rather than isolated instances. Quantitative data were downloaded directly from in-line monitoring and ATP systems, while qualitative data were compiled through controlled access to quality documents and on-site observation (Creswell & Clark, 2017).

All data were securely stored in password-protected files accessible only to authorised personnel. To preserve data integrity, each dataset was labelled by date, process type, and source. The mixed-methods data collection process ensured methodological alignment between the quantitative and qualitative strands, allowing the two datasets to inform and reinforce each other (Saunders *et al.*, 2007).

In summary, the data collection strategy combined objective performance metrics with contextual documentation and observations. This integration provided a comprehensive foundation for analysing how semi-automation and digital integration influence quality management and operational performance within a resource-constrained manufacturing environment.

4.8 Data Analysis Methods

Data analysis in this study followed the mixed-methods design structure, integrating quantitative and qualitative strands to provide both statistical and contextual insights into how semi-automation and digital integration influence quality performance. Each data type was analysed separately and then interpreted together to generate cohesive findings that addressed the study's objectives.

4.8.1 Quantitative Data Analysis

The quantitative analysis focused on identifying measurable trends and relationships within the production and quality datasets. Data extracted from ATP systems, Aging charts, and production logs were first cleaned and verified for completeness and consistency. Once validated, the data were processed using Microsoft Excel and IBM SPSS, which enabled descriptive and comparative statistical analysis (Saunders *et al.*, 2007).

Descriptive statistics were used to summarise performance indicators such as first-pass yield, process variation, and rework frequency across the two assembly methods - manual (torqued) and semi-automated (welded). Comparative analysis techniques, including mean difference calculations and trend visualisation, were applied to determine how semi-automation influenced quality outcomes relative to manual assembly.

Where relevant, correlation analysis was used to explore the relationships between process variables such as defect occurrence, production time, and automation level (Liu *et al.*, 2023). The purpose of these analyses was not only to quantify performance differences but also to identify patterns that could indicate process improvement opportunities. Visual representations such as bar charts and SPC graphs were generated to illustrate results clearly and support interpretation in Chapter Five (Wolniak & Grebski, 2023).

4.8.2 Qualitative Data Analysis

The qualitative data, derived from document reviews and observational notes, were analysed using a thematic analysis approach (Creswell, 2009). This method allowed for the identification of recurring themes and contextual factors influencing quality performance under semi-automated conditions.

The analysis followed a structured process:

- Familiarisation - reviewing and annotating quality documents, observation logs, RCA logs and audit reports to identify relevant content;
- Coding - assigning short labels to specific observations or document excerpts related to process control, system integration, and quality feedback mechanisms;
- Theme development - grouping codes into broader themes such as “process variation control,” “documentation and traceability,” and “digital feedback integration.”

These themes provided explanatory depth to the quantitative results, clarifying why certain trends occurred - for instance, how digital traceability improved fault detection or how documentation gaps affected rework. To maintain credibility, the analysis was aligned with the structured ATLAS.ti-style coding framework previously developed for quality document analysis, ensuring consistency across data sources (Creswell & Clark, 2017).

4.8.3 Integration of Quantitative and Qualitative Findings

Integration of both data strands occurred during the interpretation phase, following a concurrent triangulation approach (Creswell & Clark, 2017). This allowed quantitative trends and qualitative explanations to be compared and merged for a comprehensive understanding of the research problem. For example, quantitative data indicated measurable reductions in defects following semi-automation, while qualitative findings explained these improvements in terms of better process control and real-time monitoring.

This triangulated interpretation strengthened the overall validity of the results by confirming patterns through multiple sources of evidence (Guetterman *et al.*, 2023). It also provided a richer understanding of how technological, procedural, and contextual factors interact to influence quality management outcomes. The integrated findings informed the synthesis presented in Chapter Five, where statistical evidence and qualitative insights are combined to develop actionable recommendations for process improvement.

4.9 Reliability, Validity, and Trustworthiness

Ensuring reliability and validity is essential for maintaining the integrity of any research process. In this study, steps were taken to ensure that both the quantitative and qualitative strands produced accurate, consistent, and credible findings (Saunders *et al.*, 2007). Reliability and validity in the quantitative component focused on data precision and repeatability, while trustworthiness in the qualitative component centred on transparency, consistency, and alignment with real operational conditions (Creswell & Clark, 2017).

4.9.1 Quantitative Validity and Reliability

For the quantitative strand, validity was addressed through careful selection and verification of data sources. All production data were obtained directly from the organisation’s internal quality and process control systems, which record real-time operational information (Liu *et al.*, 2023). This ensured construct validity, as the data accurately reflected the production variables relevant to the study - including defect rates, rework occurrences, throughput, and testing results.

Internal validity was supported by ensuring consistency in data collection procedures across both manual and semi-automated production lines. Comparative analysis was conducted on equivalent product batches and within similar timeframes to minimise the influence of external factors such as operator changes or component variations. External validity was achieved by analysing multiple production runs, making the results more representative of ongoing operations rather than isolated events.

Reliability was maintained through standardised data handling processes. Data from the Acceptance Test Procedure systems and production logs were cross-checked against manual inspection records to confirm accuracy. All statistical analyses were performed using consistent formulas and procedures in Microsoft Excel and IBM SPSS, ensuring that calculations were repeatable and transparent (Saunders *et al.*, 2007). In addition, calibration records for semi-automated testing stations were reviewed to confirm that measurement instruments operated within acceptable tolerance limits, further strengthening data reliability.

4.9.2 Qualitative Trustworthiness

For the qualitative strand, trustworthiness was established through the principles of credibility, transferability, dependability, and confirmability (Creswell, 2009).

- Credibility was enhanced through triangulation, comparing information from multiple document sources - such as inspection reports, process manuals, and quality logs - to validate consistency.
- Transferability was supported by providing detailed contextual descriptions of the production environment, enabling readers to assess the applicability of findings to similar start-up or small-scale manufacturing contexts.
- Dependability was ensured by maintaining a clear and documented audit trail of all document reviews, coding decisions, and analysis steps.
- Confirmability was achieved by aligning all interpretations closely with the original records and avoiding subjective assumptions. The use of a structured ATLAS.ti-style coding framework for document analysis further strengthened analytical consistency and reduced researcher bias (Guetterman *et al.*, 2023).

Across both strands, methodological triangulation played a critical role in reinforcing validity and credibility (Creswell & Clark, 2017). Quantitative performance patterns were validated by qualitative evidence drawn from real operational documents, ensuring that results reflected both statistical reality and contextual truth.

The combined focus on validity, reliability, and trustworthiness ensured that the study's findings were not only accurate and reproducible but also meaningful within the practical realities of the manufacturing environment.

4.10 Ethical Considerations

The research was conducted in compliance with ethical principles to ensure integrity, transparency, and responsible handling of all information. The following measures were implemented throughout the study:

- Permission and Organisational Consent:
  Formal permission was obtained from the organisation to access and analyse production data, quality documentation, and system information relevant to the research.
- Confidentiality:
  All organisational and process data were treated as confidential. Sensitive production and quality records were anonymised before inclusion in the study to prevent disclosure of proprietary information.
- Anonymity:
  The company and its processes are referred to in a generalised form throughout the dissertation. No individual, department, or data source is identifiable in the published document.
- Data Security:
  All digital data and records were stored on a password-protected computer accessible only to the researcher. Backup copies were securely stored on encrypted drives to prevent unauthorised access.
- Purpose Limitation:
  Data collected from the organisation were used exclusively for this research. No information was shared or repurposed beyond the academic requirements of this study.
- Research Integrity:
  The researcher maintained neutrality during data collection and analysis, ensuring that findings were based solely on evidence rather than personal bias or institutional influence.
- Transparent and Accurate Reporting:

Results and interpretations were presented honestly, with all data sources cited accurately. No manipulation or omission of findings was performed to influence outcomes.

These measures ensured that the study was conducted responsibly, preserving the integrity of both the research process and the collaborating organisation.

4.11 Limitations of the Methodology

While the research design was carefully developed to align with the study objectives, several methodological limitations were recognised. These limitations are primarily related to the operational environment of a start-up manufacturing facility and the availability of production data during the research period.

i. Scope of Data:

The study was limited to data obtained from specific production lines involved in lithium-ion battery assembly. As such, results may not fully represent other manufacturing areas, such as cable assembly or inverter integration, which operate under different conditions.

ii. Time Constraints:

Data collection was conducted within a defined period that coincided with ongoing process changes and system upgrades. This restricted the opportunity to capture longer-term performance trends or assess the full maturity of newly implemented semi-automated systems.

iii. Process Variability:

As a developing start-up, the company’s production environment experienced frequent adjustments in process flow, equipment configuration, and workforce allocation. These operational fluctuations introduced variability that could influence defect rates and throughput comparisons between manual and semi-automated systems.

iv. Data Completeness and System Reliability:

Some digital records, particularly from early automation stages, contained gaps due to system calibration and data logging inconsistencies. These were managed through data cleaning and cross-verification with supporting quality reports to maintain analytical reliability.

v. Limited Generalisability:

The research was confined to a single case study within a specific organisational and industrial context. While findings provide valuable insights into start-up renewable-energy manufacturing, results may not be universally transferable to larger or fully automated environments.

To mitigate these limitations, the study employed data triangulation, cross-referencing multiple data sources and verifying quantitative results through qualitative documentation and observation. Despite these constraints, the methodological framework remained robust and produced valid, contextually grounded findings that address the study’s objectives effectively.

4.12 Chapter Summary

This chapter presented the methodological framework used to achieve the research aim of enhancing quality management through semi-automation and digital integration in a start-up battery manufacturing environment. The chapter outlined the philosophical foundation, research design, data collection, analysis procedures, and the measures taken to ensure validity, reliability, and ethical compliance.

The study adopted a pragmatic paradigm within a mixed-methods design, integrating both quantitative and qualitative data to provide a comprehensive understanding of the research problem. The quantitative component focused on analysing production data - including defect rates, throughput, and SPC trends - to quantify the impact of semi-automation and digital monitoring on performance. The qualitative component complemented this by examining process documentation, quality records, and observational data to contextualise the numerical results.

An abductive approach guided the study, combining deductive testing of established quality management theories with inductive insights drawn from operational evidence. The use of concurrent triangulation allowed both data strands to be integrated and interpreted collectively, producing findings that are both statistically grounded and contextually meaningful.

Ethical integrity was maintained throughout the study, with data confidentiality, organisational consent, and researcher neutrality ensured at every stage. While the study faced practical constraints such as data variability and limited scope, these were mitigated through triangulation and cross-verification to preserve analytical robustness. Overall, the chosen methodological approach was well suited to the applied nature of the research, enabling the generation of both theoretical insights and practical recommendations for improving quality performance through semi-automation and digital integration.

The next chapter, Chapter Five: Data Analysis and Discussion, presents and interprets the findings derived from the methods described here, demonstrating how the research objectives were achieved through the integration of quantitative and qualitative results.

CHAPTER FIVE: DATA ANALYSIS AND DISCUSSION

5.1 Introduction

This chapter forms the heart of the research as it builds on the foundation created in Chapters One to Four. It presents the analysis of the collected data and provides a discussion of the findings in relation to the stated research objectives. The analysis draws on SPC, scrap cost modelling, supported by production performance records and RCA logs. Together, the findings provide the evidence base for the conclusions and recommendations that follow.

5.2 Quantitative Data Analysis

5.2.1 Overview of Quantitative Data

The quantitative analysis examines production data obtained from the battery assembly line to assess the effects of semi-automation on product quality and operational efficiency. The data were collected from multiple sources, including aging test results, inline monitoring records, acceptance test procedure outcomes, throughput reports, time-study measurements, and root-cause logs. These datasets collectively represent the operational and quality performance of both manual torquing and semi-automated welding processes during the period of January 2024 to June 2025.

The dataset encompasses several core variables, namely voltage behaviour across the discharge, charge, and final-charge stages during the aging cycle; temperature behaviour during charge and discharge cycles; internal resistance and voltage behaviour during inline monitoring values for welded assemblies; and overall process performance indicators such as First Pass Yield, total throughput, and defect distribution.

Statistical analysis was performed using Microsoft Excel and IBM SPSS, enabling the computation of descriptive statistics, control charts, and inferential tests.

This analysis focuses on identifying significant trends that demonstrate the impact of semi-automation on voltage stability, variation control, thermal performance, and production efficiency. Each stage of analysis is supported by corresponding statistical evidence, graphical representation, and process interpretation. See Table 5.1:

Table 5.1: Dataset Overview: variables, sources, and timeframe

Variable	Source	Description	Period Covered
Voltage (Discharge, Charge, Final Charge)	Aging tests	Electrical stability measurements during charge - discharge cycles	Jan 2024 – Jun 2025
Temperature (Discharge, Charge, Final Charge)	Aging tests	Thermal stability measurements during charge - discharge cycles	Jan 2024 – Jun 2025
Internal Resistance & Voltage	Inline monitoring (in real-time)	Measurement of uniformity across cell joints	Jan 2025 – Jun 2025
FPY and Throughput	Production records	Yield and total number of packs assembled	Jan 2025 – Jun 2025
Defect Classification	Root Cause logs	Categorised defects (Human Error, Material, Method, etc.)	July 2024 –Jun 2025
Process Time Study	Time-tracking sheets	Task duration data for joining, assembly, and inspection	Jan 2024 – Jun 2025

5.2.2 Descriptive Statistics

Voltage Stability and Process Behaviour

Voltage data from the discharge, charge, and final-charge stages were analysed to determine the relative performance and consistency of torqued and welded battery packs. The results indicate distinct differences between the two joining methods:

Discharge stage (Figure 5.4): Torqued packs averaged 44.91 V, whereas welded packs averaged 44.25 V.

Charge stage (Figure 5.5): Torqued packs averaged 57.50 V, while welded packs averaged 56.71 V.

Final-charge stage (Figure 5.6): Torqued packs recorded 53.29 V compared with 49.96 V for welded packs.

The control charts demonstrate that torqued assemblies frequently exceeded of upper and lower control limits, signifying the presence of special-cause variation primarily linked to inconsistent torque application, operator technique, and tool calibration. In contrast, welded assemblies displayed a narrower distribution range and minimal deviations from the process mean, confirming improved repeatability and control under semi-automation.

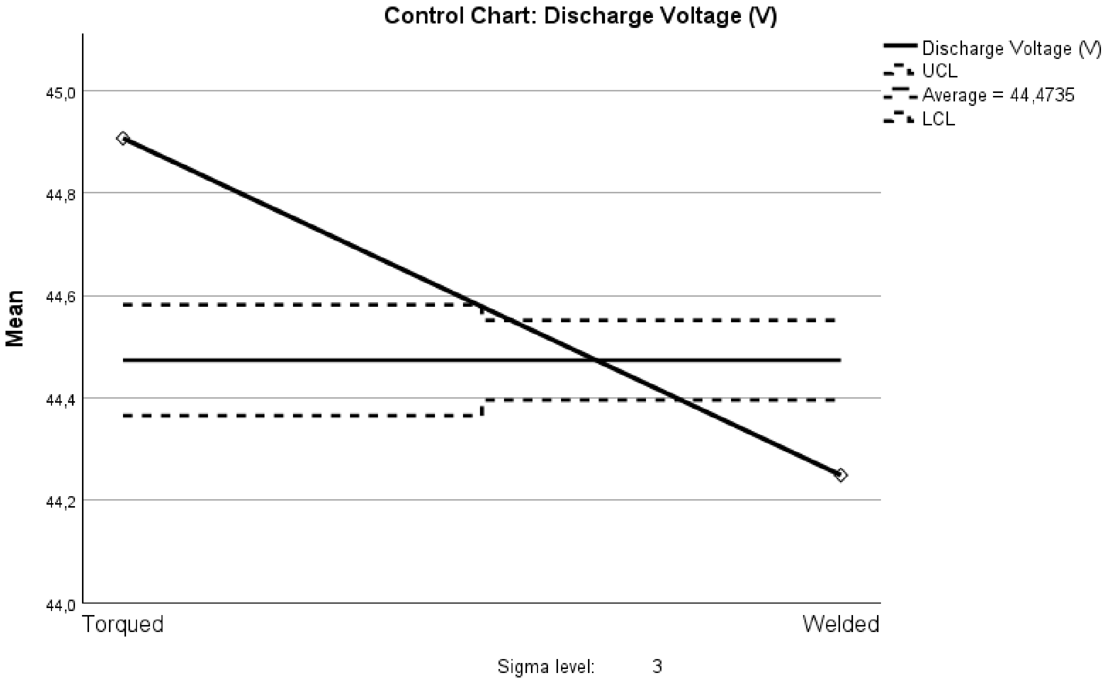

Figure 5.4: X̄–R Chart – Discharge Voltage (Torqued vs Welded)

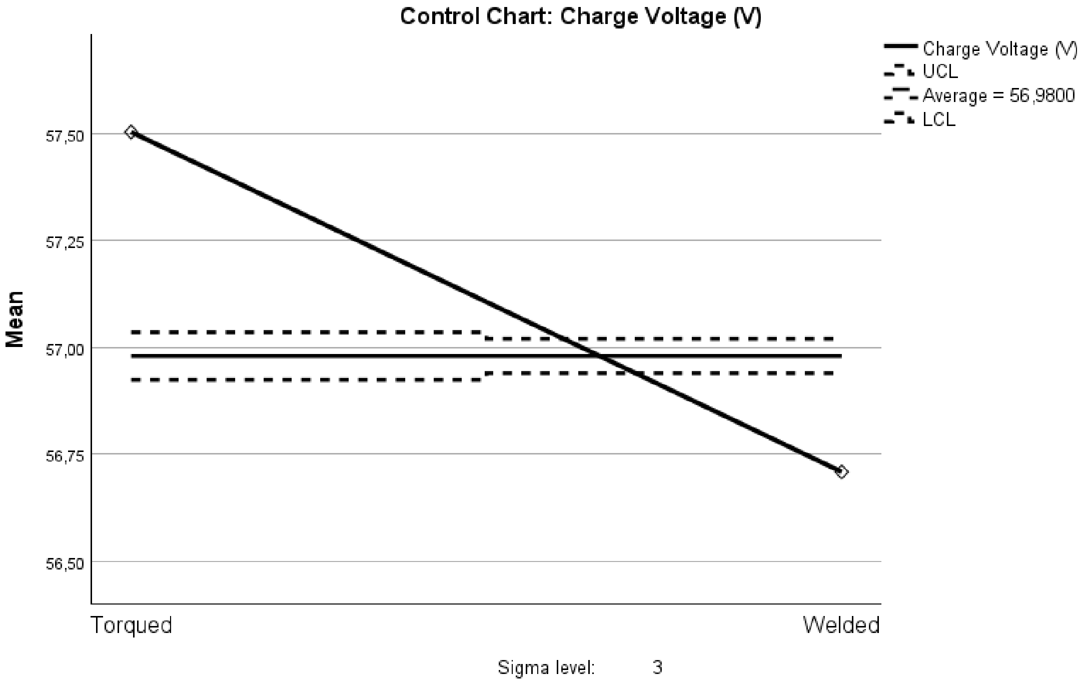

Figure 5.5: X̄–R Chart – Charge Voltage (Torqued vs Welded)

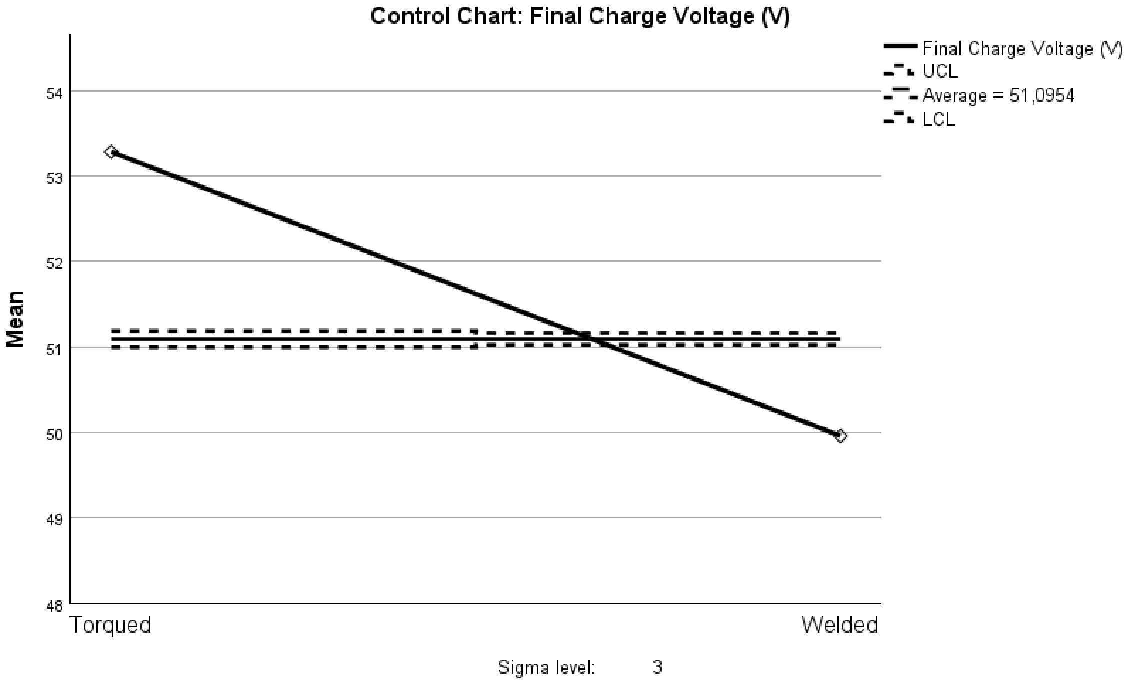

Figure 5.6: X̄–R Chart – Final-Charge Voltage (Torqued vs Welded)

The standard deviation charts (see Figure 5.16, Figure 5.17 and Figure 5.18 in the appendix) for each voltage stage further reinforce these trends, showing noticeably higher variability in torqued assemblies compared to welded ones. This greater spread in standard deviation reflects less control over voltage uniformity in manual processes, whereas welded packs exhibit tighter clustering, indicative of improved process consistency and repeatability.

In addition to voltage stability, the millivolt difference analysis (Figure 5.19, Figure 5.20, Figure 5.21, Figure 5.22, Figure 5.23 and Figure 5.24 in the appendix) provided further insight into cell balance across both assembly types. Torqued packs exhibited wider mV spreads between the highest and lowest cell voltages, suggesting uneven current distribution and potential contact resistance at joint interfaces. Welded packs, however, maintained consistently lower mV differentials, demonstrating improved uniformity and electrical connectivity resulting from the precision of laser welds.

Temperature Stability and Thermal Behaviour

The temperature control charts, Figure 5.7 to Figure 5.9 shown below, reveal a clear pattern distinguishing the thermal behaviour of torqued and welded battery packs. Across charge, discharge, and final-charge stages, torqued assemblies consistently operated at higher mean temperatures, with discharge and charge cycles averaging approximately 36 - 41 °C compared to 34 °C for welded packs. The elevated thermal profile of torqued joints indicates higher internal resistance and localised heating, symptomatic of inconsistent torque application and variable surface contact. In contrast, welded packs demonstrated lower and more uniform temperature trends, suggesting superior current transfer efficiency and improved heat dissipation achieved through consistent metallurgical bonding.

Although minor variations were observed in the standard deviation charts (see Figure 5.25, Figure 5.26 and Figure 5.27 in the appendix) both joining methods remained within control limits, confirming overall process stability. Notably, welded packs displayed tighter control during the cooling phase, with final-charge temperatures averaging around 31 °C compared to 29 °C for torqued packs, reflecting predictable and uniform cooling behaviour rather than instability. Collectively, the temperature trends confirm that semi-automated welding enhances thermal efficiency, reduces resistive heating, and delivers a more stable operating profile - attributes that directly contribute to improved product quality and energy efficiency in production.

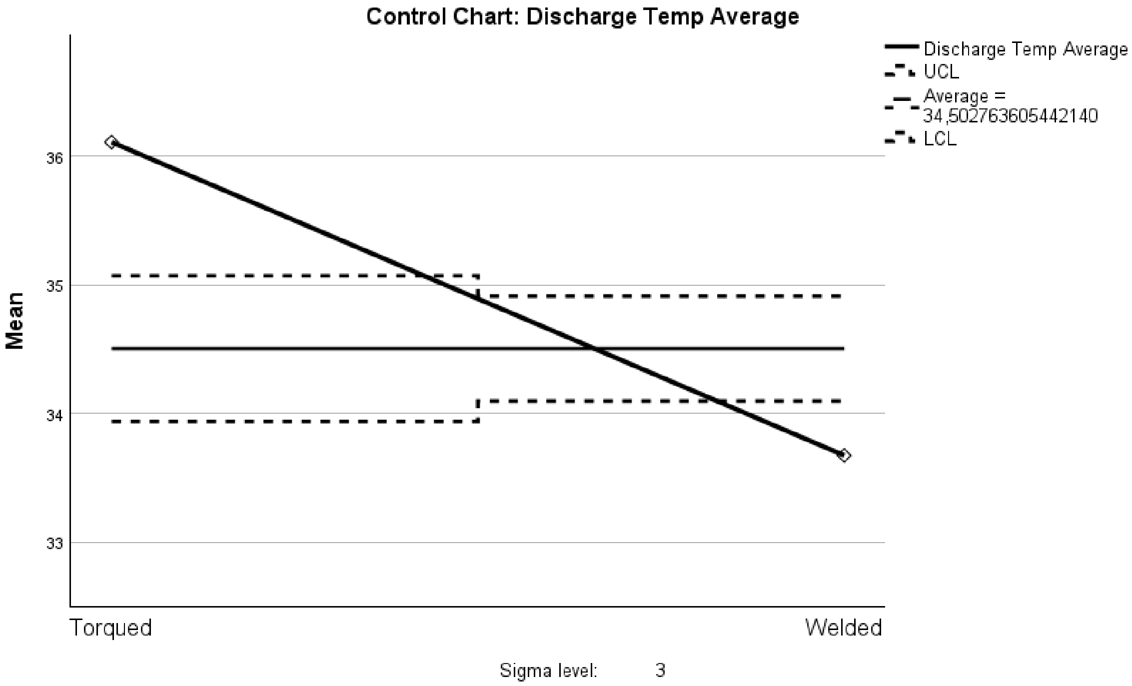

Figure 5.7: X̄–R Chart – Discharge Temperature (Torqued vs Welded)

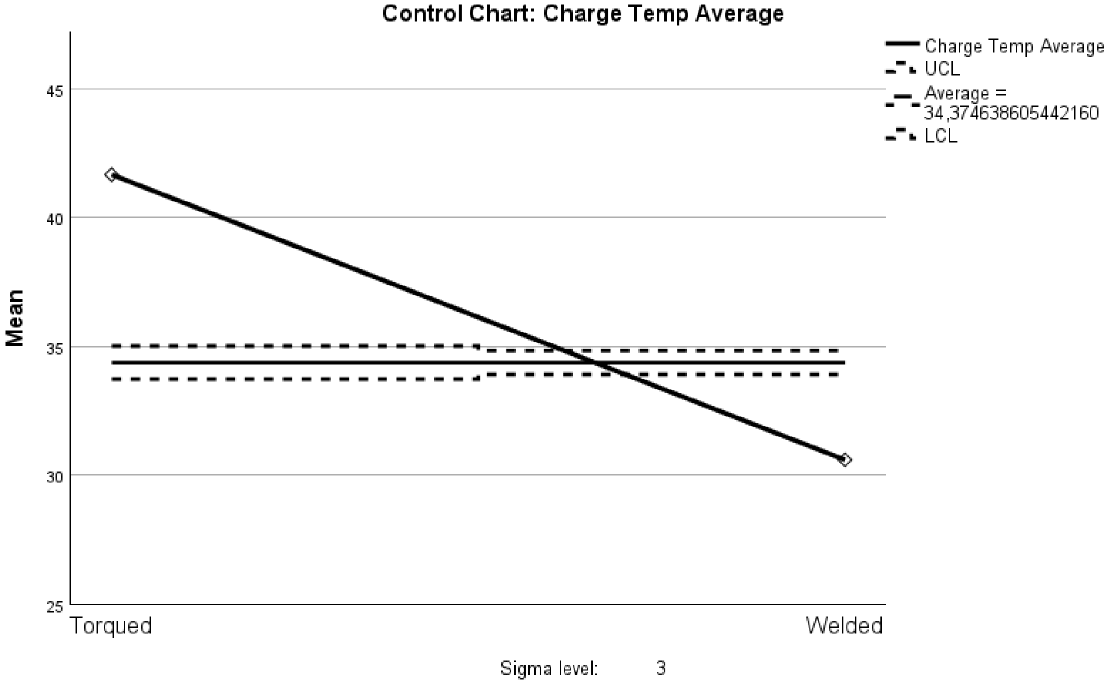

Figure 5.8: X̄–R Chart – Charge Temperature (Torqued vs Welded)

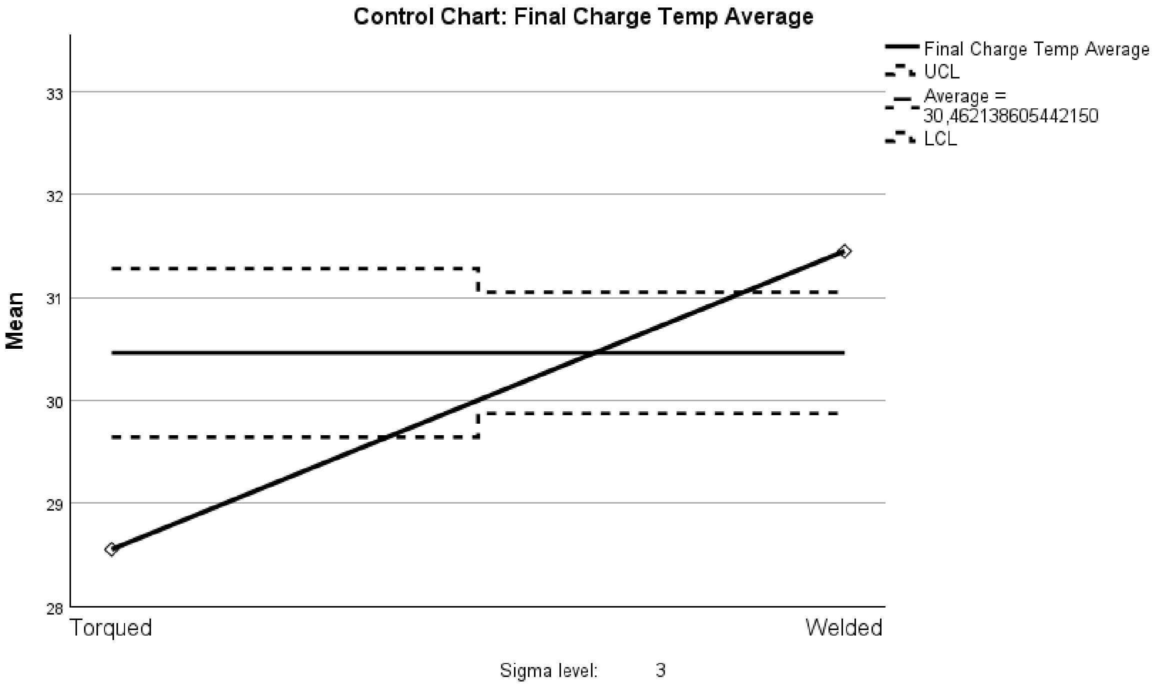

Figure 5.9: X̄–R Chart – Final Charge Temperature (Torqued vs Welded)

Voltage - Temperature Correlation

The temperature findings align closely with the voltage analysis, reinforcing that semi-automated welding improves both electrical and thermal stability. Lower temperature profiles correspond with steadier voltage control, confirming that reduced contact resistance enhances energy transfer and decreases heat generation. Together, these results demonstrate that welding achieves greater process uniformity and efficiency - validating the positive impact of semi-automation on quality performance and production consistency.

Production Efficiency Indicators

Analysis of production data from January to June 2025 revealed consistent improvement in efficiency following the introduction of semi-automated welding. First Pass Yield (Figure 5.10) for welded assemblies stabilised close to 100 %, while torqued assemblies fluctuated between 80 % and 95 %, indicating ongoing variability and reliance on manual correction. Throughput data (Figure 5.11) showed that the welded line exceeded 350 packs per month by June 2025, whereas the torqued line remained below 100 packs per month.

Time-study measurements further supported this improvement as show in Table 5.2. Average assembly duration for torqued packs was approximately 391 minutes, compared to 335 minutes for welded packs, representing a reduction of approximately 14 %. The most notable time savings occurred during the joining stages, where manual busbar and rail fitting operations were replaced with automated laser welding and controlled handling systems. Refer to Table 5.8 and Table 5.9 in the appendix for a detailed time-study.

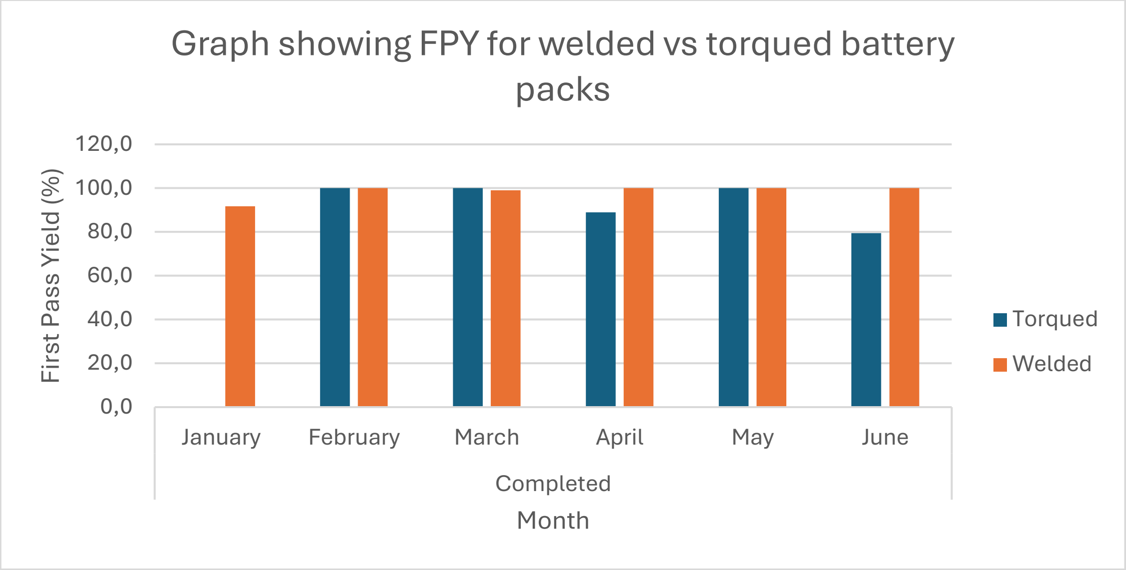

Figure 5.10: FPY for Welded vs Torqued Packs

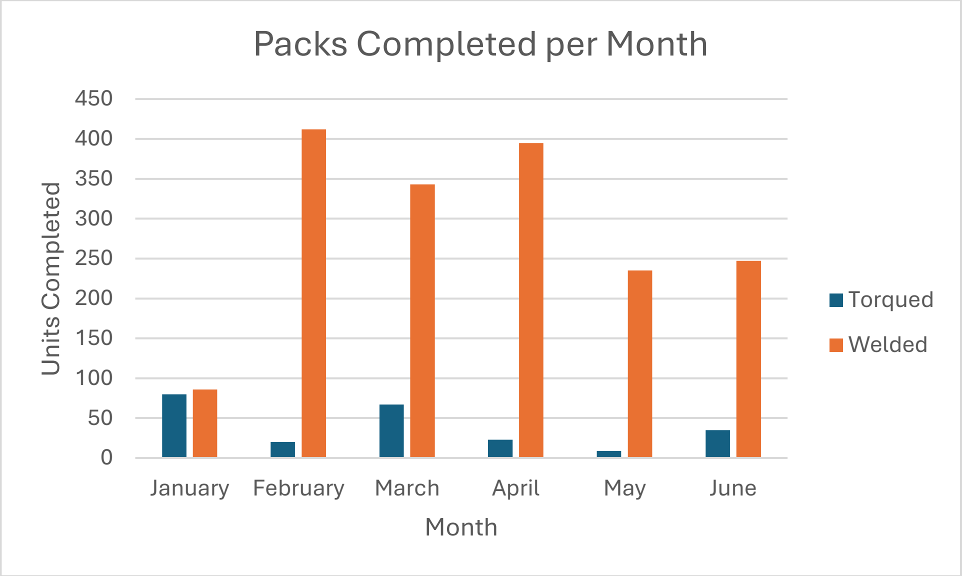

Figure 5.11: Packs completed per month

Table 5.2: Time-Study Summary – Task-Level Comparison between Torqued and Welded Processes

Process Stage	Torqued Process (min)	Welded Process (min)	Reduction (%)
Busbar Fitting	14.54	2.04	86.0
Rail Fitting	10.50	2.07	80.3
Strapping	7.49	1.29	82.8
Testing & Verification	21.00	19.80	5.7
Other Assembly Tasks	337.47	310.80	7.9
Total Assembly Time per Pack	391.00	335.00	14.3

Defect Distribution

The distribution of recorded defects in **Table 5.3** illustrates the contrasting failure patterns between the two assembly methods.

Table 5.3: Defect Type per Assembly Method

Assembly Method	Defect Type	Count
Torqued	Defective Product	4
Torqued	Human Error	24
Welded	Defective Product	174
Welded	Human Error	38

Although the total number of defects was higher in welded assemblies, this must be contextualised against total production volumes (≈ 2 100 welded packs versus ≈ 600 torqued packs). Normalised to production output, defect rates for welded packs were significantly lower. The defect categories also shifted from Man/Method causes in torqued assemblies to Machine/Material causes in welded assemblies. This transition represents a positive quality trend, as machine-driven defects are systematic, traceable, and correctable through calibration and maintenance, whereas human-related variation is less predictable and more labour-intensive to manage. Refer to Figure 5.12 below for common causes of quality risks in torqued assemblies.

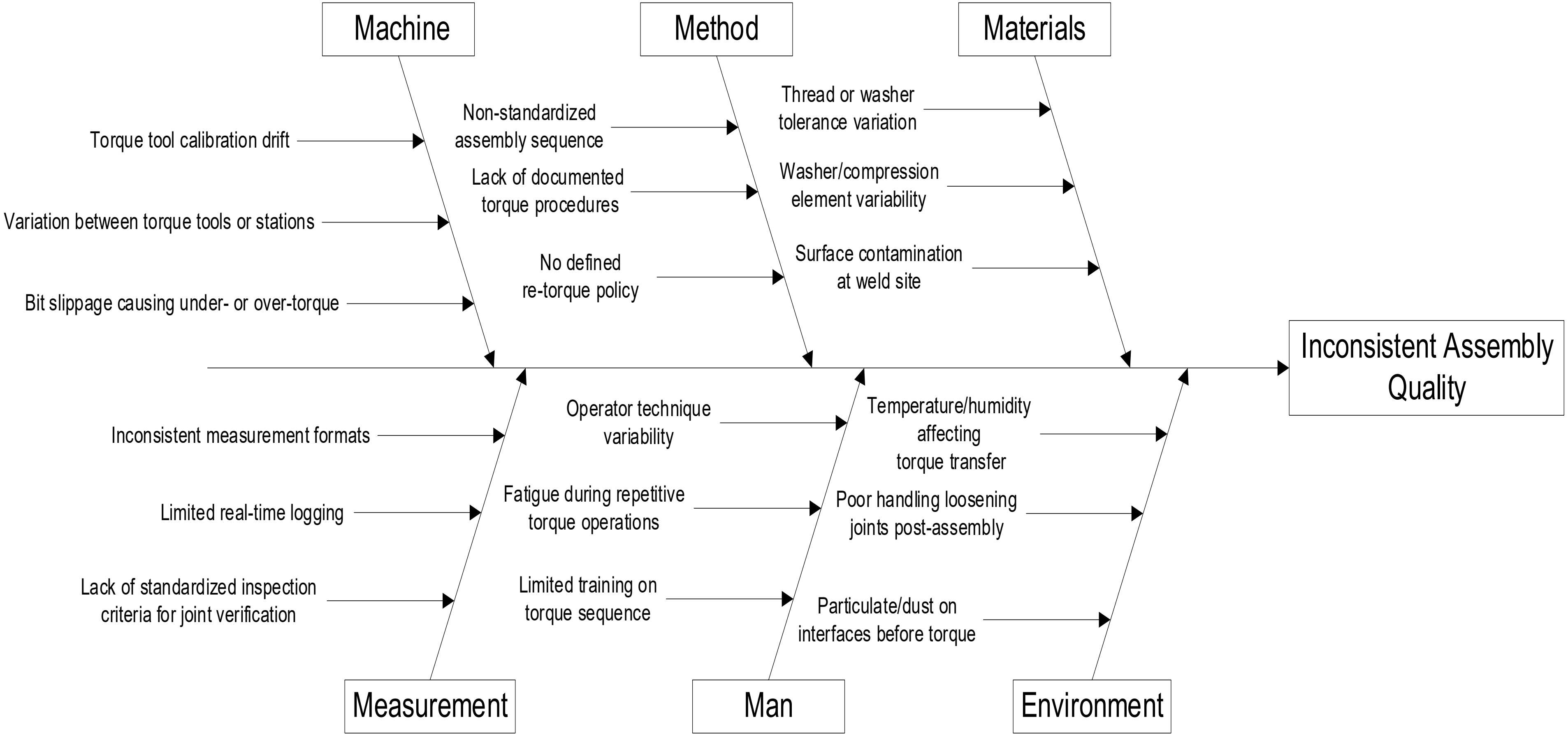

Figure 5.12: Common causes of quality risks in torqued assemblies

5.2.3 Inferential Analysis

Comparative Statistical Testing

Inferential analysis was conducted to determine whether the observed differences in mean voltages between the torqued and welded assemblies were statistically significant. The results of the independent-samples *t*-tests are summarised below in Table 5.4:

Table 5.4: Statistical comparison of voltage performance for torqued vs. welded battery packs

Parameter	*t*-value	*p*-value	Interpretation
Discharge Voltage (V)	−15.09	< 0.001	Welding significantly reduced variation
Charge Voltage (V)	−35.01	< 0.001	Highly significant improvement in voltage stability
Final-Charge Voltage (V)	−86.67	< 0.001	Extremely significant difference; improved process control

The results confirm that semi-automation has a statistically and practically significant effect on process consistency. Lower variability in welded assemblies indicates improved uniformity of electrical response, consistent with the visual trends observed in SPC charts.

Process capability indices (Cp, Cpk) were evaluated for voltage and temperature parameters to quantify variation control. All indices were below the benchmark of 1.33, indicating that both joining methods remain in the process-improvement phase. Torqued assemblies showed slightly better centering under the current limits, while welded assemblies maintained tighter overall variation. These findings are consistent with the SPC results and highlight opportunities for further optimisation before full capability is achieved.

Inline Monitoring Descriptive Statistics

Error! Reference source not found. Below are the descriptive statistics for inline, real-time, monitoring data from welded battery packs.

Table 5.5: Descriptive Statistics for real-time monitoring (Welded Packs)

Metric	N	Minimum	Maximum	Mean	Std. Deviation
Voltage (V)	1476	47.76	55.99	52.69	0.72
IR (mΩ)	1476	5.56	78.51	6.22	2.79

The voltage readings ranged from 47.76 V to 55.99 V, with an average of 52.69 V, indicating a stable process within expected performance parameters. Internal resistance values varied between 5.56 mΩ and 78.51 mΩ, averaging 6.22 mΩ. The relatively low mean IR and narrow voltage spread confirm consistent weld quality and reliable current flow across cells, reflecting effective real-time monitoring control and equipment stability.

Scrap Cost and Economic Impact

Scrap cost analysis applied a unit cell cost of R 335.90, equivalent to R 2 687.20 for an 8-cell pack and R 5 374.40 for a 16-cell pack. The average estimated scrap cost for a defective welded pack was approximately R 4030.80 per pack, compared with R 2855.15 for torqued packs. See Table 5.10 in the appendix for detailed calculations of scrap cost. Although the short-term cost appears higher for welding, the pattern reflects a learning-curve phase typical of early automation implementation. As the process stabilises, machine-related defects are expected to decline sharply, while the cost of recurring manual variation on the torqued line remains structurally embedded. The long-term financial outlook therefore favours semi-automation due to its predictable cost reduction potential once optimisation is complete.

Table 5.6: Comparative Scrap Cost and Process Impact – Torqued vs Welded

Parameter	Torqued Process	Welded Process	Interpretation
Average Pack Scrap Cost (R)	R 2855.15	R 4030.8	Higher initial loss due to process learning curve
Defect Type	Human error–related	Machine/material–related	Transition to controllable, systematic defects
Root Cause Category	Man/Method	Machine/Material	Indicates improvement in controllability

5.2.4 Summary of Quantitative Findings

The quantitative findings demonstrate clear improvements in process stability, uniformity, and throughput resulting from semi-automated welding. Across all production stages, voltage variation decreased markedly, and SPC analysis confirmed tighter control limits and improved process predictability. The First Pass Yield stabilised near 100 %, with throughput more than tripling compared to the manual process, supported by reduced rework frequency and shorter assembly times.

Although both joining methods remain below full capability benchmarks (Pp and Ppk < 1.0), welding provided a consistent foundation for optimisation and long-term improvement. The short-term increase in scrap cost is characteristic of the adjustment period following the introduction of new technology. Nevertheless, this trade-off leads to measurable benefits in process reliability, reduced rework cycles, and overall operational efficiency.

From a quality engineering perspective, the quantitative results confirm that semi-automation transitions the production system from a reactive, inspection-based approach to a proactive, process-controlled environment. This transformation establishes a strong empirical basis for subsequent qualitative and integrative analyses that explore the organisational and systemic factors influencing these outcomes.

5.3 Qualitative Data Analysis

5.3.1 Overview of Qualitative Data

The qualitative analysis complements the quantitative results by examining the organisational, behavioural, and systemic factors influencing quality performance within the battery assembly environment. Data were drawn from multiple internal sources, including internal audit reports, observation logs, and quality logs.

The coding process generated recurring categories linked to the primary themes of process control, training and competence, documentation and traceability. Sankey diagrams were used to visualise the relationships between audit findings, corrective actions, and recurring issues. The outputs reveal how operational weaknesses, skill gaps, and system fragmentation influenced the performance trends observed in the quantitative analysis.

Each theme is discussed below, supported by Sankey diagrams (Figure 5.13, Figure 5.14 and Figure 5.15) derived from ATLAS.ti outputs. These qualitative insights explain the human and systemic dimensions of the statistical results presented earlier, providing context for understanding how process improvement and semi-automation were influenced by organisational realities.

Figure 5.13: Sankey Diagram – Service Delivery and Assurance (2024)

Figure 5.14: Sankey Diagram – Quality Assurance (2024)

Figure 5.15: Sankey Diagram – Production Processes

5.3.2 Thematic Analysis

Theme 1: Process Control and Operational Consistency

Process control emerged as the most dominant theme across all audit data and observational notes. Despite clear process definitions for battery assembly, control over critical parameters such as torque accuracy, weld current, and inspection protocols remained inconsistent. Instances were recorded where operators reacted to quality issues only after failures were detected, rather than following documented reaction plans.

Variation in response procedures was common, with deviations often handled differently depending on which shift was present. This inconsistency was compounded by the lack of standardised reaction plans and incomplete documentation of deviations. As a result, similar nonconformities reappeared across audits, reflecting weak containment and feedback loops.

Limited operator training further undermined process control. Manual torque operations were particularly prone to variation due to differences in skill level and fatigue, while verbal-only instruction for semi-automated welding setup left room for interpretation errors. The absence of standard work instructions and operator verification checklists also contributed to inconsistent product outcomes.

Improvement requires formal reaction plans, structured rework protocols, and real-time monitoring integration to strengthen containment and feedback. These measures are consistent with ISO 9001:2015, which mandates documented control and evidence-based verification to maintain process conformity.

Theme 2: Documentation, Record Control, and Traceability

Audit findings revealed that document and record control remain critical weaknesses in the current Quality Management System. Discrepancies were found between barcode logs, serial number records, and production routing slips, preventing complete traceability of individual battery packs through the manufacturing and testing stages. Although a barcode-based tracking system was introduced in late 2024, misalignment between barcode generation and serial number assignment systems led to unlinked or missing records. In several cases, operators omitted barcode scans during production, resulting in fragmented traceability. As a consequence, fault tracing relied on physical inspection rather than digital records, significantly limiting root-cause identification. This lack of alignment between data sources reflects a common challenge in start-ups, where digital infrastructure evolves incrementally and manual processes remain in use alongside automated systems (Schlemitz & Mezhuyev, 2024). From a QMS perspective, incomplete traceability undermines process verification, customer confidence, and the organisation’s ability to conduct effective failure analysis.

Notably, traceability improved markedly between January 2025 and June 2025 as document control and data logging procedures matured. The company’s migration of barcode and ATP records to cloud-based storage improved accessibility and reduced information loss. However, complete integration between systems remains pending. Ensuring a single, unified traceability database that links all stages - from welding to aging to ATP - remains essential for achieving ISO 9001 alignment and long-term data reliability.

Theme 3: Training, Competence, and Employee Engagement

Training and competence were identified as recurring weaknesses in the qualitative data. Operators often lacked up-to-date training on process changes, particularly during the transition from manual torquing to semi-automated welding. This issue was highlighted across several audit entries where nonconformances were linked to procedural deviations, incomplete checklists, or uncalibrated torque tools.

Competence gaps were especially evident in tasks requiring precision, such as torque application and parameter verification during welding. Because torque errors are not always visually detectable, operators' awareness and skill level directly influenced product quality. Similar patterns have been observed in emerging manufacturing firms, where training is often treated as a one-time event rather than an ongoing development process (Oommen & Vinayagam, 2024).

The introduction of semi-automation has reduced dependency on manual skill but simultaneously increased the need for technical understanding and digital literacy. Operators now require training not only in mechanical assembly but also in interpreting inline monitoring data in real-time, and responding appropriately to alarms. Continuous, structured training programs that align with ISO 9001 Clause 7.2 (Competence) are therefore essential to ensure that semi-automation delivers sustainable quality improvements.

Theme 4: Corrective and Preventive Action and Quality Feedback

The analysis of corrective action logs, internal audits, and root-cause trackers revealed that nonconformities were being recorded but not always effectively closed. Repeated findings across audit cycles indicated that certain issues - particularly torque joint reliability and documentation lapses - were not consistently verified for effectiveness after corrective action implementation.

This gap suggests a lack of systematic CAPA verification and trend-based preventive action. In several cases, nonconformances were resolved temporarily without updating procedures or adjusting process controls to prevent recurrence. The absence of a digital CAPA tracking interface further complicated monitoring and cross-departmental accountability.

A robust CAPA framework is critical for transforming reactive problem-solving into proactive risk management. Integration of statistical data - such as SPC results, defect trends, and scrap cost analyses - into management review meetings would strengthen the link between operational performance and decision-making. This approach aligns with Narahari *et al.* (2023), who emphasise the importance of embedding CAPA into organisational culture as a mechanism for continuous improvement and learning.

5.3.3 Summary of Qualitative Findings

The qualitative findings highlight that while semi-automation and digital monitoring have improved process consistency, persistent weaknesses in documentation, traceability, and training continue to limit the full potential of the Quality Management System.

Operator competence and procedural discipline remain critical determinants of process stability, particularly in a start-up environment where formalised systems are still maturing.

The analysis confirms that many of the issues identified in quantitative results - such as variation in process control, rework frequency, and defect recurrence - are rooted in systemic and behavioural factors. Specifically, the lack of standardised reaction plans, incomplete record control, and limited feedback integration prevent continuous learning and sustained improvement.

Collectively, these themes reinforce the conclusion that technical innovation alone cannot secure quality maturity. Effective process control requires a parallel investment in human capability, structured documentation, and digital traceability. As the company transitions from reactive operations to a process-driven quality culture, these qualitative insights provide critical guidance for integrating QMS practices with semi-automated production systems.

5.4 Integration of Quantitative and Qualitative Findings (Mixed-Methods Discussion)

The integration of results presents a holistic understanding of how semi-automation and digital integration influence quality performance in a resource-constrained manufacturing start-up. Quantitative data established measurable patterns of improvement in process stability and defect trends, while qualitative findings provided context to interpret the organisational and behavioural dimensions underpinning these results.

The synthesis of both data strands demonstrates that improvements achieved through technology implementation - such as semi-automated welding, inline monitoring, and data analytics - are contingent on human factors, documentation discipline, and management commitment. The discussion below aligns these integrated findings with the four research objectives that guided the study.

5.4.1 Cross-Analysis of Findings

Objective 1: To identify the essential components of an effective QMS for a start-up.

Quantitative results revealed that process consistency, traceability, and rework containment were the strongest determinants of performance stability. SPC trends showed that while semi-automated welding achieved lower variation in final charge voltage, instability persisted in early production cycles due to inconsistent reaction plans and incomplete process documentation.

Qualitative insights reinforce these findings, showing that the absence of robust document control and incomplete traceability limited feedback and learning from nonconformances. Internal audit results repeatedly identified gaps in barcode integration, checklists, and calibration logs. These deficiencies weakened process verification and made it difficult to conduct trend-based CAPA.

Together, the findings suggest that for start-ups, an effective QMS must prioritise process control, documentation, competence management, and digital traceability before full automation maturity can be achieved. This echoes the view of Tejaningrum (2022) that QMS effectiveness in emerging firms depends on the synergy between structured processes and workforce capability rather than certification alone.

Objective 2: To determine the effect of semi-automation on product quality and production efficiency.

Quantitative analysis showed a measurable improvement in process efficiency following the introduction of semi-automated welding. Average assembly time per pack reduced by approximately 14 %, while variance in charge and discharge voltage stability narrowed significantly ($p < 0.001$). Defect analysis indicated a shift from human error–driven defects (torqued) to process control–related issues (welded), signifying a move toward more systematic, predictable quality performance.

Qualitative evidence supports these findings. Observational notes and audit themes highlighted that the main benefits of semi-automation included improved consistency, reduced operator fatigue, and faster process throughput. However, qualitative data also identified transitional challenges: operators lacked confidence with new equipment, training materials were incomplete, and troubleshooting responsibilities were not clearly assigned.

Thus, while semi-automation enhanced efficiency and reduced variation, its success was partially constrained by the maturity of human and procedural systems. In essence, semi-automation functioned as a catalyst rather than a substitute for quality management. The combination of technical control and human competence determines overall system capability.

Objective 3: To evaluate the effectiveness of real-time monitoring in early detection and resolution of quality issues.

Quantitative data from inline monitoring and Acceptance Test Procedure systems confirmed that real-time data capture improved the detection of voltage deviations and accelerated defect containment. Inline monitoring provided stable voltage and IR readings (mean ≈ 52.7 V; 6.2 mΩ), verifying process stability, while ATP records offered immediate pass/fail feedback for each pack. Yet, both systems exhibited traceability limitations - missing ATP entries and incomplete barcode scans disrupted data continuity. Qualitative findings mirrored these gaps: operators valued the responsiveness of real-time systems but cited integration challenges. The convergence between data strands indicates that real-time and inline monitoring are technically effective but under-utilised. Their full potential depends on stronger data discipline, complete system integration, and structured feedback review - aligning with Stock *et al.* (2021) who emphasise that digital tools achieve maximum value only when embedded within organisational learning loops

Objective 4: To develop strategies for integrating and automating quality processes and assess their impacts.

The integrated analysis revealed that automation and digitalisation strategies are most successful when introduced incrementally, supported by competence development and procedural refinement. Quantitative evidence indicated that while semi-automation improved consistency, process capability indices remained below optimal thresholds due to system imbalance between machine precision and procedural discipline.

Qualitative analysis provided further depth, showing that organisational culture, training, and communication gaps hindered seamless digital integration. Several audit findings documented delayed implementation of corrective actions, inconsistent data review practices, and limited operator input into system updates.

Synthesising both data strands suggests that the most sustainable path for integration in a start-up context involves phased digital adoption, cross-functional training, and real-time data utilisation. This approach fosters learning while minimising disruption. These insights support the perspective of Liu *et al.* (2023) who noted that the digital transformation of quality functions in small enterprises should evolve gradually to align with workforce readiness and resource availability. See summary of findings and recommendations in Table 5.7 below.

Table 5.7: Summary of Cross-Functional Integration Readiness Assessment

Category	Findings	Implications	Recommended Action
Automation and Digitalisation	Implementation success improves when introduced incrementally, with support for procedural refinement and operator training.	Full-scale automation without readiness may cause instability and resistance.	Adopt a phased implementation plan supported by pilot testing and training.
Process Capability	Semi-automation improved consistency, but process capability indices remain below optimal thresholds.	System imbalance between machine precision and procedural discipline limits output stability.	Align procedural discipline and standard work to machine performance levels.
Organisational Culture	Communication gaps and limited engagement hindered digital integration.	Inconsistent collaboration reduces data reliability and slows corrective action.	Enhance transparency and operator involvement in digital feedback systems.
Training and Competence	Limited structured training delayed adaptation to semi-automated systems.	Skill gaps reduce utilisation of automation capabilities.	Develop cross-functional training plans focusing on system use and problem-solving.
Corrective Action and Data Use	Delayed corrective actions and limited operator input were observed in audits.	Weak feedback loops hinder continuous improvement and traceability.	Implement digital CAPA tracking with automated reminders and performance dashboards.
Integration Strategy	Gradual integration aligned with workforce readiness ensures long-term adoption.	Phased adoption fosters learning while minimising disruption.	Adopt a roadmap for incremental digital transformation tied to competence milestones.

5.4.2 Discussion in Relation to Literature

The findings of this study align with and extend existing literature on the intersection of quality management and digital manufacturing. Consistent with the work of Duffner *et al.* (2021), the results confirm that partial automation - when supported by feedback mechanisms and data analytics - can significantly enhance process control and reduce variability. However, the findings also reinforce Tshifhumulo *et al.* (2025) who identified that in South African manufacturing, systemic barriers such as supply-chain volatility, skill shortages, and infrastructure limitations often dilute the benefits of technological advancement.

This research further supports Ukoba *et al.* (2025) who argue that successful digital transition in the renewable energy sector requires not only technological investment but also institutional learning and policy alignment. The qualitative insights presented here - particularly the emphasis on workforce competence and procedural discipline - extend this perspective by highlighting the operational micro-level challenges within start-up contexts.

The study also builds on Tereza (2024) whose work on Quality 4.0 emphasises the integration of human, digital, and procedural systems. The current findings provide empirical evidence from a real-world case that validates this theoretical premise: that sustainable quality performance in semi-automated manufacturing is driven by synergy among technical tools, process discipline, and human competence.

5.4.3 Implications for Start-Up Quality Management

The synthesis of findings underscores that start-ups in emerging economies can achieve significant quality and efficiency gains through semi-automation and digital integration, but only when foundational QMS elements are stabilised. The evidence indicates that isolated technological upgrades without procedural integration often result in temporary or uneven benefits.

Practical implications derived from this study include the need for:

- Incremental automation strategies - introducing semi-automation in manageable phases supported by immediate feedback mechanisms.
- Integrated digital traceability systems - ensuring consistent data capture from production to testing stages.
- Continuous competence development - aligning operator training with evolving technology and digital literacy requirements.
- Real-time CAPA verification - linking statistical performance indicators directly to management review cycles.

These recommendations are particularly relevant for start-ups in the renewable energy sector, where limited resources and dynamic scaling create tension between rapid production demands and formal quality control. The integrated findings confirm that the maturity of quality systems depends as much on people and processes as on the sophistication of the tools used.

5.5 Summary of the Chapter

This chapter presented a comprehensive analysis of both quantitative and qualitative findings. Quantitative results demonstrated measurable improvements in process efficiency, voltage stability, and defect containment following semi-automation.

Qualitative results contextualised these improvements by identifying the organisational, procedural, and human factors influencing their sustainability.

By integrating both data strands, the study confirmed that while technological interventions drive measurable improvement, their long-term success depends on documentation discipline, operator competence, and process control maturity. The mixed-methods discussion thus provides a balanced, evidence-based understanding of how semi-automation and digital integration collectively enhance quality management within a start-up battery assembly environment.

The next chapter will build upon these insights to formulate conclusions and recommendations, presenting practical frameworks for scaling digital quality systems and guiding start-up manufacturers toward ISO 9001 maturity in renewable energy production.

CHAPTER SIX: CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

This chapter concludes the study by summarising its purpose, main findings, theoretical implications, and practical contributions. The study aimed to evaluate how semi-automation and digital integration enhance quality management in a start-up battery manufacturing environment within the renewable energy sector. Guided by four key objectives, the research investigated the foundational components of a QMS suitable for start-ups, examined the impact of semi-automation on product quality and operational efficiency, assessed the effectiveness of real-time monitoring, and proposed strategies for integrating and automating quality processes in resource-constrained contexts.

A mixed-methods approach was adopted to achieve comprehensive insights. Quantitative data were analysed using statistical tools and SPC-based performance metrics, while qualitative data - derived from internal audits, observations, and ATLAS.ti coding - provided contextual depth and organisational understanding. Together, these methods allowed the study to triangulate technical, operational, and behavioural factors influencing quality performance.

The chapter is organised into eight sections: a summary of the study, a synthesis of key findings per objective, overarching conclusions, practical recommendations, theoretical and managerial contributions, limitations, directions for future research, and a closing summary that reaffirms the study's academic and practical significance.

6.2 Summary of the Study

Chapter One introduced the research background, rationale, problem statement, aim, and objectives. It highlighted the challenge of implementing structured quality management practices in a start-up environment transitioning toward Industry 4.0.

Chapter Two presented a review of existing literature on quality management, semi-automation, and digital integration. It established the theoretical foundation by tracing the evolution from inspection-based quality approaches to Quality 4.0 paradigms, identifying a gap in empirical studies focused on start-ups in the renewable energy sector.

Chapter Three outlined the research design and methodology, justifying the use of a mixed-methods strategy to capture both measurable process performance data and contextual qualitative insights. The chapter described data sources, analysis tools, and ethical considerations.

Chapter Four detailed the system and process context, describing the operational setup of the company's assembly facility, including its transition from manual to semi-automated welding and its integration of real-time monitoring systems.

Chapter Five presented and interpreted the study's findings. Quantitative data demonstrated measurable improvements in process efficiency, defect rates, and product stability following semi-automation, while qualitative analysis revealed organisational challenges related to documentation, training, and traceability.

Collectively, these chapters show that the study successfully achieved its research aim: to provide an integrated understanding of how semi-automation and digital integration can enhance quality management in emerging renewable energy manufacturing start-ups.

6.3 Summary of Key Findings

6.3.1 Objective 1: To establish the essential components of an effective QMS for a start-up in the energy sector

The findings identified documentation, process control, competence management, and traceability as essential components of a functional QMS in a start-up environment. Quantitative results underscored that lack of documentation discipline directly correlated with inconsistent process control and higher defect rates. Qualitative data reinforced this by showing recurring audit findings related to incomplete records, poor calibration logs, and weak feedback mechanisms.

The study concludes that for start-ups, QMS implementation must focus on simplified but standardised procedures, ensuring adaptability without compromising control. The foundation should emphasise digital traceability, data accuracy, and structured competence development before advanced automation can yield sustainable benefits.

6.3.2 Objective 2: To determine the effect of semi-automation on product quality and production efficiency in battery assembly lines

Quantitative analysis demonstrated that semi-automation significantly improved process consistency and throughput. Assembly cycle time per pack decreased by approximately 14%, and variation in final charge voltage and discharge performance narrowed substantially. Statistical results ($p < 0.001$) confirmed the effect as significant. Qualitative data supported these trends by highlighting operator perceptions of improved uniformity, reduced fatigue, and easier defect containment. However, it also revealed transitional challenges, including incomplete operator training and unclear accountability for equipment adjustments. adjustments.

The study concludes that semi-automation enhances quality and efficiency by stabilising critical processes, but its impact depends on workforce readiness, equipment maintenance, and clear procedural frameworks.

6.3.3 Objective 3: To determine the effectiveness of real-time monitoring in the early detection and resolution of quality issues

Real-time monitoring proved instrumental in enabling early detection of process deviations. The ATP system provided immediate feedback on pass/fail outcomes and recorded voltage anomalies that facilitated faster corrective actions. Quantitative trends confirmed reduced downtime and fewer undetected failures. Qualitative insights revealed that while monitoring improved visibility, its full potential was constrained by incomplete data capture and under-utilisation of analytics in management reviews. Thus, real-time monitoring enhances responsiveness but requires system integration and disciplined data practices to achieve continuous improvement.

6.3.4 Objective 4: To develop strategies for integrating and automating quality processes, and to assess their anticipated impacts on operations

The study developed a set of phased integration strategies suitable for start-up contexts. These included incremental automation based on process maturity, cross-functional training to build digital competence, and the use of low-cost monitoring and data capture tools.

Qualitative evidence suggested that cultural adaptation and leadership involvement were vital for sustaining these improvements. The study concludes that incremental, human-centred automation supported by real-time feedback systems is the most effective approach for resource-constrained start-ups.

6.4 Conclusions

The research concludes that semi-automation and digital integration can significantly enhance quality management and operational performance in start-up manufacturing settings - but only when supported by structured processes, competent personnel, and disciplined data practices.

Technological tools alone are insufficient; their success depends on embedding them within a systematic QMS that integrates human, digital, and procedural dimensions. The study highlights that while semi-automation reduces human error and variability, sustainable improvement arises from closed-loop systems that connect process data to decision-making and continuous training.

From a theoretical standpoint, this study extends traditional quality management frameworks by demonstrating their applicability within Industry 4.0-aligned start-up environments. It bridges the conceptual gap between classical QMS principles (ISO 9001 and TQM) and modern digital manufacturing realities, positioning Quality 4.0 as a hybrid model - where process control, real-time monitoring, and human competence co-evolve.

Contextually, the research provides rare empirical evidence from a South African renewable energy start-up, highlighting how digitalisation efforts must contend with infrastructure constraints, skill shortages, and evolving organisational culture. Achieving data-driven quality improvement in such contexts requires balancing agility with control - an insight critical for similar enterprises across developing economies.

6.5 Practical Recommendations

6.5.1 Recommendations for Start-Up Management

Implement semi-automation gradually, starting with processes that yield measurable improvements in repeatability and operator workload.

Invest in competence-based training programmes that integrate both technical skills and digital literacy.

Establish leadership routines - such as daily quality reviews and visual management boards - to sustain a culture of continuous improvement.

Embed accountability and communication channels between production, quality, and maintenance teams to accelerate feedback and corrective action.

6.5.2 Recommendations for Quality System Implementation

Develop lean but standardised procedures to ensure operational control without creating administrative burden.

Integrate real-time monitoring outputs directly with QMS records (e.g., linking ATP data to nonconformance logs).

Deploy digital dashboards that visualise key metrics - defect trends, FPY, and SPC alerts - to enable proactive management decisions.

Formalise CAPA verification through documented evidence reviews and trend-based analyses.

6.5.3 Recommendations for Technology Integration

Prioritise low-cost, modular digital tools such as barcode-based traceability, cloud data logging, and Excel-driven SPC dashboards.

Use a phased automation roadmap, progressing from semi-automated to fully automated operations only after stabilising baseline processes.

Ensure interoperability among devices and databases to avoid information silos.

Periodically evaluate ROI to balance innovation costs with measurable quality and efficiency outcomes.

6.6 Theoretical and Managerial Contributions

6.6.1 Theoretical Contributions

This study contributes to the theoretical advancement of Quality 4.0 by contextualising it for small-scale, resource-limited manufacturing environments. It extends ISO 9001 and TQM principles by demonstrating how digital traceability, semi-automation, and real-time data can be integrated into flexible QMS architectures suited to start-ups. Furthermore, it validates the socio-technical systems perspective, showing that quality performance arises from balanced interaction between human skills, digital tools, and process structure. The research thus bridges the gap between conventional quality management and digital transformation theories in emerging economy contexts.

6.6.2 Managerial Contributions

From a managerial perspective, the study provides actionable guidance for leaders seeking to implement cost-effective quality systems in start-ups. It highlights how incremental automation, workforce development, and structured documentation

Directly influence performance.

Managers can apply the findings to build scalable quality systems that evolve with business growth, using real-time monitoring data for evidence-based decision-making and preventive maintenance planning.

6.7 Limitations of the Study

While the research provides valuable insights, several limitations are acknowledged. The study was conducted within a single start-up facility, which limits the generalisability of findings across the broader renewable energy sector. Data availability was restricted to existing production and testing records; additional time-series data could strengthen trend validation. Furthermore, the analysis primarily covered an 18 month operational window, limiting the ability to observe long-term sustainability impacts. Despite these constraints, triangulation through mixed-methods analysis ensured credible and reliable findings, appropriate for exploratory research in emerging contexts.

6.8 Recommendations for Future Research

Future studies could expand on this work by:

- Conducting comparative studies across multiple renewable energy manufacturers in South Africa to validate and generalise the QMS-digital integration model.
- Undertaking longitudinal analyses to assess how automation maturity influences quality over time.
- Exploring the role of artificial intelligence and predictive analytics in small-scale manufacturing to automate defect prediction and maintenance scheduling.
- Investigating policy frameworks that support digital transformation and quality assurance capacity-building in start-up ecosystems.

Such research would advance understanding of how Industry 4.0 principles can be effectively scaled in South Africa, contributing to both academic knowledge and regional industrial development.

6.9 Contribution to Knowledge

This study contributes to the body of knowledge on quality management in renewable energy manufacturing by providing empirical evidence from a small-scale solar energy start-up operating in a resource-constrained environment. While existing literature extensively addresses quality management systems within large, mature manufacturing organisations, limited research focuses on the practical implementation and impact of semi-automation and digital integration within start-up contexts in the renewable energy sector. This research helps to address that gap by contextualising quality management principles within the realities of early-stage manufacturing operations.

A key contribution of this study lies in demonstrating how semi-automation and basic digital tools can enhance product quality and process stability without the immediate need for full-scale automation or formal certification to multiple international standards. Through the application of SPC techniques to battery pack production data, the study provides a practical framework for identifying process variability, defect trends, and quality risks in battery manufacturing. This demonstrates how SPC can be practically applied within the low-volume, high-variability manufacturing conditions of renewable energy start-ups.

6.10 Chapter Summary

This chapter synthesised the outcomes of the study, demonstrating that semi-automation and digital integration enhance quality performance when grounded in structured, human-centred management systems. It presented the conclusions, practical and theoretical contributions, limitations, and future research directions derived from the empirical evidence.

The study contributes to both scholarship and practice by bridging the gap between traditional QMS frameworks and emerging digital manufacturing paradigms. It provides a roadmap for start-ups to transition from manual, reactive quality control toward proactive, data-driven operations. In doing so, it strengthens the foundation for sustainable manufacturing and competitiveness within South Africa's growing renewable energy sector.

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APPENDIX

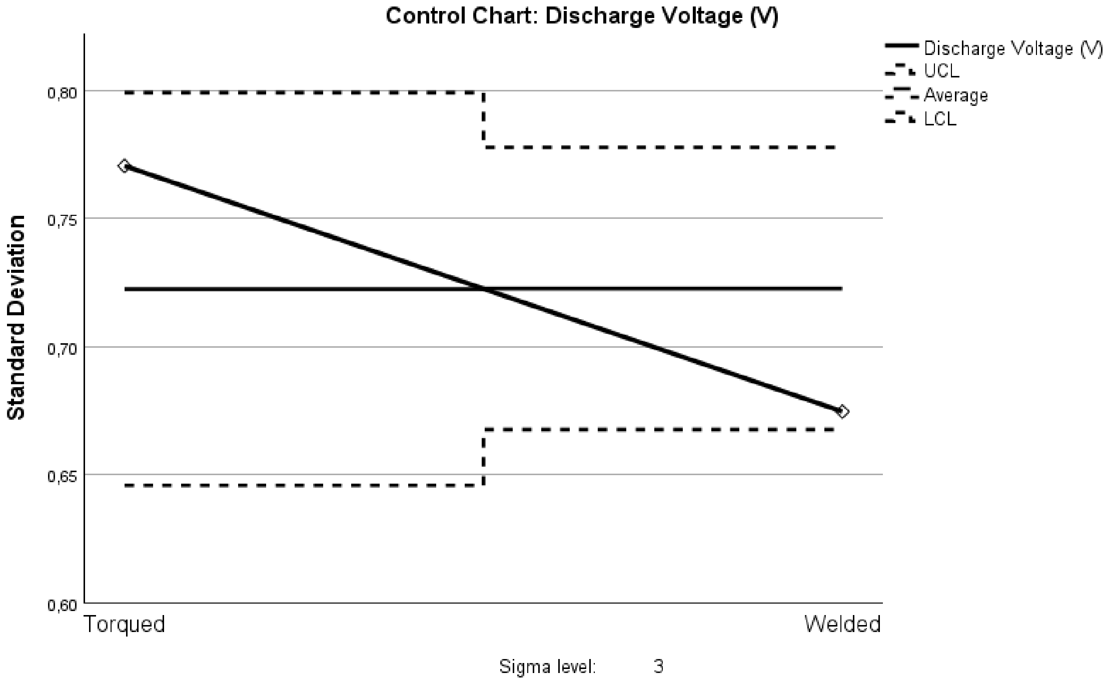

Figure 5.16: Control Chart of Discharge Voltage (Standard Deviation) for Torqued and Welded Packs

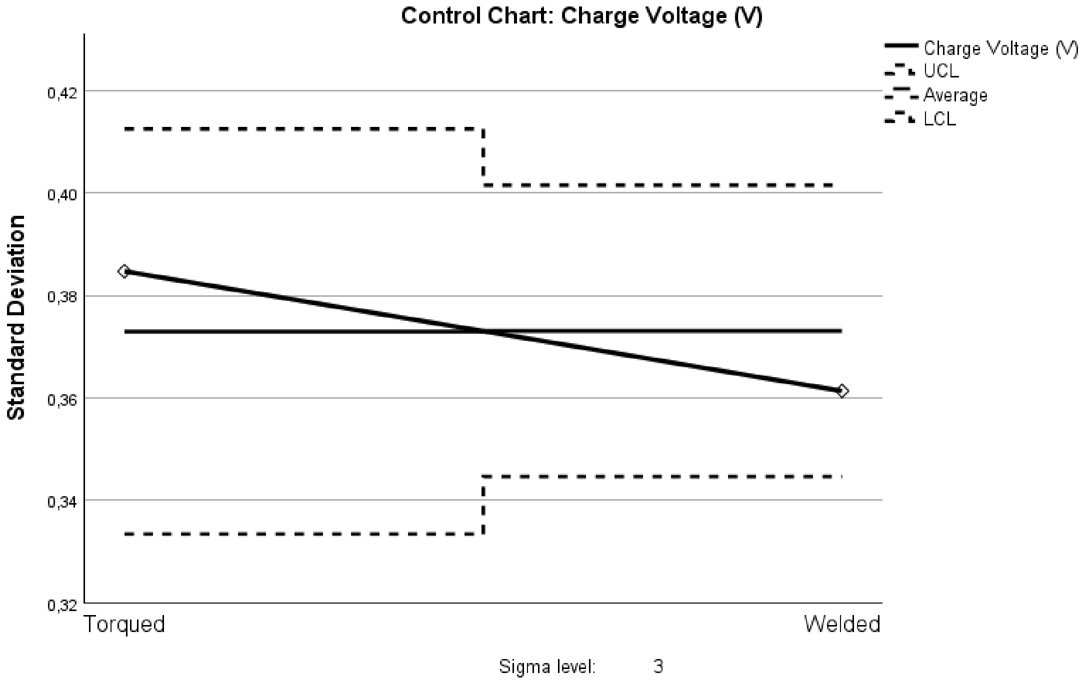

Figure 5.17: Control Chart of Charge Voltage (Standard Deviation) for Torqued and Welded Packs

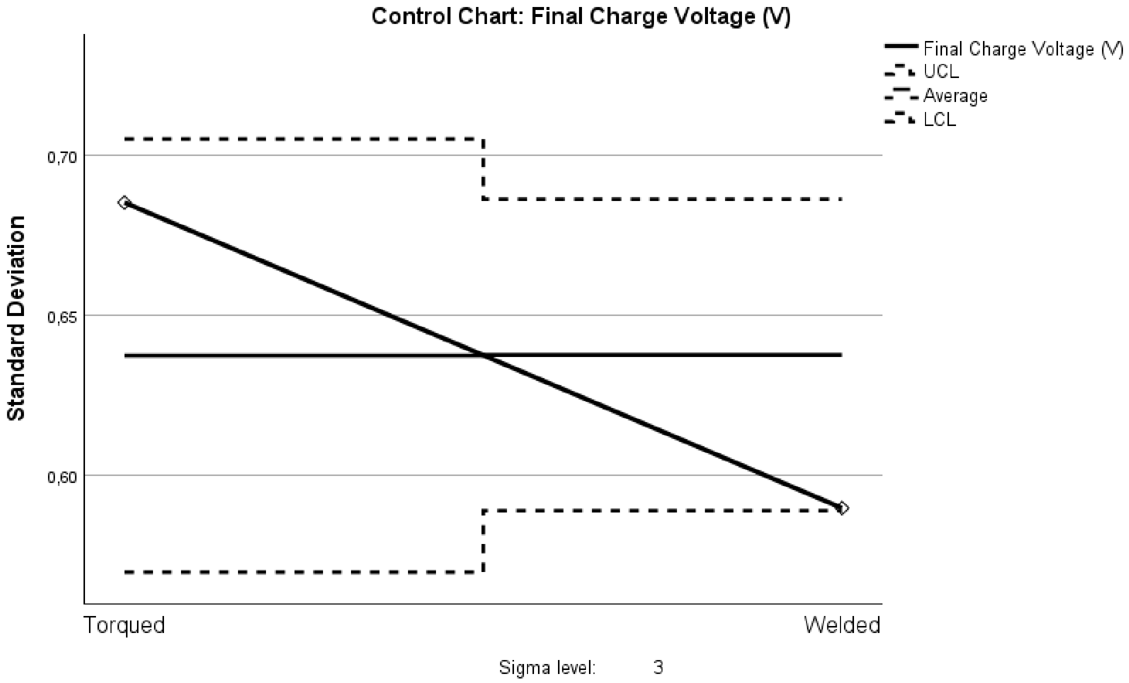

Figure 5.18: Control Chart of Standard Deviation for Final Charge Voltage in Torqued and Welded Packs

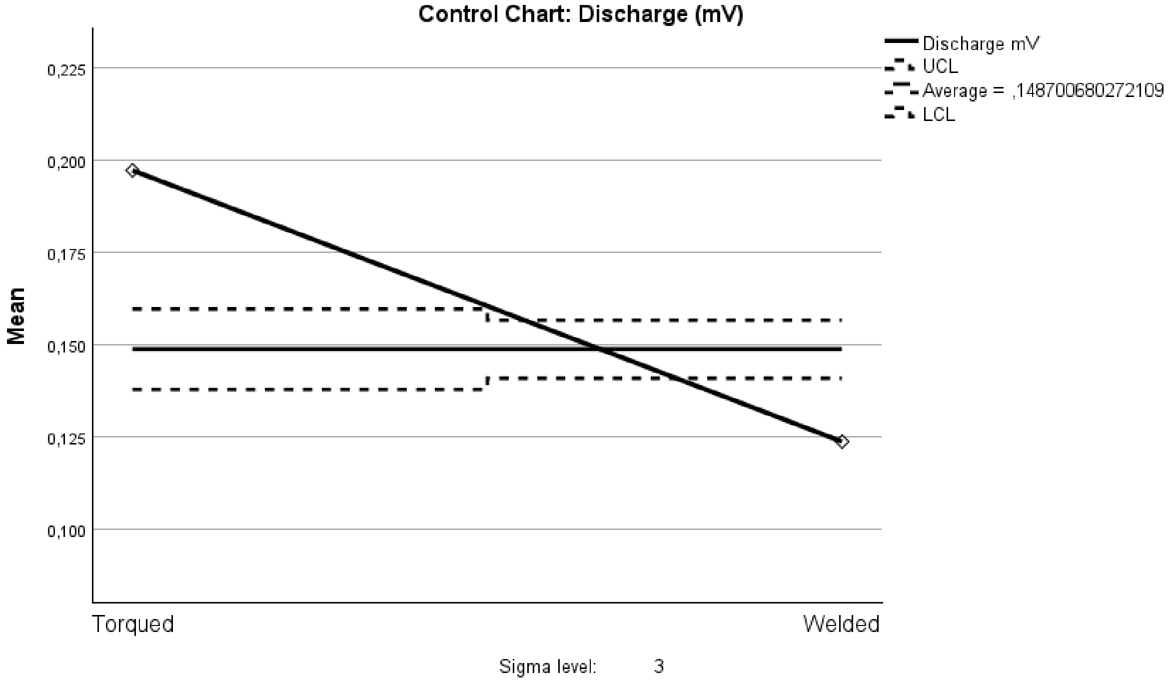

Figure 5.19: Control Chart of Discharge mV (Mean) for Torqued and Welded Packs

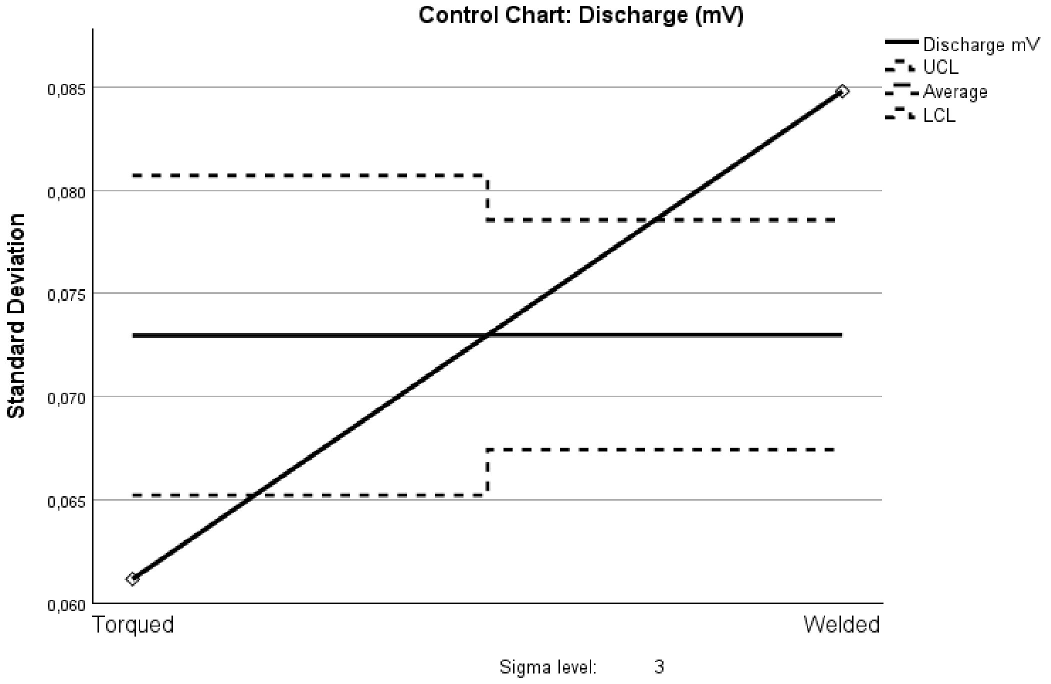

Figure 5.20: Control Chart of Discharge mV (Standard Deviation) for Torqued and Welded Packs

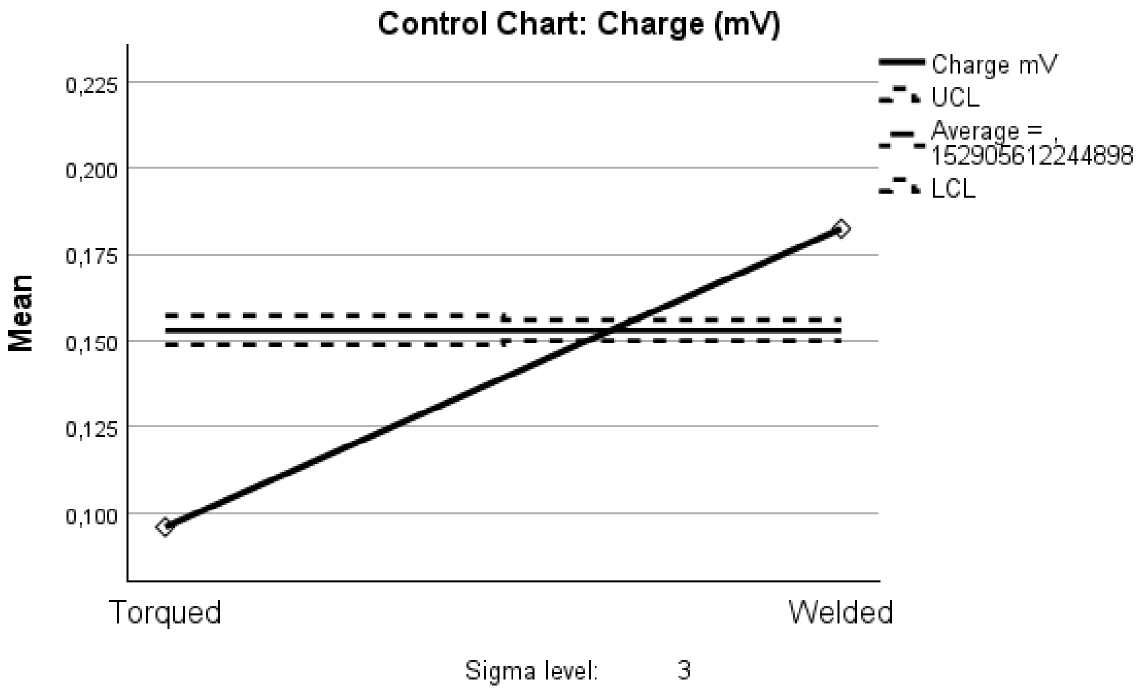

Figure 5.21: Control Chart of Charge mV (Mean) for Torqued and Welded Packs

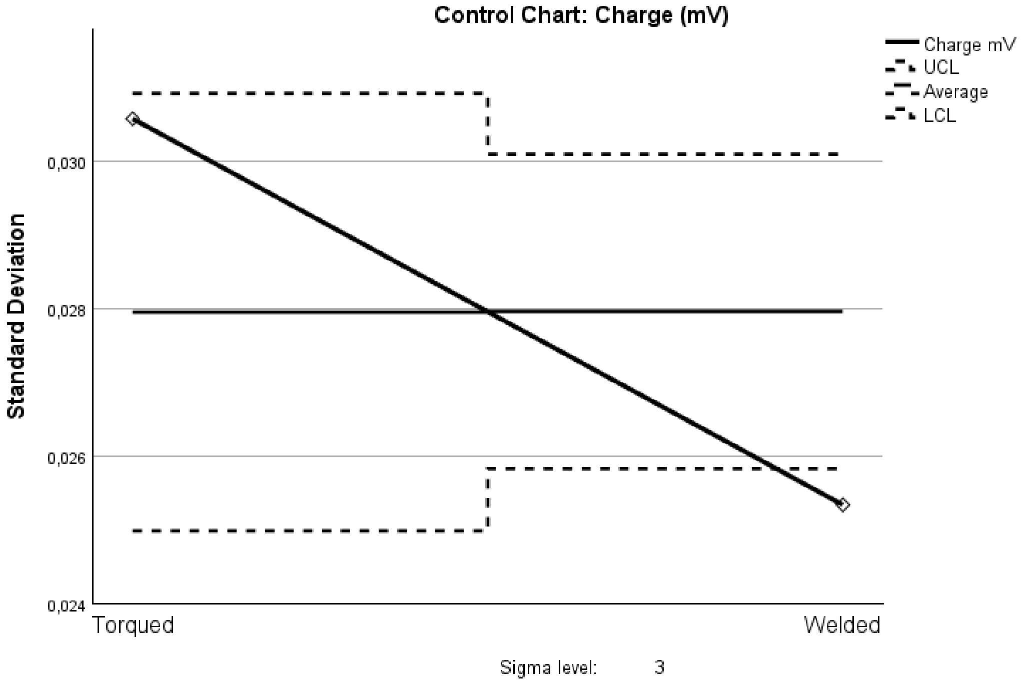

Figure 5.22: Control Chart of Charge mV (Standard Deviation) for Torqued and Welded Packs

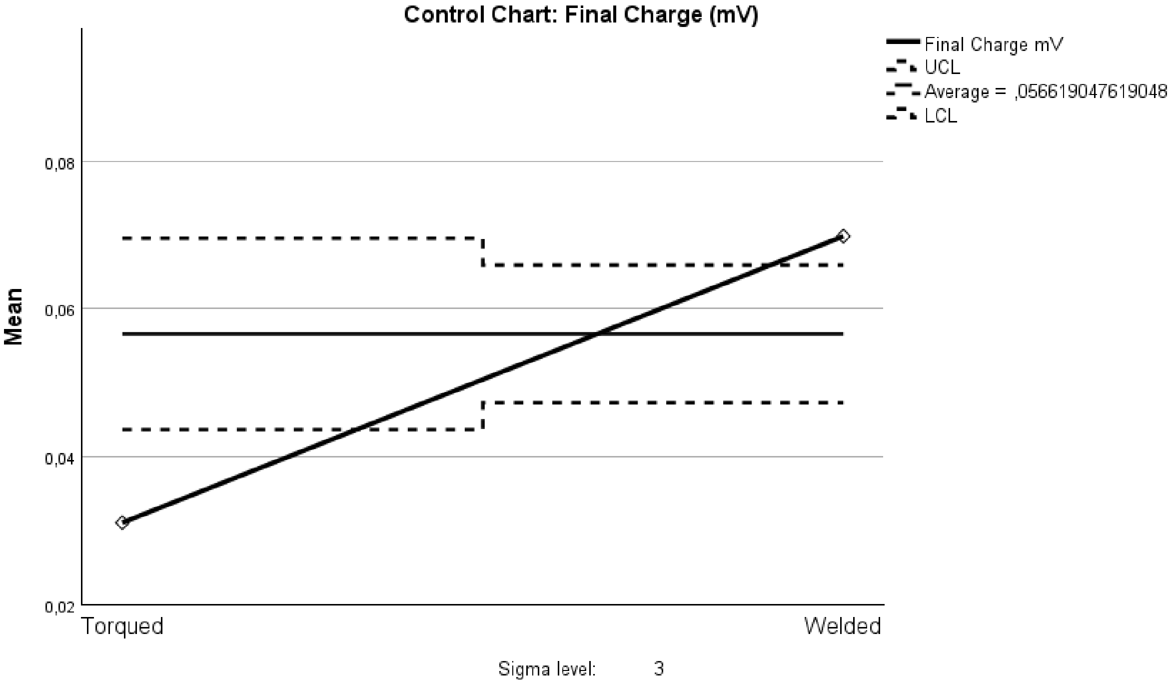

Figure 5.23: Control Chart of final Charge mV (Mean) for Torqued and Welded Packs

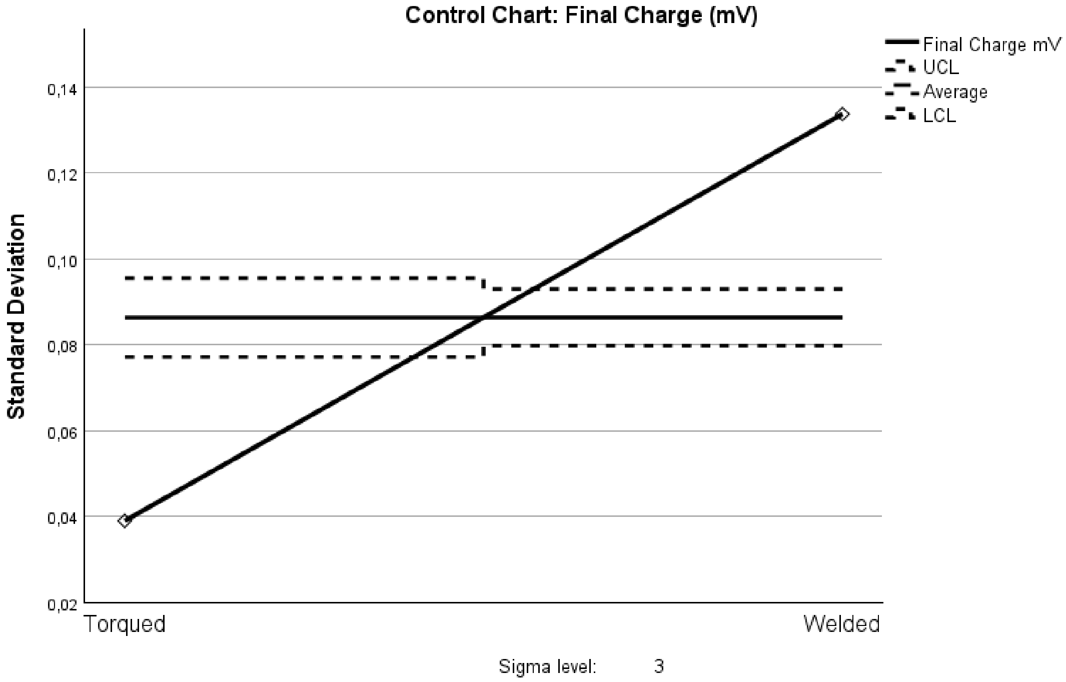

Figure 5.24: Control Chart of Final Charge mV (Standard Deviation) for Torqued and Welded Packs

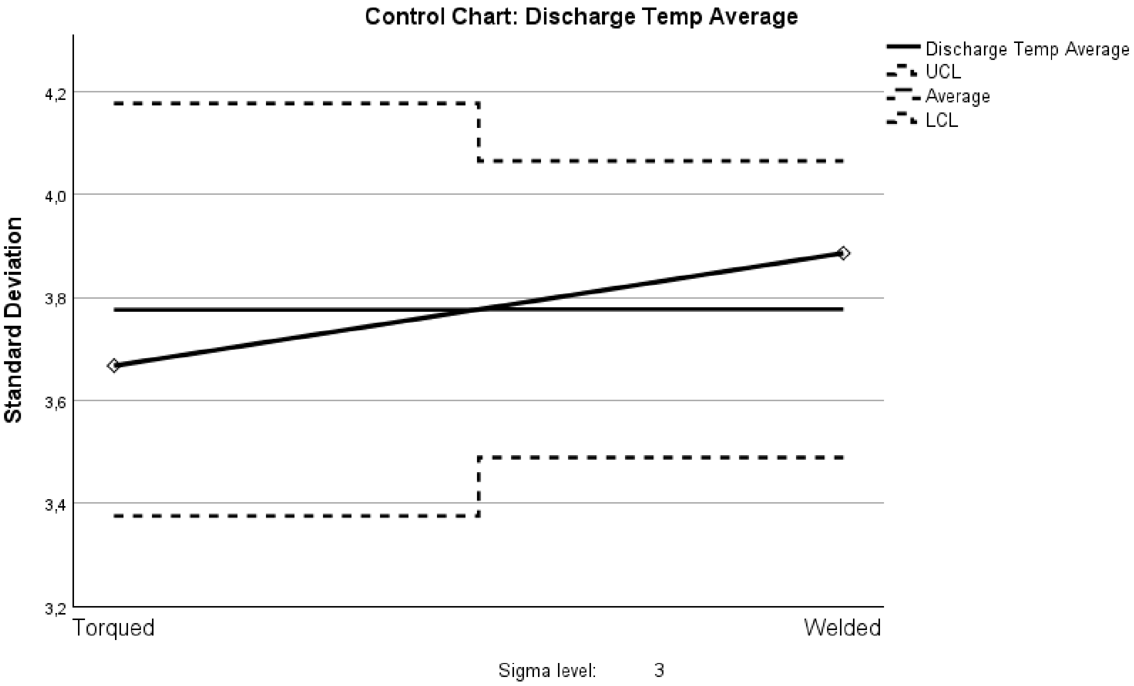

Figure 5.25: Control Chart of Discharge Temperature (Standard Deviation) for Torqued and Welded Packs

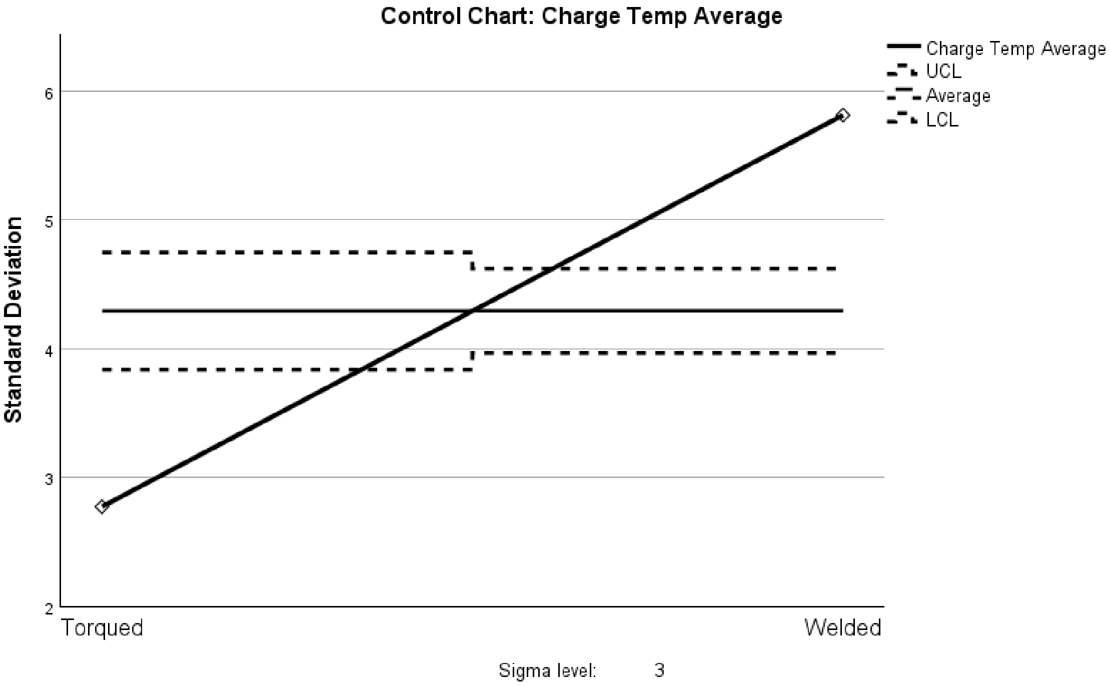

Figure 5.26: Control Chart of Charge Temperature (Standard Deviation) for Torqued and Welded Packs

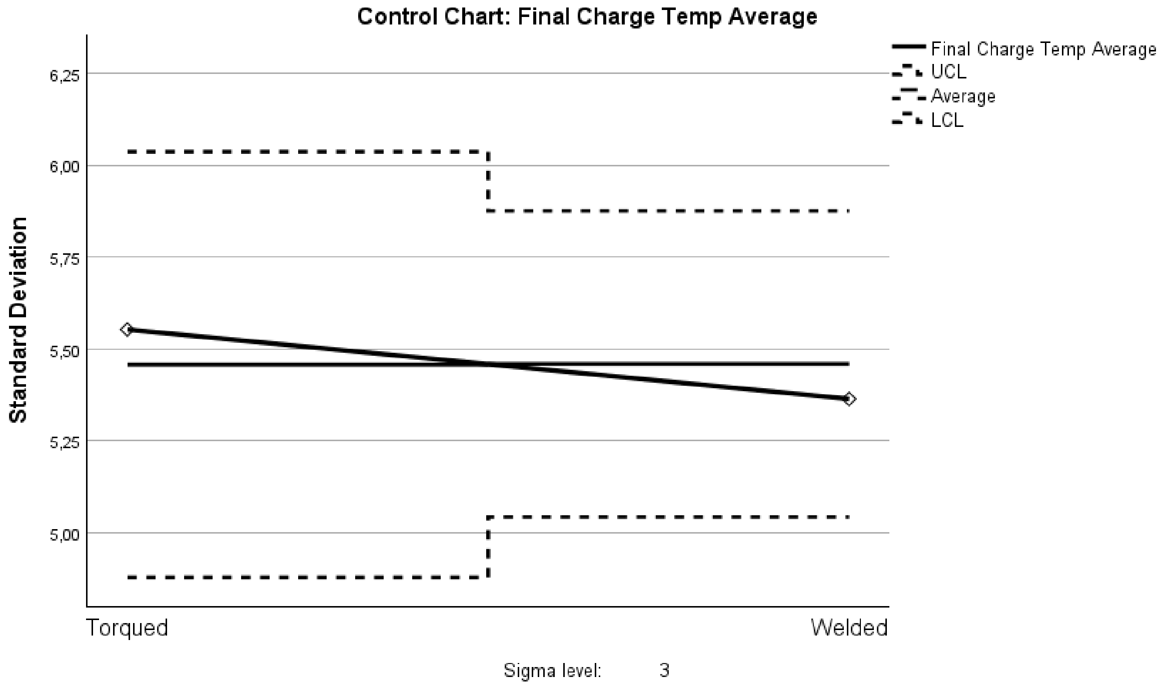

Figure 5.27: Control Chart of Final Charge Temperature (Standard Deviation) for Torqued and Welded Packs

Table 5.8: Time Study Data - Torqued Battery Pack Assembly

Stage	Operation	Time (min)
1	Sorting (1-16 cells)	1.97
2	Cutting plastic spacers	3.99
3	Strapping (8S)	7.49
4	Cable fit on BMS & install in metalwork	14.62
5	Fit sockets	8.54
6	Cut PET to fit cells	1.17
7	Fit cells	6.38
8	Busbars fitting	14.54
9	Fit rails	10.50
10	Fitting both looms	21.77
11	Powering up	11.09
12	Relocating labels	3.26
13	QC	19.23
14	Aging	252.00
15	Parameters	1.12
16	Scan	5.57
17	Cover	4.57
18	Boxing	3.24

Table 5.9: Time Study Data - Welded Battery Pack Assembly

Stage	Operation	Time (min)
1	Sorting	1.93
2	Strapping	1.29
3	Cable fit on BMS & install in metalwork	14.62
4	Fit sockets	8.54
5	Packing & Scan	2.03
6	Optical scan	1.40
7	Laser cleaning	1.52
8	Busbar packing	0.44
9	Laser welding	2.04
10	Testing & crane operation	2.07
11	Fitting both looms	21.77
12	Powering up	11.09
13	Relocating labels	3.26
14	QC	19.23
15	Aging	252.00
16	Parameters	1.12
17	Scan	5.57
18	Cover	4.57
19	Boxing	3.24

Table 5.10: Average cost for battery packs

Cost and Calculations	
Per Cell	R 335.90
8 Cell Pack	R 2 687.20
16 Cell Pack	R 5 374.40
Torqued Battery Pack - Average	$\frac{R\ 335.90 + R\ 5374.40}{2} = R\ 2855.15$
Welded Battery Pack - Average	$\frac{R\ 5374.40 + R\ 2687.20}{2} = R\ 4030.80$