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Operational performance, workforce dynamics, and strategic implications for pressure piping fabrication in the South African construction industry

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Operational performance, workforce dynamics, and strategic implications for pressure piping fabrication in the South African construction industry

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To my wife, Lise, and my daughters, Miané and Emma, for their support and love throughout this journey. While I embarked on a new career and pursued my MBA, my wife managed our household with precision and care, enabling both me and my kids to achieve our goals, me in the classroom and them on the athletics track.

ABSTRACT

This research explores the impact of automated welding technologies on operational performance, workforce dynamics, and financial viability within a mid-sized South African construction company focused on high-pressure piping fabrication. The study aims to determine whether adopting automation can improve efficiency, enhance weld quality, address workforce challenges, and deliver favourable financial returns.

A mixed-methods approach was employed, incorporating qualitative interviews with management and a quantitative survey of employees alongside archival data and supplier claims. The research reveals that automation significantly reduces fabrication times (up to 73.7% for larger pipe diameters), improves weld quality by lowering failure rates to below 1%, and offers financial feasibility with a two-year payback period under optimal workload conditions.

Contrary to initial concerns, the study found minimal workforce resistance, particularly among blue-collar workers, provided upskilling opportunities are available. Automation is positioned to increase capacity rather than reduce jobs, aligning with South Africa's socio-economic need to maintain and grow skilled employment.

The findings emphasise the importance of a localised approach to automation adoption, considering South Africa's unique challenges, such as slower technology uptake and traditional investment mindsets. Recommendations include developing tools for real-time workload assessment, ensuring workforce involvement through tailored training, and exploring automation beyond welding to enhance overall fabrication efficiency.

This study provides insights for industry stakeholders, contributing to the discourse on automation in construction and offering a case study on balancing technological advancement with socio-economic realities.

Key Words: Automation, Welding, Operational Efficiency, Skilled Labour, Internal Rate of Return (IRR), Pipe Spool Fabrication, South African Construction, Technology Adoption, Workforce Dynamics, Labour Segmentation

TABLE OF CONTENTS

ACKNOWLEDGEMENTS ..... **II**

ABSTRACT ..... **III**

TABLE OF CONTENTS ..... **IV**

LIST OF TABLES ..... **VI**

LIST OF FIGURES ..... **VII**

DEFINITIONS ..... **VIII**

1. INTRODUCTION TO THE RESEARCH **1**

A. Primary beneficiaries of the research 1
B. Main Objectives 1
C. Background of the study 1
D. Research Problem 2
E. Rationale 2
F. Delimitations of the study 3
G. Chapter Outline 4

2. LITERATURE REVIEW **5**

A. Research Introduction 5
B. Welding Automation History 5
C. RQ1: Automation's role in improving welding efficiency 5
D. RQ2: Enhancing quality through spool welding automation 7
E. RQ3: Automation, Job Displacement and Its Impact On Skilled Labour in South Africa 7
F. Benefits of human-robot collaboration 8
G. Analytical Framework 8
H. Conclusion 9
I. Summary of Hypotheses 10

3. RESEARCH METHODOLOGY **11**

A. Research Design 11
B. Data Collection Methods 11
C. Population and Sample 12
D. The Research Instruments 12
E. Population and sample 12
F. Data Analysis Strategies and Interpretation 13
G. Quality Assurance 13
H. Ethical Considerations 13

4. PRESENTATION OF RESEARCH RESULTS **14**

A. Overview of Data Sets 14
B. RQ1: What are the efficiency implications of adopting automated welding technologies in pipe spool welding? 16
C. RQ2: What is the impact of automated pipe spool welding on quality? 21
D. RQ3: How does automated pipe spool welding impact blue-collar workers in the case study company? 24
E. What is the financial viability of adopting automated welding technologies, as quantified through the Internal Rate of Return (IRR)? 26

5. DISCUSSION OF RESEARCH FINDINGS **31**

A. Introduction 31
B. Summary of Key Findings 31
C. Integration of Findings with Theoretical and Conceptual Frameworks 32

6. SUMMARY, CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS 34

A. Summary 34
B. Conclusions 34
C. Limitations 35
D. Recommendations 36
E. Opportunities for Future Research 36

7. REFERENCE LIST 37

8. APPENDICES 39

A. Appendix A –Instrument 1: Management Questionnaire 39
B. Appendix B – Instrument 2: Labour Force Questionnaire 40
C. Appendix C – Instrument 3: Abicor Binzel Interview Questionnaire 41

LIST OF TABLES

Table 1: Quantitative data collection methods 11
Table 2: Qualitative data collection methods 12
Table 3: Strategies per data type 13
Table 4: Linking of Qualitative Themes to Labour Force Questions 15
Table 5: Heat map of semi-structured interview themes related to RQ 1 and H1 17
Table 6: Heat map of semi-structured interview themes related to RQ 2 and H2 21
Table 7: Heat map of semi-structured interview themes related to RQ3 and H3 24
Table 8: Heat Map of Themes from semi-structured interviews related to RQ4 and H4 27
Table 9: Payback period with manhour data corresponding to Figure 11 29
Table 10: IRR with manhour data corresponding to Figure 15 30

LIST OF FIGURES

Figure 1: Classification of Welding Technologies (Favi et al., 2021) 3
Figure 2: Steps in the pipe spool fabrication process (Wang et al., 2009) 3
Figure 3: Industrial Robotics Zone (Pires et al., 2003) 6
Figure 4: Impact of automation on the creation of new tasks (Acemoglu & Restrepo, 2019) 6
Figure 5: Relative time attributed to welding, compared to other steps in the fabrication process for different pipe diameters (Reutzel et al., 2006) 7
Figure 6: Conceptual Framework Derived From Literature 9
Figure 7: Data Collection Process for Dataset 1 14
Figure 8: Box plot of responses to Q3.2 in the employee survey 18
Figure 9: Total fabrication time for manual vs automated welding, considering the company's current weld duration data per size compared to weld speed claims from robotic equipment suppliers 19
Figure 10: Unit Cost Reduction as a result of automated welding 20
Figure 11: Higher Profit Margin as a Result of Automation for Varying Manhour Loading 20
Figure 12: Box plot of responses to Q3.1 in the employee survey 23
Figure 13: Shop vs Field ratios and Failure Rates per Distinction 23
Figure 14: Payback Period (Months) for Automation, based on the investment cost quoted 29
Figure 15: Relationship between IRR, workload and weekly utilisation for the replacement of four to six welders 30

DEFINITIONS

Arc Welding: Arc welding is a type of welding that uses an electric arc to generate heat for fusing metals. In this study, arc welding refers specifically to circumferential welding processes used in high-pressure pipe fabrication (Pipe Welding Terminology - Weparto, 2023).

Blue Collar: Blue-collar workers in South Africa are mainly unskilled or semi-skilled workers who perform work of a manual nature (Brand-Labuschagne et al., 2013)

Factored Diameter Inch (FDI): Factored Diameter Inches (FDI) = Nominal Pipe Size (NPS) x Wall Factor x Material Factor x Weld Type Factor ("Pipe Fabrication Institute Bulletin TB-10," 2021). In this report, the wall, material, and weld factors equal 1.

Hurdle Rate: The minimum rate of return a company requires before proceeding with an investment. It represents the threshold that an investment must exceed to be considered viable.

Internal Rate of Return (IRR): The IRR is a financial metric used to assess an investment's profitability. It represents the discount rate at which cash flows' net present value (NPV) equals zero. This study evaluates the viability of investing in automated welding technologies (Internal Rate of Return Calculator (IRR) up to 5 Years—Calculator Academy, 2025).

Non-Destructive Testing (NDT): NDT refers to inspection methods used to evaluate the quality and integrity of materials or welds without causing damage. Standard techniques include X-ray and ultrasonic testing, which identify weld defects in high-pressure piping (What Is Destructive and Nondestructive Testing? What's the Difference? Fit Welding, 2025).

Payback Period: The payback period is the time it takes for an investment to recover its initial costs through generated cash flow (Bashir, 2025).

Spool Welding Robot (SWR): The SWR is a specific automated welding system for pipe spool fabrication. It is characterised by its ability to perform high-quality, consistent welds with reduced time and human input compared to manual welding processes ("Binzel-Abicor," 2025).

Weighted Average Cost of Capital (WACC): The average rate a company must pay to finance its assets, calculated by combining the cost of debt and the cost of equity, weighted by their respective proportions in the company's capital structure (Knowledgiate - Cost of Capital: Understanding the Key Elements, 2025).

1. INTRODUCTION TO THE RESEARCH

This study explores the impact of automated welding on a mid-sized South African construction company's operational performance. While the methodology and analytical framework adhere to academic research standards, the outcomes are intended to provide actionable insights and a robust recommendation regarding the viability of capital investment in automated welding.

The research evaluates the case study company's potential transition from manual to automated welding, focusing on empirical data analysis of operational performance and comparative market insights. It will provide the company with crucial data on automation's quality, efficiency, and cost implications, supporting strategic investment decisions. Additionally, it will assess the strategy and consequences for the workforce, ensuring a comprehensive understanding of automation's potential impact.

a. Primary beneficiaries of the research

The primary audience for this research is the management team of the Company, whilst secondary stakeholders include:

- Industry peers that are considering similar technological investments.
- Policymakers interested in the economic implications of automation in the construction industry.
- Academic researchers and students focusing on the intersection of technology, labour, and industry performance.

b. Main Objectives

The end goal of this research is to equip the Company's decision-makers with robust, data-driven insights to determine whether investing in automated welding technology is a feasible and strategically sound decision. The primary research objectives are:

- To evaluate whether automated welding improves operational efficiency.
- To assess quality enhancement in welding through automation.
- To examine the socio-economic impact on blue-collar workers.
- To determine the financial viability of automated welding via IRR and payback models.

In the broader sense, the study seeks to contribute to the discourse on automation within the construction industry by presenting a case study of its potential impacts in the South African context. It aims to bridge the gap between theoretical research and practical application, offering a precedent for evidence-based decision-making in adopting new technologies.

c. Background of the study

Fabrication, as it pertains to high-pressure piping within the petrochemical and energy sectors, is a critical process comprising the cutting, shaping, and welding of pipe components into designated subassemblies known as spools. Fabrication may occur in specialised shops with advanced equipment

for efficiency, while installation occurs on-site, typically employing manual welding techniques (Nayyar, 2000).

High-pressure piping projects are frequently varied, requiring specialised trade skills and artisans such as fitters, boilermakers, and welders. Adherence to contemporary quality standards is crucial in pressure piping fabrication facilities to ensure compliance with stringent quality management and control requirements (Antaki, 2003).

d. Research Problem

With low GDP growth (0.6%) and a 1.4% construction sector downturn in 2023 (StatsSA, 2023), South African firms must cut costs and improve efficiency via automation. However, despite the imperative to adopt new technologies, there exists reluctance towards welding automation within the construction industry (Akinradewo et al., 2018). This reluctance is contrasted with a critical shortage of skilled welders, contributing to a variance in welding quality (Windapo, 2016). Furthermore, the economic landscape, marked by high unemployment rates (StatsSA, 2023), underscores the need to address employment uncertainty amidst technological advancement (le Roux, 2018).

Against this backdrop, the research aims to investigate whether the integration of automated welding technologies for high-pressure piping fabrication can serve as a multifaceted solution to the challenges of efficiency improvement, welding quality enhancement, and employment uncertainty within the South African construction sector, thus reshaping the dynamics of labour and technology utilisation (Koçak & Holding, 2010; Penny & Kohlhöfer, 2006).

The study seeks to answer the following research questions:

1. **RQ1:** What are the efficiency implications of adopting automated welding technologies in pipe spool welding?
2. **RQ2:** What is the impact of automated pipe spool welding on quality?
3. **RQ3:** How does automated pipe spool welding impact blue-collar workers in the case study company?
4. **RQ4:** What is the financial viability of adopting automated welding technologies, as quantified through the Payback Period and Internal Rate of Return (IRR)?

While global studies have explored welding automation in manufacturing, little empirical research exists on its implementation within the South African construction sector—particularly in mid-sized firms. This gap is significant, as the industry faces simultaneous pressures of cost reduction, skilled labour shortages, and declining productivity.

e. Rationale

The study will critically analyse the Company's manual welding practices and contrast them with the efficiencies of automated welding. It will provide data on quality and efficiency improvements and the strategic advantages of adopting automation, including workforce implications. The objective is to give the Company and industry stakeholders actionable insights to navigate the decision-making process regarding adopting automated welding technologies.

f. Delimitations of the study

This study evaluates a single case study focusing on circumferential arc welding in South Africa. The blue block in Figure 1 shows and highlights the welding category within which research will be conducted in the Arc Welding technology type.

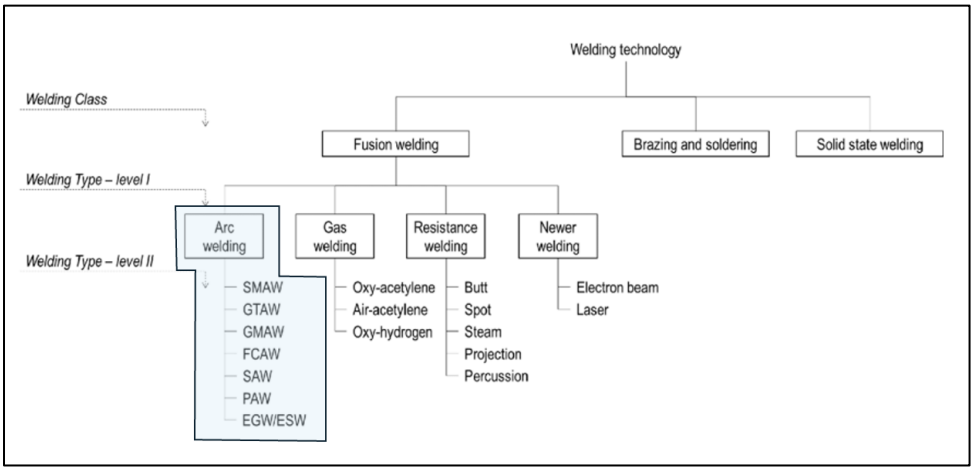


Figure 1: Classification of Welding Technologies (Favi et al., 2021)

Spool welding consists of multiple steps in the fabrication process, as shown in Figure 2 below (Mosayebi et al., 2012). This study will specifically focus on optimising the roll welding step (highlighted in blue), which will constitute the most significant portion of welding for piping spool fabrication.

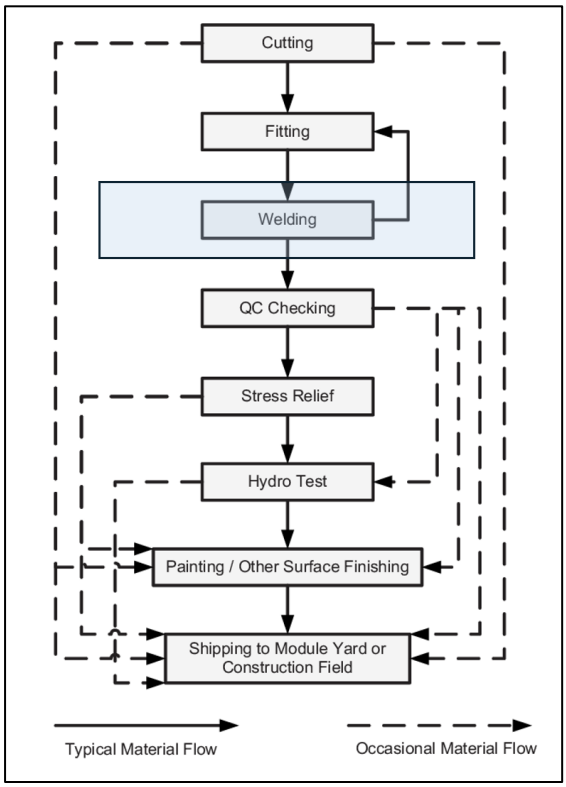


Figure 2: Steps in the pipe spool fabrication process (Wang et al., 2009)

This study will exclude the following:

1. Processes not directly related to welding, such as material procurement, Handling, Transportation
2. Welding processes other than circumferential arc welding, such as spot and structural welding.
3. Global market and labour analyses outside the South African context.

This study assumes supplier technical data to be reliable and that the case study company is representative of mid-sized South African fabricators. It is further assumed that the economic environment will remain broadly stable during the projection horizon

g. Chapter Outline

Chapter 1 provides an introduction that establishes the context and importance of the study within the South African Context. A literature review follows this in Chapter 2, which examines the research questions. Chapter 3 details the research methodology, describing the research design, data collection methods, and analytical techniques. In Chapter 4, the research findings are presented, followed by Chapter 5, which discusses the meaning of the findings. Finally, Chapter 6 presents conclusions, recommendations and limitations. Appendices include research instruments and data results.

2. LITERATURE REVIEW

a. Research Introduction

The literature review examines the comparative cost and efficiency of automated versus manual welding, the maturity of automated welding technologies in enhancing weld quality, and the implications of automation for the current skills gap in the industry.

b. Welding Automation History

Chen et al. (2014) explain that arc welding, introduced in the 19th century, relied on human operators, making it labour-intensive and skill-dependent. As manufacturing evolved, semi- and fully-automated robotic welding was adopted to address human limitations. Chen further explains that the progression of welding technology has experienced the following four major phases:

1. **Phase I:** Manual welding with low efficiency and consistency.
2. **Phase II:** Introduction of automation and robotics, which is challenging to model and control.
3. **Phase III:** Improvement with "teach and playback" robots, offering offline programming but limited real-time adaptability.
4. **Phase IV:** Implementing intelligent systems capable of active monitoring and control will signify a shift from human-physical to human-cyber-physical systems in welding processes (Zhou et al., 2019).

While there is a general readiness to embrace automation within South Africa's construction sector, a specific reticence towards adopting welding automation persists, which remains less prevalent than other technologies (Akinradewo et al., 2018).

c. RQ1: Automation's role in improving welding efficiency

Industrial robotics and mechanised apparatus have emerged as essential components in industrial welding to meet high-volume production demands. This shift is attributed to the recognition that manual welding often reduces output rates due to strenuous work conditions and substantial physical requirements (Kah et al., 2015). The ever-evolving market dynamics and intensified competition compel manufacturers to identify and implement the most effective production methodologies. Evidence presented in Figure 3 by Pires et al. (2003) indicates that robotic systems offer a more cost-effective performance per unit than manual welding and inflexible automated solutions within the scope of small to medium-scale production.

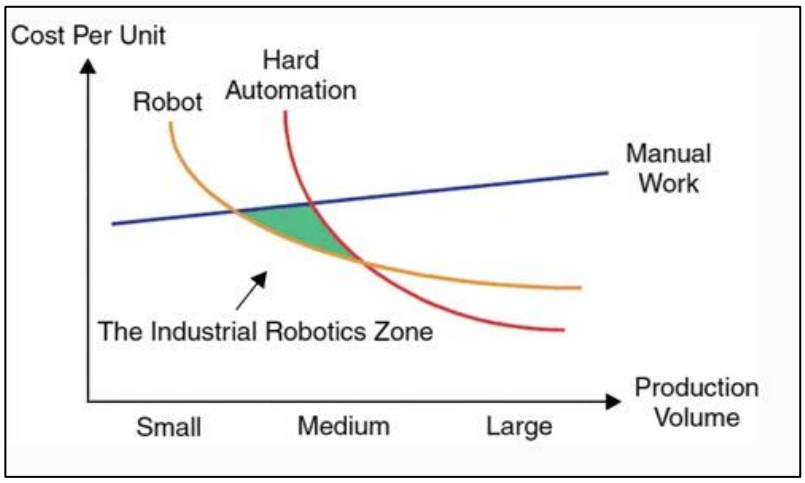


Figure 3: Industrial Robotics Zone (Pires et al., 2003)

Figure 4 illustrates the framework Acemoglu & Restrepo (2019) developed, which supports the findings by Pires et al. and demonstrates the efficiency implications of adopting automation through the redistribution of tasks between capital and labour. It shows the division of production tasks between capital and labour, with tasks above a certain threshold (I) being performed by labour and those below it by capital. This indicates the differentiation of automated and non-automated tasks. Advances in I denote the integration of automation technologies, whereas increases in N suggest the creation of new tasks requiring human labour (Acemoglu & Restrepo, 2019).

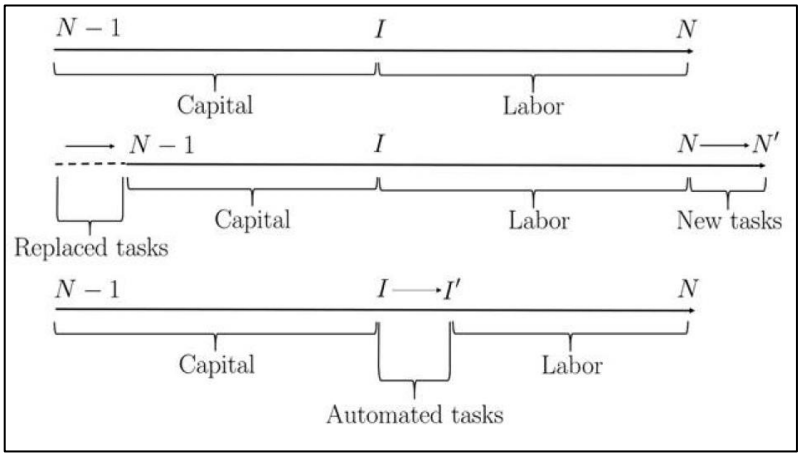


Figure 4: Impact of automation on the creation of new tasks (Acemoglu & Restrepo, 2019)

Spool welding robots weld faster than human welders. The reallocation of the welding task from labour to capital is advantageous for high-pressure pipe fabrication, which accounts for a substantial part of the process. The welding time varies with pipe size and forms a more significant part of the process than other activities like handling, cleaning, and fit-up, as shown in Figure 5 below.

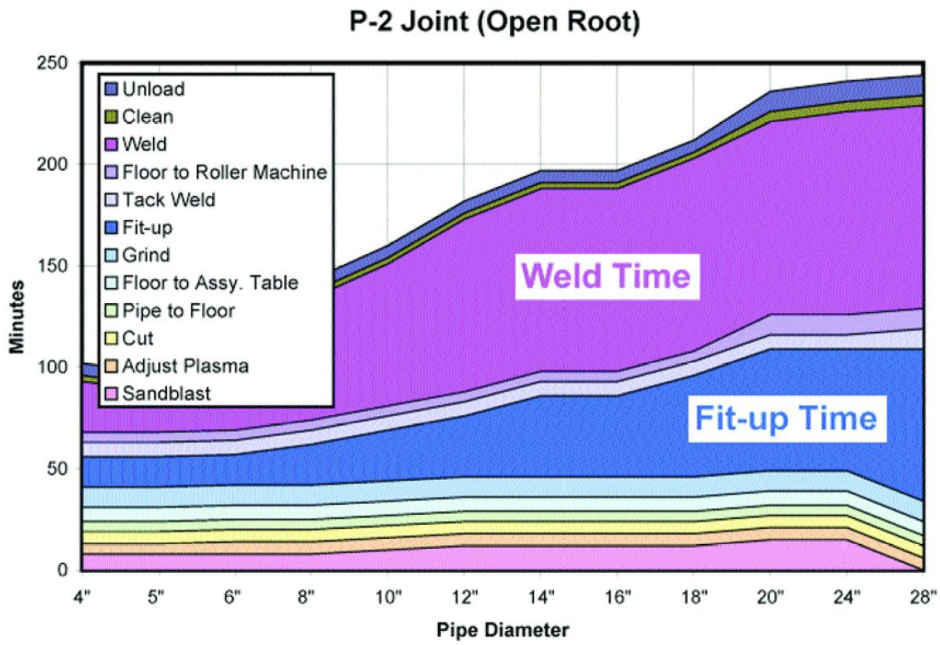


Figure 5: Relative time attributed to welding, compared to other steps in the fabrication process for different pipe diameters (Reutzel et al., 2006)

d. RQ2: Enhancing quality through spool welding automation

Until recently, the expansion of automation in welding was hindered by technological limitations in robotic perception (Reutzel et al., 2006). Traditional robots couldn't rival human sensory depth, struggling with complex tasks like nuanced object identification. This has evolved significantly with the advent of Industry 4.0, transitioning from operator-controlled to sensor-driven with artificial intelligence (AI). Central to autonomous welding are vision sensors, which, combined with AI, have enhanced the precision and quality of robotic welding (Eren et al., 2023).

e. RQ3: Automation, Job Displacement and Its Impact On Skilled Labour in South Africa

Historical parallels may be drawn with the Luddite movement of the early 19th century in examining societal attitudes towards automation. Daniel B. le Roux (2018) notes that in societies already facing high levels of inequality, such as South Africa, the introduction of automation could potentially result in Luddism, especially given the high unemployment rate and the current skills gap. This movement was led by English textile workers, who protested against the changes brought about by the Industrial Revolution, which they believed threatened their jobs. The destruction of labor-saving machines characterised this movement. These historical events serve as an archetype for modern opposition to automation and technological change, a sentiment that arises from the fear of unemployment and skill redundancy. The term 'Luddite' has since been used more broadly to describe those resistant to technological change for fear of its impact on employment (Archer, 2015; Le Roux, 2018).

However, Acemoglu and Restrepo (2019) argue that the progression of technology is more than just substituting human work with automated systems. If that were the case, our economy would rely on an ever-narrowing scope of traditional tasks and jobs, leading to a consistent decrease in labour's

contribution to national income. However, technological development often goes hand in hand with creating new tasks where human skills are more beneficial. These innovations not only boost productivity but also lead to a reinstatement of labour into a more comprehensive array of functions, shifting the nature of production towards more labour-intensive activities. This reinstatement effect, which contrasts with the job-displacing impact of automation, actually increases both the proportion of income earned by labour and the overall demand for workers (Acemoglu & Restrepo, 2019).

f. Benefits of human-robot collaboration

Human-robot work collaboration (HRWC) refers to scenarios where robots assist humans by taking on repetitive tasks, reducing the risk of repetitive strain injuries and allowing humans to concentrate on more complex duties that robots cannot handle (You et al., 2018).

This operational advancement, particularly noted during the fabrication phase, has been linked to improved working conditions and heightened safety standards by utilising advanced machinery and computer programming for tasks that are generally more hazardous and labour-intensive (Oke et al., 2019). Chang et al. (2022) argue that the application of robots in construction could effectively address the challenges of worker availability, safety, and health. They project a future where robots perform tasks and accumulate trade skills and knowledge, parallel to a new generation of human workers who will be trained to operate these advanced machines, thus ensuring project delivery within deadlines and budgets (Chang et al., 2022).

However, it is hypothesised that adopting automated welding could be a strategic solution to the industry's existing shortage of skilled welders. Such technology is anticipated to offer significant upskilling opportunities and enhance the quality and safety of high-pressure piping fabrication. Ultimately, this could result in a more efficient, precise, and regulated welding process, addressing the risks currently associated with manual welding and closing the skilled labour gap.

g. Analytical Framework

i Theoretical Framework

The theoretical framework of this study is anchored in the theories of technological evolution in industrial practices and the socio-economic impact of automation on the labour market. It draws from the historical narrative of the progression of welding technology, as characterised by Chen et al. (2014) and Zhou et al. (2019), moving through phases from manual to automated and, ultimately, to intelligent systems integrated with AI. This framework also incorporates economic theories, as elucidated by Acemoglu & Restrepo (2019), which examine the interplay of the displacement and reinstatement effects of automation in the labour market.

This study's theoretical framework provides the basis for understanding how advancements in welding technology enhance operational efficiencies and reshape labour dynamics within the construction industry, particularly in the South African context. It supports exploring how intelligent automation can address cost, quality, and skilled labour shortages simultaneously.

ii Conceptual Framework

Central to this framework are cost and efficiency improvements through automation, the enhancement of weld quality via AI and vision sensors, and the broader implications for the labour market, especially regarding skill gaps and unemployment rates.

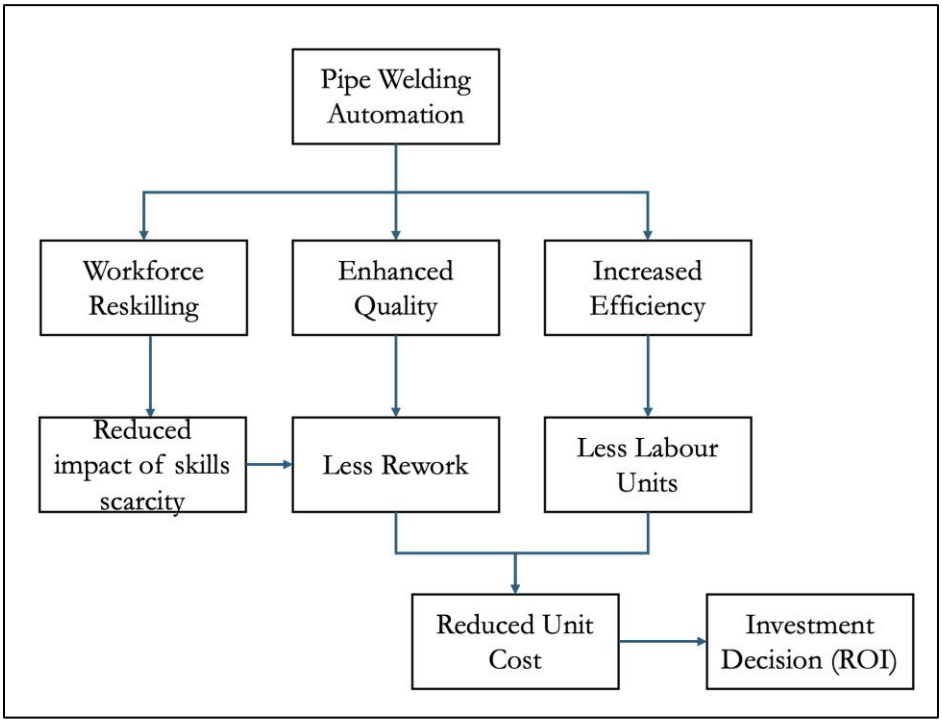


Figure 6: Conceptual Framework Derived From Literature

h. Conclusion

The literature review highlights a significant shift in the welding industry, driven by technological advancements from manual processes to advanced automated and intelligent systems. Historical shifts and current studies show that automation is not just a replacement for human labour but an opportunity for improvement and progress.

The theoretical and conceptual frameworks derived from the literature emphasise the dual impact of automation: it poses both a challenge and an opportunity for the workforce. While job displacement is a concern, the potential for new technologically augmented roles provides a counterbalance that could drive labour demand and contribute to economic growth.

Advances in AI and vision sensor technologies have overcome previous limitations, paving the way for spool welding robots to achieve higher efficiency and better quality in welds. The implications for South Africa's construction industry are significant, offering a future where collaboration between humans and robots could address current skill gaps while meeting the growing demands of modern production standards.

This study will provide crucial insights into enhancing operational efficiency, reducing costs, and improving the quality and reliability of energy projects through the adoption of automated welding technologies. By examining the perceptions of energy leaders, the research will highlight opportunities for workforce development and upskilling, aligning with national priorities to address unemployment and prepare for technological advancements. Additionally, the study's findings will inform strategic decision-making, promote sustainability by reducing energy consumption and waste, and offer a valuable case study that can serve as a reference for similar initiatives within and beyond South Africa, thus supporting the broader energy landscape transformation.

i. Summary of Hypotheses

Hypothesis 1 (H1): Automated welding technologies reduce the cost per unit of welded material in high-pressure pipe fabrication compared to manual welding methods.

Hypothesis 2 (H2): Automated welding technologies enhance the quality of welds in high-pressure pipe fabrication more consistently than manual welding methods.

Hypothesis 3 (H3): Adopting automated welding technologies within private industrial sector energy project development models will create new job roles and enhance upskilling opportunities.

Hypothesis 4 (H4): When implemented in medium- to large-scale welding operations, automated welding technologies will demonstrate a favourable Internal Rate of Return (IRR), contingent on workload predictability and operational efficiency.

3. RESEARCH METHODOLOGY

a. Research Design

A comparative case study design is selected for this study. This design is particularly suitable as it allows for an in-depth analysis of the welding processes within the case study in a mid-sized South African construction company. It compares these processes with the potential of automated welding technologies. The study adopts a pragmatist paradigm, favouring mixed methods to allow triangulation of qualitative insights and quantitative metrics. The comparative nature of this case study will involve quantitative methods, predominantly collecting data on weld quality, speed, and associated costs for both manual and automated welding, as well as qualitative approaches to determine management and business needs for automation.

b. Data Collection Methods

This is a convergent parallel mixed methods study where qualitative and quantitative data were collected and analysed simultaneously. It determined operational impacts quantitatively and explore management perspectives on adopting automation qualitatively.

Table 1: Quantitative data collection methods

Research Question	Factor	Method	Data Collection Approach	Dependent Variables (DV)	Independent Variables (IV)
RQ1, H1	Welding Speed	Manual Welding	Company specific speeds and norms	Weld speed, expressed in minutes/hours	1. Material Type 2. Wall Thickness 3. Pipe Diameter
		Automated	Speed claims from technology performance specifications		1. Material Type 2. Wall Thickness 3. Pipe Diameter
RQ2, H2	Quality	Manual Welding	Welder Performance from Archival Data	Weld Quality, expressed as a failure rate percentage	1. No of Butt Welds
		Automated Welding	Quality claims for technology performance specifications		1. No of Butt Welds
RQ3, H3	Workforce Peception	Automated Welding	Employee Questionnaire	Perceived Impact of Automation on employees	1. Role within company 2. Demographic factors 2. Previous experience with Automation
RQ4, H4	Cost	Manual Welding	Cost per weld, based on labor rates and Costing Model	Cost per FDI (Factored Diameter Inch)	1. Material Type 2. Wall Thickness 3. Pipe Diameter 4. Welder Wage
		Automated Welding	Capital cost of automated welding, with IRR and Payback calculation		1. Material Type 2. Wall Thickness 3. Pipe Diameter

Table 2: Qualitative data collection methods

Factor	Method	Data Collection Approach	Dependent Variables (DV)	Independent Variables (IV)
Management Perception	Automated Welding	Management Questionnaire	Perceived value of automation	1. Financial factors 2. Strategic Alignment 3. Workforce considerations

c. Population and Sample

i Sample and Sampling Method

The study compares the Company's manual welding operations with automated welding for operational and cost impact. It will help management make an informed decision about adopting automation, considering factors like increased efficiency, quality, and the potential for strategic advantage and workforce enhancement.

d. The Research Instruments

i Managerial Questionnaire

Please refer to Appendix A for the Managerial Questionnaire.

ii Workforce Questionnaire

Please refer to Appendix B for the Managerial Questionnaire

iii Archival Data Analysis

Available archival data will include examining the company's historical welder performance and showing data on failure rates per welder as a percentage. Additionally, data will be collected on current welder compensation to determine overhead costs. Please refer to the consent form from the Company in Appendix C.

iv Development of payback and IRR model

Develop an IRR and payback model based on the capital cost required and operational cost per FDI, considering the company's current costing methodology.

v Technology Performance Specifications

Research manufacturer documents detailing automated welding systems' capabilities to compare against manual techniques.

e. Population and sample

i Case Site

The primary population for this research is the operational workforce and management at a mid-sized South African construction company with a strategic focus on high-pressure piping fabrication. This company is selected as the case site due to its established manual welding processes and the potential consideration of transitioning to automated welding technologies. The Company represents the South

African construction sector's welding operations, making it an appropriate case for understanding the broader implications of welding automation in similar industrial contexts.

ii Justification

The Company's detailed records of welding operations and willingness to consider technological advancement provide a rich source of empirical data. Their operation size and market position also offer a microcosmic view of the more significant industry trends, challenges, and opportunities regarding automation.

iii Sample and sampling method

Given the Company's specific context, the following number of participants and data points will be selected using purposive sampling.

1. The questionnaires were circulated to the company's 95 employees. Of 95 employees, 60% were white-collar and 40% blue-collar. Blue-collar worker response rate was 37% including blue-collar and white-collar workers from the Engineering and Construction divisions.
2. Analysis of 17 archived projects of welding operations.
3. 11 interviews with executives, project managers, technical experts and financial stakeholders in the company to provide qualitative insights.

f. Data Analysis Strategies and Interpretation

Table 3: Strategies per data type

Data Type	Strategy and interpretation
Quantitative	Descriptive and inferential statistics (ANOVA) and regression analysis.
Qualitative	Thematic analysis from management and employee questionnaires

Findings were interpreted alongside existing literature, facilitating a comprehensive understanding of the implications of automated welding technologies. This mixed methods approach ensured a nuanced exploration of empirical data and subjective insights, guiding informed decision-making for the Company's strategic investments. The linkage between qualitative themes from management interviews and survey questions in the labour force questionnaire was established to enhance data triangulation and validity. This ensured that quantitative questions were directly derived from qualitative insights.

g. Quality Assurance

This study employs a comprehensive approach to enhance its findings' external validity and transferability, providing a detailed case study of the company to allow for application to similar industrial contexts. Triangulation, purposive sampling, and cross-validation of interview themes and survey responses were applied to ensure internal validity and reliability. Reliability and dependability were underpinned by a precise, systematic data collection and analysis methodology, ensuring the study's findings are consistent and reproducible within the sector.

h. Ethical Considerations

Participants received detailed study briefs. Data anonymisation and right to withdraw were upheld.

4. PRESENTATION OF RESEARCH RESULTS

a. Overview of Data Sets

i Dataset 1: Management Interviews

This dataset includes insights from 11 semi-structured interviews with senior-level staff (Managers, Senior Managers, and Directors) at the case study company, following the process outlined in Figure 7 (Clarke & Braun, 2017). Participants were selected based on their seniority to ensure perspectives on strategic and technical matters. The interviews explored current welding methods, the company's appetite for automation, perceived benefits and disadvantages, and its impact on direct field labour (blue-collar workers).

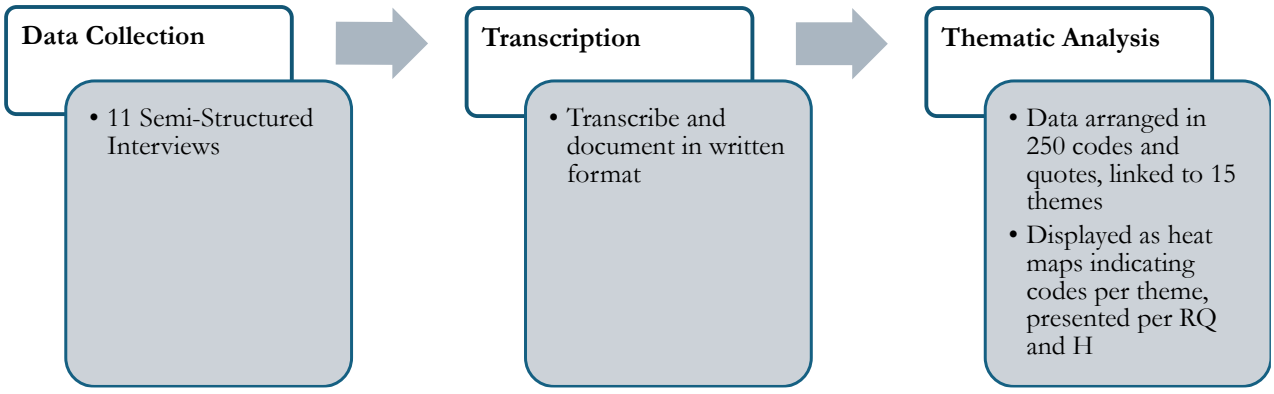


Figure 7: Data Collection Process for Dataset 1

Findings from this dataset are integrated across multiple research questions. Relevant visuals, such as thematic maps and summaries, are presented in Sections 4.b, 4.c, 4.d and 4.e, where these themes are analysed about the research questions.

ii Dataset 2: Employee Survey

This dataset consists of responses from a Likert-scale questionnaire distributed in hard copy to the Company's employees who voluntarily participated. Care was taken to ensure representation across roles, including engineering, administrative and management staff (White Collar) and unskilled, semi-skilled and skilled artisans (Blue Collar).

To enhance the presentation of research results, a table linking the themes from management interviews to the labour force questionnaire questions is provided in Table 4. This linkage demonstrates that the quantitative survey questions were derived from the qualitative themes identified during management interviews, ensuring consistency between the two datasets. This addition supports the validity and coherence of the research findings by showing how employee perceptions were explored based on managerial insights.

Table 4: Linking of Qualitative Themes to Labour Force Questions

Theme No.	Main Themes from Management Interviews	Corresponding Labour Force Questionnaire Questions
1	Acceptance and adoption of Pipe Spool Automation in South Africa	2.2, 3.5, 5.1, 5.2
2	Automation as a result of leadership innovation culture and strategy	5.2, 5.3
3	Context Specific applications for Automation	3.3, 3.7
4	Investment Criteria and Pre-Requisites	5.1, 5.2, 5.3
5	Labour Impact as a result of Automation	2.3, 3.5, 3.7, 4.1, 4.2
6	Market positioning and client perceptions on Automated Welding	5.2, 5.3
7	Quality Criteria for Welding activities	None
8	Improved quality as a result of automation	3.1
9	Increased speed and productivity as a result of automation	3.2, 3.4, 5.3
10	Perceived Disadvantages of Automation	2.3, 3.5
11	Reduced occupational risk as a result of automation	3.3, 3.4
12	Manual Welding as the Status Quo	2.1, 2.3
13	Manual weld durations and cost estimation	5.1, 5.3
14	Disadvantages of Human Involvement in Manual Welding	2.3, 3.5
15	When human involvement is a pre-requisite	3.6

The questionnaire used a 5-point Likert scale (1 = Strongly Disagree to 5 = Strongly Agree) and generated 95 responses. Data analysis involves descriptive statistics, regression analysis, ANOVA, and T-tests.

Findings from this dataset are integrated into the discussion of multiple research questions. Sections 4.b, 4.c, and 4.d and 4.e present relevant visuals and statistical summaries to support key insights.

iii Dataset 3: Manual Weld Failure Rates

This dataset comprises archival data collected over the past two years, reflecting current operational practices at the Company. It includes failure rates from 17 projects where non-destructive X-ray testing (RT) was a prerequisite. Failure rates were calculated as the percentage of failed welds relative to the total welds X-rayed.

iv Dataset 4: Welding Speed Data

Dataset 4 is based on a South African Standard Times database commonly used in the petrochemical industry to estimate weld durations for high-pressure piping. The Company adopted this database for labour duration estimations and subsequent cost projections in proposals and quotations. Experienced personnel within the company verified the database's validity during management interviews (Dataset 1), resulting in high confidence in its reliability.

The database covers manual welding durations for pipe diameters ranging from 2" to 24" and applies to commonly used carbon steel grades. It exclusively pertains to manual welding, while estimates for automated welding are derived separately from technology supplier claims (Dataset 5).

Findings from this dataset are integrated into Sections 4.b and 4.e, where welding efficiency and financial implications are analysed.

v Dataset 5: Supplier Data on speed and quality claims

This dataset comprises technical data and case study information provided by a welding equipment supplier. The supplier was selected based on the availability of detailed technical documentation and relevant case studies. The dataset includes supplier claims regarding speed and quality improvements achieved through automated welding technologies.
This dataset forms a key input for comparing automated and manual welding speed (Dataset 4) and contributes to Sections 4.b and 4.c, where welding efficiency and financial implications are analysed.

vi Dataset 6: Financial Evaluation Model

This dataset includes the Payback Period and IRR calculation model developed to evaluate the financial viability of transitioning to automated welding. The model focuses on incremental labour costs, excluding material costs, to ensure independence from factors that remain unchanged between manual and automated welding. Internal rates for labour categories, including welders, boilermakers, assistants, supervisors, and QC personnel, were used. These rates account for total cost-to-company, including salaries and overheads.

Revenue per Factored Diameter Inch (FDI) was determined using the Company's current quoting philosophy, which incorporates time requirements for welding, supervision, and QC percentages. Standard contingency and profit margins were applied to develop a market-related revenue per FDI. Costs per FDI were calculated based on internal rates and weld times for manual welding, as outlined in Dataset 4, and compared with automated welding costs derived from supplier data (Dataset 5).

A benchmark IRR range of 15-20% was set, reflecting the company's Weighted Average Cost of Capital (WACC)—the average rate the company must pay to finance its operations, blending the cost of debt (interest on borrowings, adjusted for tax) and the cost of equity (returns expected by shareholders). WACC incorporates inflation, opportunity costs, and market risks, serving as a key benchmark for investment decisions. The Senior Manager of Finance confirmed that a 15% and 20% hurdle rate is acceptable for the company.

The input data is highly reliable, as labour rates are based on the current company rates, and revenue per FDI aligns with market-related prices. The dataset is integral to Section 4.e, where the financial implications of automated welding are analysed.

b. RQ1: What are the efficiency implications of adopting automated welding technologies in pipe spool welding?

i Hypothesis 1 (H1)

Automated welding technologies reduce the cost per unit of welded material in high-pressure pipe fabrication compared to manual welding methods.

ii Qualitative Findings

Table 5 illustrates the distribution of themes and codes across roles related to RQ1 and H1 derived from semi-structured management interviews in Dataset 1.

Table 5: Heat map of semi-structured interview themes related to RQ 1 and H1

Main Themes	Count of Codes/Quotes											
	Director: Fabrication and Wear	Director: Operations Support	Manager: Safety Sasolburg	Manager: Sasolburg Workshop	Proposal Manager	QA/QC Inspector and IPE	Senior Manager: E&I	Senior Manager: Execution	Senior Manager: Fabrication	Senior Manager: Quality	Senior Manager: SHEQ	**Grand Total**
Context Specific applications for Automation		3		2		1	1	3	2	1	1	**14**
Increased speed and productivity as a result of automation	1	1		2	1		2	1	2			**10**
Manual Welding as the Status Quo	2	2	1	1	1	2	1	2	3	1	2	**18**
Manual weld durations and cost estimation		2		2	2		1			1		**8**
Grand Total	**3**	**8**	**1**	**7**	**4**	**3**	**5**	**6**	**7**	**3**	**3**	**50**

The data overwhelmingly shows that the Company relies on ***manual welding processes*** without significant automation. This reliance underscores the opportunity to introduce automation to improve efficiency.

- *"At the moment, the Company doesn't have any automated welding processes. All our welding is done manually."* ***(Senior Manager: Fabrication, Interview 02)***

Manual welding in the company involves standardised metrics for estimating durations based on weld sizes. This method ***provides baseline data*** for comparing the time-saving benefits of automation.

> *"We have developed a database amongst the experienced personnel in the company, which documents the expected time that it will take a manual welder to perform different butt weld sizes, as well as weld speed per length of linear welding performed."* ***(Manager: Sasolburg Workshop, Interview 06)***

Automation offers significant ***efficiency improvements. For example,*** repetitive welding of large pipes can be completed in a fraction of the time required for manual methods.

- *"A machine could weld a 10-inch pipe in an hour or two, whereas a manual welder might take a full eight-hour shift."* ***(Senior Manager: E&I, Interview 03)***

Automation is ***most applicable*** in controlled environments ***like workshops***, which are better suited to repetitive and large-scale tasks. Field applications face challenges due to environmental factors and labour considerations.

- *"Automated welding is not ideal for fieldwork due to environmental factors. It's much better suited for controlled environments like workshops."* ***(Senior Manager: Quality, Interview 05)***

iii Quantitative Findings

Employee Perceptions of Productivity Improvements

Based on the employee survey data, white-collar workers consistently rated the productivity benefits of automation significantly higher (M = 4.15, SD = 0.988) than blue-collar workers (M = 2.46, SD = 1.379). A t-test confirmed this difference was statistically significant ($t(93) = 6.940$, $p < 0.001$). Regression analysis indicated that the labour category was the strongest predictor of perceptions, explaining 35.5% of the variance ($R^2 = 0.355$, $p < 0.001$). Blue-collar workers expressed notably lower expectations of automation efficiency than their white-collar counterparts. Blue-collar workers had a higher variability in responses. Whilst the variability was less for white-collar colleagues, some outliers were observed, possibly due to isolated pockets of scepticism. The outliers, however, do not significantly impact the mean.

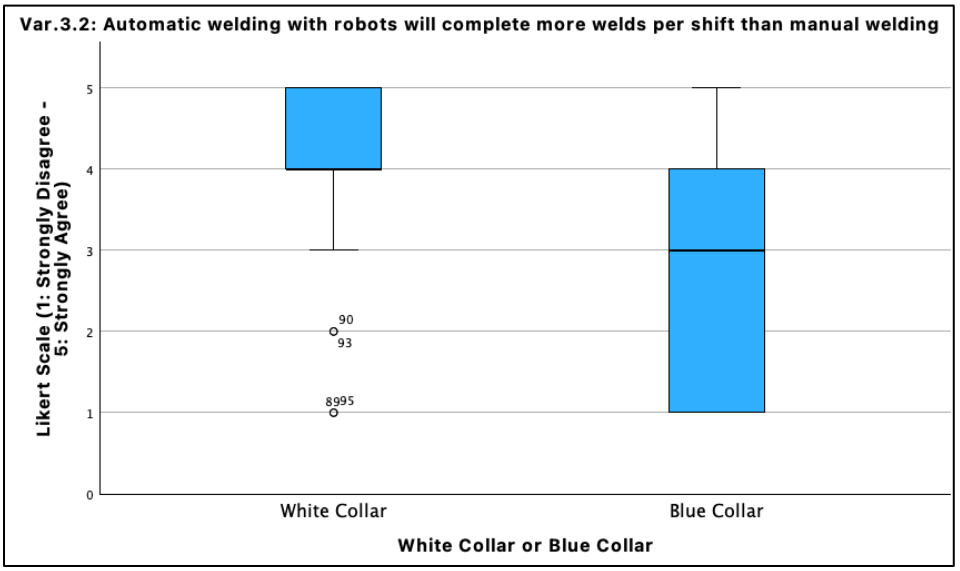


Figure 8: Box plot of responses to Q3.2 in the employee survey

Weld Duration Data

Claims from Novarc Technologies suggest that the SWR robot can significantly reduce welding time (*SWR Production - FDI per Shift*, n.d.). Figure 9 shows a 73.7% reduction in fabrication time for a 24" butt weld and a 47.5% reduction for a 2" weld, demonstrating significantly reduced fabrication times across all pipe diameters. The times shown in the figure include the fitting, tacking, and welding time.

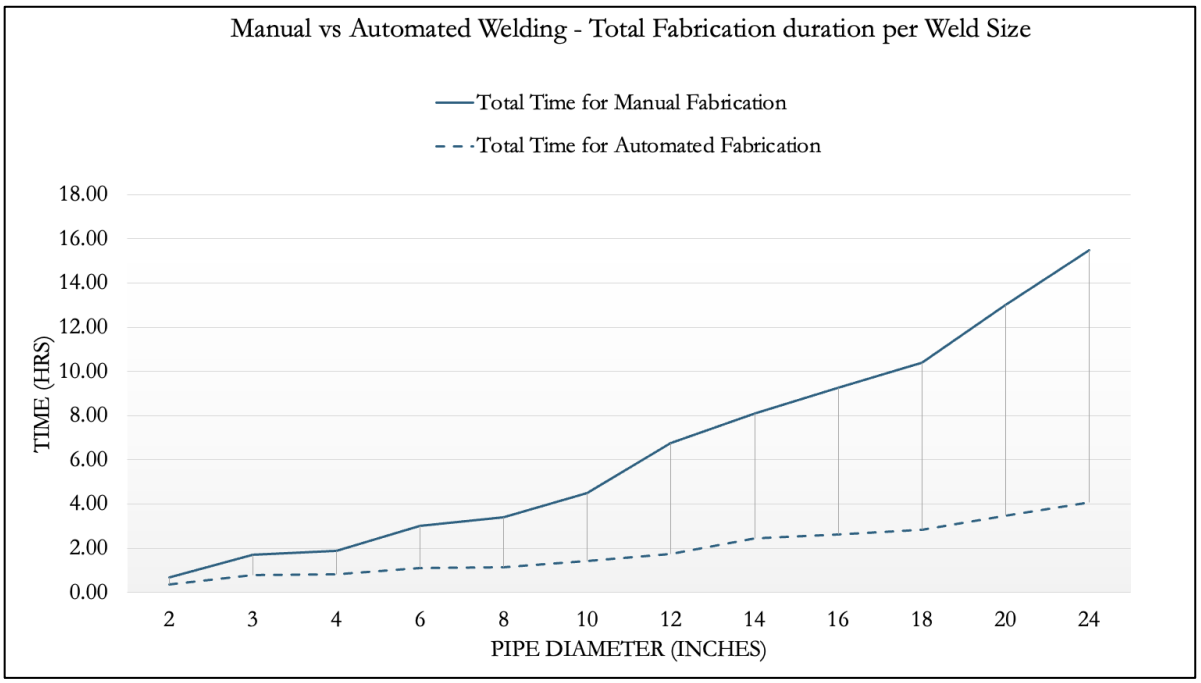


Figure 9: Total fabrication time for manual vs automated welding, considering the company's current weld duration data per size compared to weld speed claims from robotic equipment suppliers

Unit Cost Reduction

Figure 10 is based on the costing model developed as part of Dataset 6, demonstrating the consistent cost advantage of automated welding, with a steeper incline in costs for manual welding as utilisation increases. The model shows that:

- Automated welding consistently yields lower per FDI costs than manual welding across all utilisation rates.
- At maximum utilisation (144 hours/week), the unit cost for automated welding is R243.99, significantly lower than the manual welding cost of R577.71 – a 58% reduction.
- The cost per FDI increases as weekly manhour utilisation rises. This trend is observed for manual and automated welding, although the increase is more pronounced for manual welding.

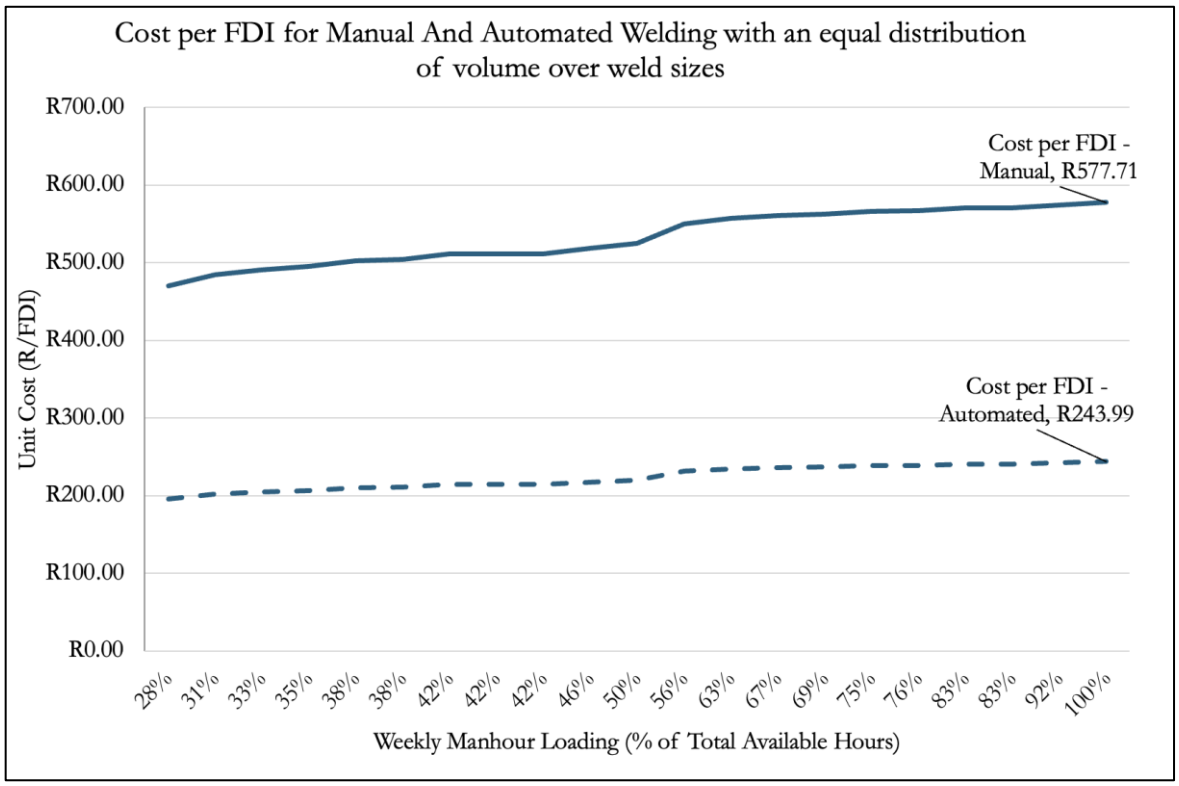


Figure 10: Unit Cost Reduction as a result of automated welding

Consequently, a significant increase in profit margin is expected, as illustrated in Figure 11. The figure demonstrates a profit margin of 72% at 100% loading for automated welding, compared to only 33% for manual welding under similar conditions.

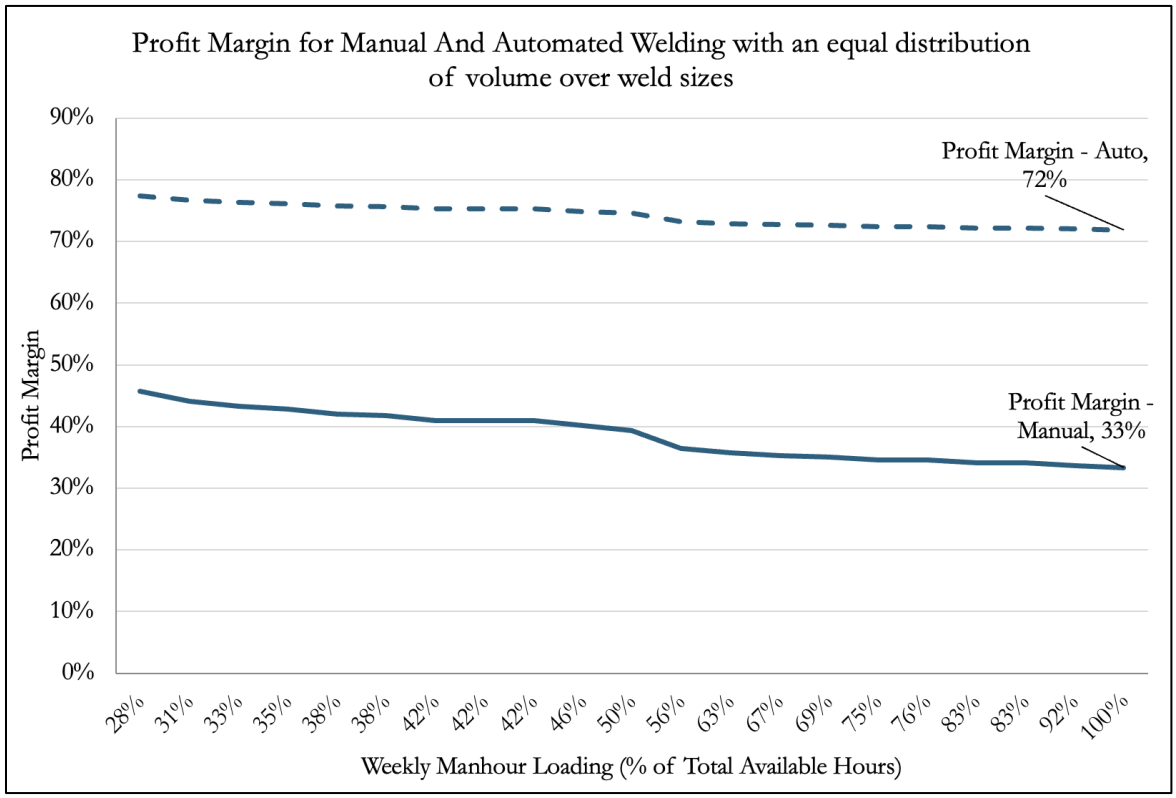


Figure 11: Higher Profit Margin as a Result of Automation for Varying Manhour Loading

iv Triangulation and Conclusion

Triangulated data from interviews, surveys, and performance metrics consistently highlights the efficiency advantages of automated welding. Supplier claims and company records confirm that automation significantly reduces fabrication times across all pipe diameters. The costing model demonstrates that automated welding consistently offers lower costs per FDI than manual methods.

Automation is most effective in controlled workshop environments, where repetitive tasks and stable conditions maximise efficiency and cost savings. These findings strongly align with Hypothesis 1 (H1), affirming that automated welding technologies reduce the cost per unit of welded material and deliver substantial time and cost efficiencies in high-pressure pipe fabrication.

c. RQ2: What is the impact of automated pipe spool welding on quality?

i Hypothesis 2 (H2)

Automated welding technologies enhance the quality of welds in high-pressure pipe fabrication more consistently than manual welding methods.

ii Qualitative Findings

The heat map illustrates the distribution of themes and codes across roles derived from semi-structured interviews related to RQ2 and H2. It highlights the company's current quality-focused approach and management's perceptions of the quality improvements expected from Automation.

Table 6: Heat map of semi-structured interview themes related to RQ 2 and H2

	Count of Codes/Quotes											
Main Themes	Director: Fabrication and Wear	Director: Operations Support	Manager: Safety Sasolburg	Manager: Sasolburg Workshop	Proposal Manager	QA/QC Inspector and IPE	Senior Manager: E&I	Senior Manager: Execution	Senior Manager: Fabrication	Senior Manager: Quality	Senior Manager: SHEQ	**Grand Total**
Quality Criteria for Welding activities	5	2		1		2	2		6	5		23
Improved quality as a result of automation	1	1	2	1	1		3	1	1	2	1	14
Grand Total	**6**	**3**	**2**	**2**	**1**	**2**	**5**	**1**	**7**	**7**	**1**	**37**

Despite automation's potential advantages, the company's current manual welding processes maintain ***strict quality standards***, as evidenced by ISO 3834 accreditation and periodic welder qualifications. This underscores the existing focus on quality assurance while highlighting opportunities for automation to enhance these processes further.

- *"We are ISO 3834 certified, which governs the quality process and ensures that we follow the procedures to ensure consistent quality."* ***(Director: Operations Support, Interview 07)***

Manual welding processes rely heavily on monitoring welder performance through repair rates and non-destructive testing. The company enforces an internal threshold of less than 5% but aspires to meet the industry standard of a 2% repair rate, which is considered exemplary.

- *"If a welder has a repair rate above 5% for a project, we'll call them back to identify the cause of the issue."* ***(Senior Manager: Quality, Interview 05)***
- *"The industry norm for a good repair rate is around 2%, which is much more acceptable."* ***(Senior Manager: Quality, Interview 05)***

The interviews consistently highlighted the quality improvements that can be achieved through automation in pipe spool welding. The 23 codes and corresponding quotes demonstrate that automation can minimise human error, standardise weld configurations, and ensure consistent quality, particularly in controlled environments.

Automation removes inconsistencies caused by ***human factors*** such as fatigue, distraction, or emotional state. Automating processes like temperature control and weld monitoring reduces the likelihood of defects such as porosity and inclusions.

- *"Automation offers better control over variables like speed, temperature, and power, which reduces defects like porosity and inclusions."* ***(Senior Manager: Execution, Interview 08)***

Automated systems ***operate with precision***, adhering to programmed parameters without deviations caused by ***human fatigue*** or variability.

- *"If the setup is done correctly, you will gain consistency in the product quality as you remove the human element."* ***(Director: Operations Support, Interview 07)***

Automation has the potential to significantly ***reduce defect and failure rates***, translating to higher reliability and fewer reworks.

- *"Even reducing welding failure rates by 10% to 15% would be a game-changer in terms of quality and reliability."* ***(Senior Manager: E&I, Interview 03)***

iii Quantitative Findings

Employee Perceptions of Automation Quality

Based on the employee survey data, white-collar workers consistently rated the ability of automated welding to reduce weld failures significantly higher ($M = 3.88$, $SD = 1.027$) than blue-collar workers ($M = 2.31$, $SD = 1.409$). A t-test confirmed this difference was statistically significant ($t(93) = 6.246$, $p < 0.001$). Regression analysis indicated that the labour category (white-collar vs blue-collar) was the strongest predictor of perceptions, explaining 30.2% of the variance ($R^2 = 0.302$, $p < 0.001$). Blue-collar workers expressed notably lower expectations of automation's ability to improve weld quality than white-collar counterparts ($B = -1.468$, $p < 0.001$). Age did not significantly influence perceptions.

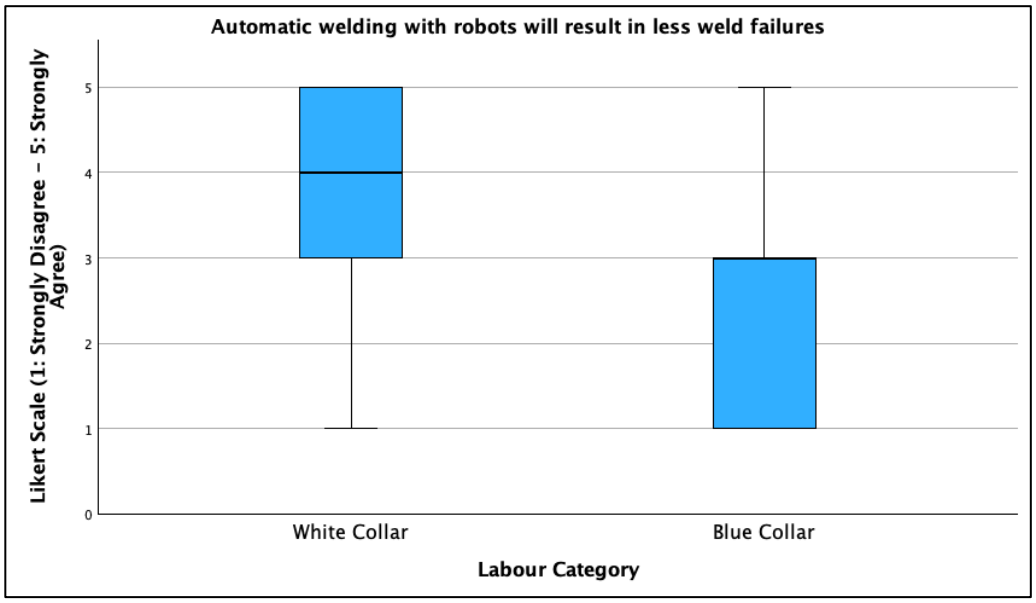


Figure 12: Box plot of responses to Q3.1 in the employee survey

Comparison of company-specific manual quality performance against automation claims

Historical data (secondary data) on weld quality performance statistics from 17 projects requiring X-rays as a non-destructive testing method were collected. This information provided a baseline for current welder performance based on historical data. Nine hundred ninety-five welds were x-rayed, with 83% completed in the shop and 17% in the field. Figure 13 shows the shop and field failure rates were 4.01% and 6.85%, respectively. By comparison, automation technology such as the Spool Welding Robot (SWR) by Binzel Abicor claims weld failure rates of less than 1%, significantly outperforming shop and field manual welding processes.

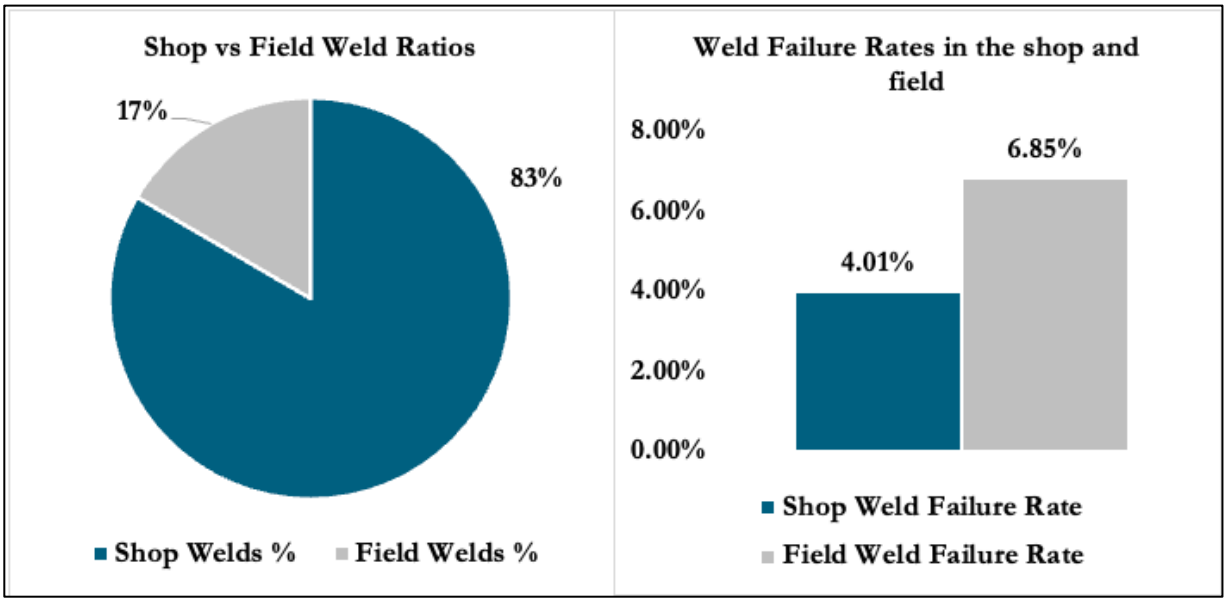


Figure 13: Shop vs Field ratios and Failure Rates per Distinction

iv Triangulation and Conclusion

The triangulated results for RQ2 and H2 highlight a robust alignment between qualitative insights, quantitative data, and historical performance comparisons, confirming the significant quality

improvements associated with automated welding technologies in pipe spool fabrication. Qualitative findings underscore the advantages of automation in minimising human error, ensuring consistency, and reducing failure rates. Quantitatively, white-collar workers rated the impact of automation on reducing weld failures significantly higher than blue-collar workers, with statistical analysis confirming labour categorisation as the strongest predictor of these perceptions ($R^2 = 0.302$, $p < 0.001$). The historical data, showing failure rates of 4.01% in shop welding and 6.85% in field welding, contrasts sharply with claims from automation suppliers, such as the Spool Welding Robot (SWR), which achieves failure rates below 1% ("Binzel-Abicor," 2025). Together, these findings strongly support H2, affirming that automated welding enhances weld quality more consistently than manual methods.

d. RQ3: How does automated pipe spool welding impact blue-collar workers in the case study company?

i Hypothesis 3 (H3)

Adopting automated welding technologies within private industrial sector energy project development models will create new job roles and enhance upskilling opportunities.

ii Qualitative Findings

The heat map illustrates the distribution of themes and codes across roles derived from semi-structured interviews related to RQ3 and H3, highlighting the impact that may be expected on blue-collar workers due to automation.

Table 7: Heat map of semi-structured interview themes related to RQ3 and H3

	Count of Codes/Quotes											
Main Themes	**Director: Fabrication and Wear**	**Director: Operations Support**	**Manager: Safety Sasolburg**	**Manager: Sasolburg Workshop**	**Proposal Manager**	**QA/QC Inspector and IPE**	**Senior Manager: E&I**	**Senior Manager: Execution**	**Senior Manager: Fabrication**	**Senior Manager: Quality**	**Senior Manager: SHEQ**	**Grand Total**
Labour Impact as a result of Automation	1	4	7	3	2	1	5	3	2	1	3	32
Reduced occupational risk as a result of automation			7					1	2		1	11
Disadvantages of Human Involvement in Manual Welding		1		5	1				2			9
When human involvement is a pre-requisite			1			2	1			2		6
Grand Total	**1**	**5**	**15**	**8**	**3**	**3**	**6**	**4**	**6**	**3**	**4**	**58**

Management strongly emphasised the potential for automation to catalyse ***skill development*** among blue-collar workers, transitioning their roles from manual welders to operators or maintenance specialists.

- *"Some employees can be upskilled to operate the equipment. We've already seen success with upskilling, for example, training one of our drivers to operate a CNC machine."* ***(Director: Fabrication and Wear, Interview 09)***

Initial resistance among blue-collar workers is a recurring theme, with ***fears of job displacement*** and the perception of being ***replaced by automation***. Management noted that older workers may feel threatened, whereas younger workers are more likely to embrace the change.

- *"Their immediate reaction would likely be that robots or AI will replace them, putting their jobs at risk."* ***(Proposal Manager, Interview 01)***
- *"Older employees might view automation as a threat, which could lead to potential job losses and labour relations issues."* ***(Senior Manager: Execution, Interview 08)***

Management highlighted the potential for automation to improve working conditions, ***reducing exposure*** to safety risks and ergonomic strain.

- *"Automation would significantly reduce risks, such as exposure to fumes, arc flashes, UV rays, or physical strain from welding."* ***(Manager: Safety Sasolburg, Interview 10)***

Manual welding processes introduce several ***inefficiencies and risks***, mainly due to the variability and unpredictability of human factors. Automation solves these limitations by standardising processes and reducing reliance on human performance.

- *"The main challenge with any manual welding process is the human factor, which I see as the biggest risk."* ***(Senior Manager: Fabrication, Interview 02)***
- *"The human factor makes it possible for welders to weld faster or slower, based on the pressure and/or psychological factors that are applicable on a specific day."* ***(Manager: Sasolburg Workshop, Interview 06)***

Although welders may no longer be physically welding, their ***roles evolve*** to include oversight, configuration, and quality assurance for automated systems. This highlights that human expertise remains essential in achieving the full benefits of automation.

- *"Automation doesn't necessarily mean replacing someone. You'd still need welders and quality inspectors, just with their roles slightly adjusted."* ***(Manager: Safety Sasolburg, Interview 10)***

iii Quantitative Findings

The regression model showed that the labour category (white-collar vs. blue-collar) significantly influenced willingness to learn automation, with blue-collar workers being less willing than their white-collar counterparts. However, age was not a significant predictor. The model did not significantly explain anxiety about automation, and none of the predictors, including labour category or age, showed notable influence.

White-collar workers reported more excellent experience with robots and automation ($M = 2.35$ vs. $M = 1.43$) and a higher willingness to learn automation technologies ($M = 4.02$ vs. $M = 2.74$). They also

rated automation's benefits significantly higher than blue-collar workers, particularly regarding reduced physical strain (M = 4.30 vs M = 2.57) and career opportunities (M = 3.72 vs M = 2.40).

iv Triangulation and Conclusion

The findings provide substantial insights into RQ3 and H3, which examine the impact of automated welding technologies on blue-collar workers and the potential for new job roles and upskilling. Both qualitative and quantitative data affirm the potential for automation to create technical roles, such as welding robot operators and maintenance specialists, supporting the hypothesis (H3). However, the findings also reveal resistance among blue-collar workers, driven by concerns over job displacement. While management perceives this anxiety to be more pronounced among older employees, quantitative data shows no significant difference in anxiety levels between white-collar (M = 2.48) and blue-collar workers (M = 2.46), suggesting that resistance may not be age-dependent but rather tied to broader workforce apprehensions.

Both datasets emphasise that human expertise will remain critical in automation processes, with workers taking on oversight, configuration, and quality assurance roles. Additionally, automation offers substantial safety and ergonomic benefits, reducing physical strain and exposure to hazards. However, white-collar workers rated these benefits significantly higher (M = 4.30) than blue-collar workers (M = 2.57), reflecting a gap in perception that may influence acceptance.

The findings validate H3, highlighting the potential for automation to upskill blue-collar workers and transform their roles. However, targeted engagement and training are essential to address resistance and perceived barriers across all workforce demographics, ensuring a smoother transition to automated technologies.

e. What is the financial viability of adopting automated welding technologies, as quantified through the Internal Rate of Return (IRR)?

i Hypothesis 4 (H4)

When implemented in medium- to large-scale welding operations, automated welding technologies will demonstrate a favourable Internal Rate of Return (IRR), contingent on workload predictability and operational efficiency.

ii Qualitative Findings

The heat map in Table 8 illustrates the distribution of themes and codes across roles derived from semi-structured interviews related to RQ4 and H4, highlighting perceived investment criteria and management's susceptibility to invest in automation.

The qualitative data reveals that South Africa's construction and fabrication industries are ***slowly adopting*** automated welding technologies. This reluctance stems from a traditional mindset and short-term views that dominate the industry:

- *"The industry tends to be slow in adopting new technologies."* ***(Proposal Manager, Interview 01)***

- *"For decades, this manual approach has been the standard in South Africa, despite technological advancements globally."* ***(Senior Manager: E&I, Interview 03)***

However, global leaders such as China are cited as examples of countries successfully advancing welding automation, highlighting a need for South Africa to catch up in innovation.

Table 8: Heat Map of Themes from semi-structured interviews related to RQ4 and H4

	Count of Codes/Quotes											
Main Themes	**Director: Fabrication and Wear**	**Director: Operations Support**	**Manager: Safety Sasolburg**	**Manager: Sasolburg Workshop**	**Proposal Manager**	**QA/QC Inspector and IPE**	**Senior Manager: E&I**	**Senior Manager: Execution**	**Senior Manager: Fabrication**	**Senior Manager: Quality**	**Senior Manager: SHEQ**	**Grand Total**
Acceptance and adoption of Pipe Spool Automation in South Africa		1		1	1	1	2				1	7
Automation as a result of leadership innovation culture and strategic direction	5	3	2	2	4		2	2	1		3	24
Investment Criteria and Pre-Requisites	6	4	1	1	2	5	4	9	6	3	3	44
Market positioning and client perceptions on Automated Welding Capabilities	4	4		2	4	2	3	3	2	2	1	27
Perceived Disadvantages of Automation	1							1		1		3
Grand Total	**16**	**12**	**3**	**6**	**11**	**8**	**11**	**15**	**9**	**6**	**8**	**105**

The Company's leadership is portrayed as forward-thinking and ***innovation-driven***, emphasising automation as a ***strategic priority***:

- *"The Company likes to lead. They have this mindset of wanting to be the best at what they do right from the start."* ***(Senior Manager: SHEQ, Interview 04)***
- *"We are characterised by our innovation mindset. It is also aligned with our values to always want to improve and move forward."* ***(Manager: Sasolburg Workshop, Interview 06)***

The feasibility of automation hinges on several financial and operational factors, including Payback Period, steady workload, and appropriate market research:

- *"Proper market research is essential to understand the opportunities and justify the investment."* ***(Senior Manager: Fabrication, Interview 02)***
- *"Without a steady pipeline of high-pressure piping work, companies may not see the value in investing in automation."* ***(QA/QC Inspector and IPE, Interview 11)***

Clients generally view ***automation favourably***, mainly when it delivers quality and efficiency. Automation is seen as a way to establish the Company's competitive edge and attract clients, particularly as a first-mover in the market.

- *"Clients generally care about the end result - quality and on-time delivery. As long as those are met, I don't foresee resistance from clients."* ***(Senior Manager: Execution, Interview 08)***
- *"Automation would position us in a different league, allowing us to deliver work more efficiently and compete more effectively in the market."* ***(Senior Manager: Fabrication, Interview 02)***

While the potential benefits of automation are evident, the assumed ***high capital cost*** is considered a disadvantage. However, a decision-making framework is essential to assist decision-makers in evaluating the viability of investing in automation.

- *"Cost would probably be the main concern. Automation could be expensive, but if it brings value - like shorter project timelines or better-quality work - it might justify the investment."* ***(Senior Manager: SHEQ, Interview 04)***

iii Quantitative Findings

Payback Period and IRR Model Results

The model focuses on a scenario where the welding scope is evenly distributed across various pipe sizes, as research indicates that the cost per FDI differs depending on pipe size. Figure 14 illustrates the payback period (in months) for adopting the SWR Spool Welding Robot by Novarc Technologies, with an investment cost of R13,500,000**.** This analysis highlights the relationship between workload, manhour utilisation, and the payback period for replacing manual welders with automated welding solutions. Based on insights from the management interviews, a two-year payback period is considered highly favourable. Achieving this requires a minimum workload of 545 FDI per week of manual welding scope replaced with a single welding operator.

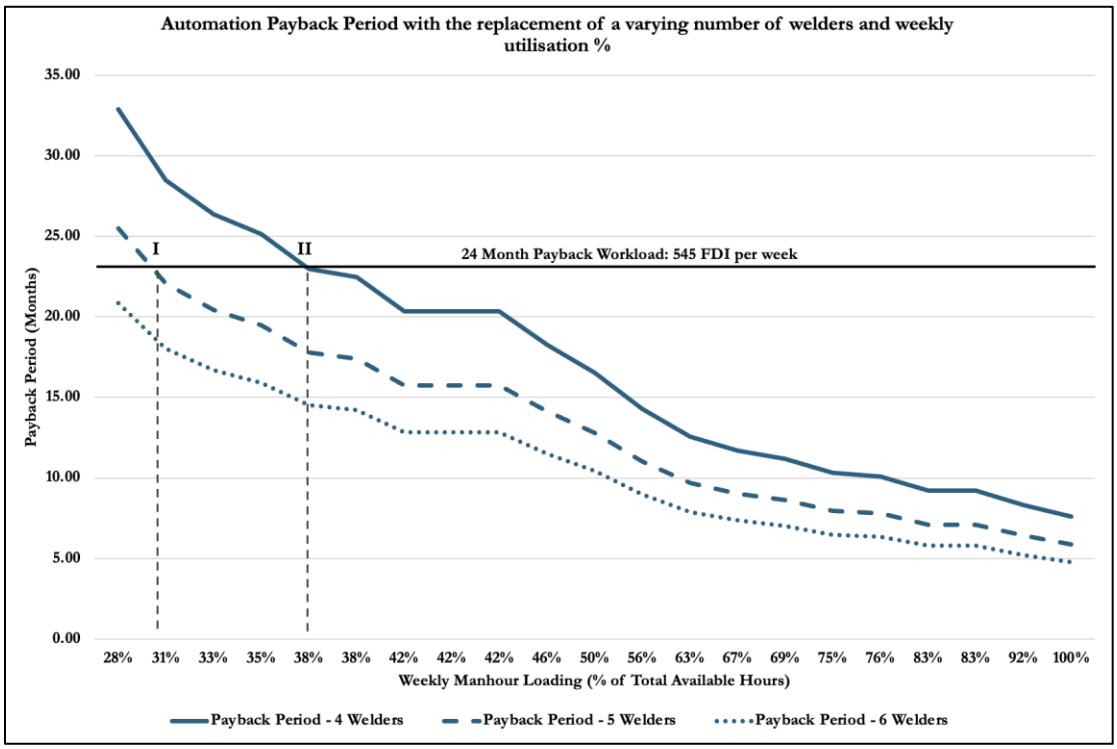


Figure 14: Payback Period (Months) for Automation, based on the investment cost quoted

A higher manual workload results in a faster payback if replaced with automation, which correlates with increased weekly manhour utilisation, as illustrated in the graph. The 545 FDI line intersects the five-welder graph (manual welding equivalent) at point I and the 6-welder graph at point II, demonstrating that:

- A utilisation rate exceeding 31% for manual welders or a rate greater than 38% for four welders ensures a payback within 24 months if a single SWR Welding Robot replaces this equivalent.
- If a single SWR welding robot replaces this equivalent, even a minimum utilisation rate of 28% for six manual welders achieves a payback period of less than 24 months.

Table 9: Payback period with manhour data corresponding to Figure 11

Point	Payback Period	Weekly Workload Required	Manhour Loading	No of Welders replaced	No. of Shifts	Hours per Shift	Days per Week	No of Hrs
I	24 Months	545 FDI	31%	5	1	9	5	45/144
II	24 Months	545 FDI	38%	4	1	9/11	6/5	55/144

As shown in Figure 11, increasing weekly manhour loading leads to a higher cost per FDI, which reduces the profit margin per FDI. However, as shown in Figure 15, higher manhour loading generates more weekly revenue and cash flow, positively impacting the Internal Rate of Return (IRR).

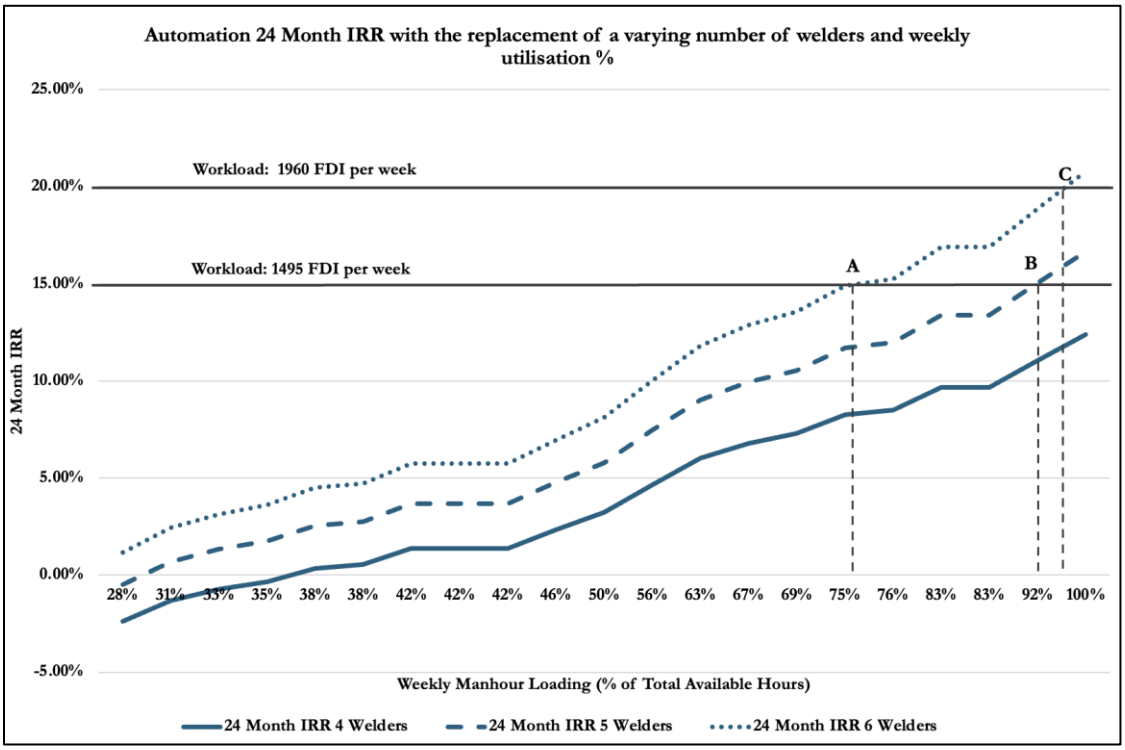


Figure 15: Relationship between IRR, workload and weekly utilisation for the replacement of four to six welders

Figure 15 demonstrates the workload and manhour combinations required for different IRRs. If a hurdle rate of 15% is required, a weekly workload of 1495 FDI is necessary. For a hurdle rate of 20% over two years, a workload of 1690 FDI per week is required. These conditions translate to the following combinations, corresponding to points A, B and C in Figure 15:

Table 10: IRR with manhour data corresponding to Figure 15

Point	IRR (2 Years)	Weekly Workload Required (FDI)	Manhour Loading	No of Welders replaced	No. of Shifts	Hours per Shift	Days per Week
A	15%	1495	75%	6	2	9	6
B	15%	1495	92%	5	2	11	6
C	20%	1690	100%	6	2	12	6

iv Triangulation and Conclusion

The findings for RQ4 and H4 confirm the financial viability of adopting automated welding technologies under medium- to large-scale operations, contingent on workload predictability and operational efficiency. Qualitative insights emphasise leadership's forward-thinking approach and the importance of steady workloads to justify investments. At the same time, quantitative analysis demonstrates favourable returns, including a two-year payback period with a minimum workload of 545 FDI per week. Achieving a 15% IRR requires 1,495 FDI per week, whereas a 20% IRR necessitates 1,690. Despite concerns over high capital costs, both datasets converge to highlight automation's financial potential when supported by strategic workload planning and consistent execution, providing a clear framework for decision-makers.

5. DISCUSSION OF RESEARCH FINDINGS

a. Introduction

The study assessed automated welding's efficiency, quality, workforce impact, and financial viability in a South African construction firm.

To reiterate, the research sought to address four core questions:

- **RQ1:** What are the efficiency implications of adopting automated welding technologies in pipe spool welding?
- **RQ2:** What is the impact of automated pipe spool welding on quality?
- **RQ3:** How does automated pipe spool welding impact blue-collar workers in the case study company?
- **RQ4:** What is the financial viability of adopting automated welding technologies, as quantified through the Payback Period and Internal Rate of Return (IRR)?

Each question was explored through a corresponding hypothesis:

- **H1:** Automated welding technologies reduce the cost per unit of welded material in high-pressure pipe fabrication compared to manual welding methods.
- **H2:** Automated welding technologies enhance the quality of welds in high-pressure pipe fabrication more consistently than manual welding methods.
- **H3:** Adopting automated welding technologies will create new job roles and enhance upskilling opportunities.
- **H4:** Automated welding technologies will demonstrate a favourable IRR when workload predictability and operational efficiency are ensured.

b. Summary of Key Findings

i RQ1: What are the efficiency implications of adopting automated welding technologies in pipe spool welding?

The data support the hypothesis that automated welding significantly reduces fabrication times and unit costs per Factored Diameter Inch (FDI) compared to manual welding. Automation achieves efficiency gains of up to 73.7% for larger pipe diameters in controlled workshop environments. These findings align with Hypothesis 1 (H1).

ii RQ2: What is the impact of automated pipe spool welding on quality?

The analysis confirms that automated welding enhances weld quality by reducing failure rates to less than 1%, outperforming manual welding processes with shop and field failure rates of 4.01% and 6.85%, respectively. These results strongly support Hypothesis 2 (H2).

iii RQ3: How does automated pipe spool welding impact blue-collar workers in the case study company?

The data suggest that while automation offers opportunities for upskilling blue-collar workers into technical roles, it faces resistance due to perceived job displacement risks. Management emphasises the need for engagement and training to address these concerns. Human expertise remains critical in automation processes. The findings partially support Hypothesis 3 (H3).

iv RQ4: What is the financial viability of adopting automated welding technologies, as quantified through the Payback Period and Internal Rate of Return (IRR)?

The analysis identifies workload predictability and operational efficiency as key factors for financial viability. Automation achieves a two-year payback period with a weekly workload of 545 FDI, a 15% IRR at 1,495 FDI, and a 20% IRR at 1690 FDI per week. These results validate Hypothesis 4 (H4), demonstrating favourable financial outcomes for medium—to large-scale operations under optimal conditions.

c. Integration of Findings with Theoretical and Conceptual Frameworks

The findings align closely with the proposed conceptual framework (Figure 6) while validating the theoretical principles of technological evolution and the socio-economic impacts of automation (Chen et al., 2014; Zhou et al., 2019; Acemoglu & Restrepo, 2019). The theoretical framework provides a lens to interpret how automation reshapes industrial practices and labour dynamics. The findings support Acemoglu & Restrepo's reinstatement effect—automation does not just displace labour but reallocates tasks. This is evident in blue-collar workers being upskilled to operator roles.The conceptual framework demonstrates how these shifts are operationalised in the context of the case study, highlighting context-specific barriers and opportunities unique to South Africa's construction sector.

i Workforce Reskilling and the Reinstatement Effect

The findings on workforce reskilling demonstrate how automation transitions blue-collar workers into technical roles such as robotic operators. This directly supports Acemoglu and Restrepo's (2019) "reinstatement effect," which theorises that automation displaces tasks and creates new opportunities for labour in higher-value roles. While the quantitative analysis did not identify significant predictors of automation-related anxiety (e.g., labour category or age), qualitative insights from white-collar management interviews revealed pockets of resistance and concern about automation's impact on labour dynamics. This resistance, somewhat reminiscent of "Luddite-like" fears, reflects apprehensions about the broader implications of technology adoption rather than direct personal displacement.

Interestingly, blue-collar workers—the group most directly impacted by automation—exhibited less resistance in the findings. This suggests a potential disconnect between managerial perceptions of workforce readiness and the actual sentiments of those on the ground. Addressing this disparity through

targeted engagement, transparent communication, and inclusive reskilling initiatives could help align managerial expectations with workforce realities. By alleviating skills scarcity and fostering a sense of security, automation ensures the workforce remains relevant and adaptable, aligning with broader socio-economic goals.

ii Enhanced Quality and Reduced Rework

The theoretical framework highlights the progression of welding technology toward intelligent systems capable of minimising human error. This is practically realised through enhanced quality achieved by automated welding, as seen in the significantly lower failure rates (e.g., <1% failure rate of automated welds compared to 4-6% in manual processes). These improvements reduce rework, ensure consistent adherence to stringent quality standards, and operationalise the theoretical argument for automation as a tool for superior precision and reliability. This aligns with global findings, yet the study emphasises the importance of adapting automation processes to localised operational conditions.

iii Increased Efficiency and Productivity Gains

The findings on efficiency gains, including significant time and cost reductions, reflect the economic theories of productivity increases associated with automation. Theoretical principles of task redistribution between labour and capital are embodied in the shift of repetitive and standardised tasks to machines, while human roles focus on oversight and quality assurance. However, South Africa's slower adoption pace compared to global leaders highlights entrenched manual practices and short-term investment mindsets as significant barriers. Automation enables faster welding times across all pipe diameters, reinforcing the conceptual framework's emphasis on increased efficiency leading to lower labour costs.

iv Cost Reduction and Strategic Investment Decision

Reduced unit costs, supported by minimised rework and fewer required labour units, align with the theoretical framework's premise of economic efficiency as a driver of technological adoption. The financial metrics—favourable payback periods and IRRs—confirm that automation addresses operational challenges and provides a viable return on investment, strengthening the strategic case for adoption. While cost concerns persist, particularly regarding initial capital outlay, the findings provide actionable financial benchmarks to support investment decisions, offering clear conditions for achieving competitive returns.

6. SUMMARY, CONCLUSIONS, LIMITATIONS AND RECOMMENDATIONS

a. Summary

This study examined the adoption of automated welding technologies within a South African construction company, addressing efficiency, quality, workforce impacts, and financial viability. The findings confirmed that automation significantly reduces fabrication times and costs, enhances weld quality by minimising failure rates and offers opportunities for workforce upskilling in technical roles. While most blue-collar workers did not resist automation, targeted engagement and training remain essential to address potential uncertainties and ensure a smooth transition.

Automation achieved favourable financial outcomes, including a two-year payback period and a 15-20% IRR under optimal workload conditions. The study validates automation's potential as a solution to operational and socio-economic challenges in South Africa, provided it is implemented with a localised approach that considers workforce dynamics and industry-specific barriers.

b. Conclusions

This study demonstrates the transformative potential of automated welding technologies within the South African construction industry, addressing critical operational, financial, and socio-economic challenges. By integrating findings with theoretical and conceptual frameworks, the research presents a cohesive narrative: automation can simultaneously address cost reduction, quality enhancement, and workforce development, offering a compelling case for strategic investment.

i Efficiency Gains

Automation significantly improves fabrication times and reduces unit costs, with efficiency gains of up to 73.7% in controlled workshop environments. These improvements validate its role as a tool to enhance competitiveness in the construction sector.

ii Quality Improvements

Automated welding technologies deliver superior consistency and precision, reducing weld failure rates to less than 1%. This is a substantial improvement over manual processes and confirms automation’s capability to meet the stringent quality standards that the company is used to.

iii Workforce Impact of Automation

Automation within the company is intended to increase capacity and efficiency, not replace the existing workforce. This approach ensures stable or growing employment, particularly by creating skilled technical roles. Emphasis should be placed on upskilling employees, creating new opportunities, and addressing job displacement concerns, especially in developing countries like South Africa. The findings highlight opportunities for reskilling the workforce into higher-value roles such as robotic operators. Contrary to initial assumptions and white-collar perceptions, the study found no significant workforce anxiety about job displacement. Instead, blue-collar workers showed openness to automation when supported by upskilling initiatives and clear role transitions.

iv Financial Viability

Automation is financially feasible under optimal conditions, with favourable payback periods and internal rates of return (IRR). These outcomes are contingent on accurate workload assessments and effective planning, reinforcing its viability as a strategic investment priority.

v Contextual Challenges and Localisation

The research highlights the importance of addressing unique barriers within South Africa, including slower adoption rates and traditional investment mindsets. A localised approach considering the socio-economic context is crucial for fully realising automation's benefits.

c. Limitations

i Case Study Scope

The research is based on a single case study within a medium-sized South African construction company. While the findings provide valuable insights, they may not fully represent the experiences and challenges of other companies in the industry, particularly larger or smaller organisations or those operating in different geographical contexts.

ii Workforce Representation

While the study includes data from both blue-collar and white-collar workers, the variability in perspectives and the potential underrepresentation of blue-collar (35/95 responses) workers may limit the generalisability of findings regarding workforce perceptions and reskilling opportunities.

iii Reliance on Supplier Data

The study incorporates technical performance claims from automation equipment suppliers for comparisons with manual welding processes. These claims may not fully reflect real-world conditions and could lead to overly optimistic expectations about automation performance.

iv Technology-Specific Focus

The study focuses exclusively on the Novarc SWR Spool Welding Robot and its applicability to pipe spool fabrication. Other welding applications or automation technologies may produce different results, warranting further investigation to generalise the findings beyond this specific technology.

v Welding-Specific Focus

The study primarily examines automated welding technologies in pipe spool fabrication. While this study demonstrates a significant reduction in welding time, other fabrication activities, such as fitting and tacking, now represent a more significant portion of the total fabrication time. This highlights a substantial opportunity for future research into time-optimization technologies and strategies for these complementary activities.

vi Operational and Maintenance Costs

This research does not account for operational costs, such as consumables and electricity usage. While supplier claims suggest that automation may offer a favourable cost comparison to manual welding, these claims have not been independently validated. Additionally, maintenance costs associated with

automated welding systems were not compared with the maintenance demands of manual welding processes, leaving an opportunity for further cost analysis.

vii Workforce Awareness and Automation Perceptions

The study indicates that the blue-collar workforce is not anxious about introducing automation. However, this lack of concern may stem from a limited understanding of the potential impact of automation on their roles. It is possible that many blue-collar workers do not fully comprehend what automation entails or how it could affect their employment, which may explain the absence of strong feelings or resistance. This limitation highlights the need to explore workforce awareness and education further on automation and the importance of clear communication during future automation rollouts.

d. Recommendations

i Determining Optimal Investment Timing

Currently, the Company does not have the workload to justify the investment. However, the company should determine when to invest in automation by assessing whether their workload meets the minimum thresholds identified through the financial model and IRR calculations. Therefore, the company must develop a tool or method to quantify their workload accurately in real-time, expressed in FDI. This will enable them to identify when the threshold FDI is reached, providing a clear signal to proceed with the investment in automation.

ii Workforce Involvement in Rollout

To ensure a successful transition to automation, the company must actively involve its workforce by conducting skill assessments to identify candidates for upskilling and developing tailored training programs for operator and maintenance roles. Early engagement through informational sessions, hands-on workshops, and partnerships with equipment suppliers for specialised training will build trust and competency. Mentorship opportunities, clear communication about role transitions, and incentives for participation can further ensure a positive attitude. These efforts will empower employees to view automation as a career growth opportunity, providing a smooth rollout and minimising disruption.

e. Opportunities for Future Research

1. Investigate automation for non-welding fabrication activities such as weld preparation, fitting and tacking.
2. Study automation's operational costs in operational contexts, including consumables, maintenance, and electricity.
3. Examine how workforce perceptions change after automation is implemented.
4. Assess automation's performance in field settings compared to workshops.
5. Expand research to include multiple companies and regions for comparative analysis.

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8. APPENDICES

a. Appendix A –Instrument 1: Management Questionnaire

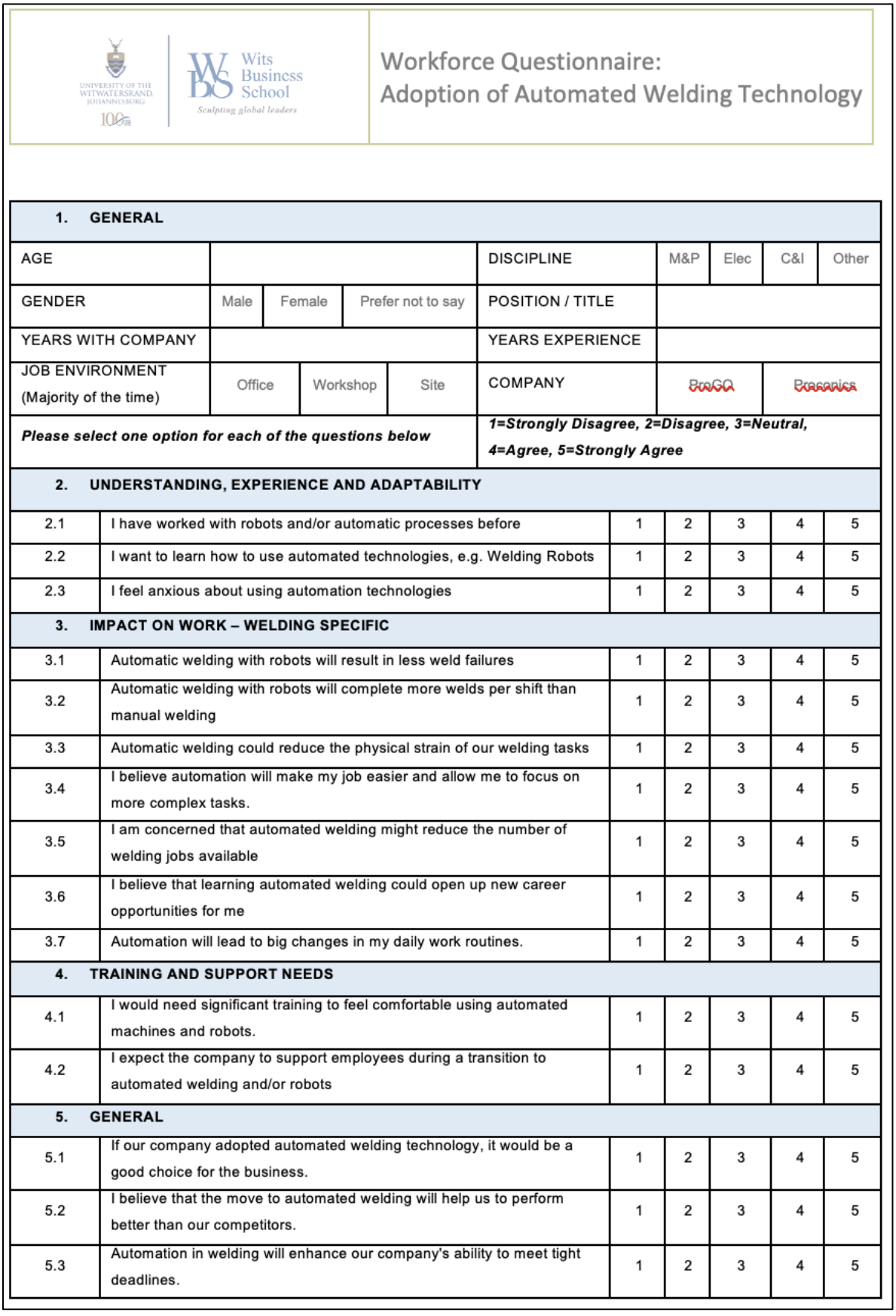


Management Interview Questionnaire:
Adoption of Automated Welding Technology

1. GENERAL			
NAME		DEPARTMENT	
JOB TITLE		CONTACT INFO:	
COMPANY		DATE & TIME	

2.	**CURRENT PRACTICES**	**Category**
2.1	Can you describe the current welding processes used in the company?	
2.2	How do you measure the efficiency and quality of current welding practices?	
3.	**PERCEPTION OF AUTOMATION**	
3.1	What is your general perspective on the adoption of automated welding technologies?	
3.2	Are there any concerns or reservations you have about moving towards automation?	
4.	**INVESTMENT READINESS**	
4.1	What factors would influence the decision to invest in automated welding technologies?	
4.2	How do you prioritize investment in new technologies within the company?	
5.	**EXPECTED BENEFITS**	
5.1	What are the critical financial metrics you would evaluate when considering an investment in automation?	
6.	**WORKFORCE IMPACT**	
6.1	How do you anticipate automated welding technology impacting the workforce in terms of roles, skills required, and job security?	
6.2	What are your plans for upskilling or retraining employees in light of automation?	
7.	**QUALITY CONTROL**	
7.1	How might automated welding improve the quality of work, and how important is this factor in your decision-making process?	
7.2	What quality control challenges do you currently face that automation could potentially solve?	
8.	**INDUSTRY STANDARDS AND COMPLIANCE**	
8.1	How does compliance with industry standards and safety regulations factor into your decision to adopt new welding technologies?	
8.2	Are there any regulatory incentives or barriers that impact your decision on automation?	
9.	**LONGER-TERM VISION**	
9.1	How does automation fit into the company's long-term strategic goals?	
10.	**DECISION-MAKING PROCESS**	
10.1	Can you describe the process by which new technologies are evaluated and decisions are made regarding their adoption?	
10.2	Who are the key stakeholders involved in the decision to invest in new technologies, and how are their opinions considered?	
11.	**RETURN ON INVESTMENT**	
11.1	What timeframe do you consider when expecting a return on investment from new technologies?	
11.2	Could you share any expectations or targets for return on investment for automation technologies?	
12.	**COMPETITIVE ADVANTAGE**	
12.1	How important is maintaining a competitive edge in the industry to your company's investment decisions?	

b. Appendix B – Instrument 2: Labour Force Questionnaire



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Workforce Questionnaire:
Adoption of Automated Welding Technology

1. GENERAL							
AGE			DISCIPLINE	M&P	Elec	C&I	Other
GENDER	Male	Female	Prefer not to say	POSITION / TITLE			
YEARS WITH COMPANY				YEARS EXPERIENCE			
JOB ENVIRONMENT (Majority of the time)	Office	Workshop	Site	COMPANY	~~BraGC~~	~~Braganica~~	
Please select one option for each of the questions below				***1=Strongly Disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly Agree***			

2. UNDERSTANDING, EXPERIENCE AND ADAPTABILITY						
2.1	I have worked with robots and/or automatic processes before	1	2	3	4	5
2.2	I want to learn how to use automated technologies, e.g. Welding Robots	1	2	3	4	5
2.3	I feel anxious about using automation technologies	1	2	3	4	5
3. IMPACT ON WORK – WELDING SPECIFIC						
3.1	Automatic welding with robots will result in less weld failures	1	2	3	4	5
3.2	Automatic welding with robots will complete more welds per shift than manual welding	1	2	3	4	5
3.3	Automatic welding could reduce the physical strain of our welding tasks	1	2	3	4	5
3.4	I believe automation will make my job easier and allow me to focus on more complex tasks.	1	2	3	4	5
3.5	I am concerned that automated welding might reduce the number of welding jobs available	1	2	3	4	5
3.6	I believe that learning automated welding could open up new career opportunities for me	1	2	3	4	5
3.7	Automation will lead to big changes in my daily work routines.	1	2	3	4	5
4. TRAINING AND SUPPORT NEEDS						
4.1	I would need significant training to feel comfortable using automated machines and robots.	1	2	3	4	5
4.2	I expect the company to support employees during a transition to automated welding and/or robots	1	2	3	4	5
5. GENERAL						
5.1	If our company adopted automated welding technology, it would be a good choice for the business.	1	2	3	4	5
5.2	I believe that the move to automated welding will help us to perform better than our competitors.	1	2	3	4	5
5.3	Automation in welding will enhance our company's ability to meet tight deadlines.	1	2	3	4	5

c. Appendix C – Instrument 3: Abicor Binzel Interview Questionnaire



Abicor Binzel Interview Questionnaire: SWR

1. GENERAL			
NAME		DATE & TIME	
JOB TITLE		CONTACT INFO:	
2. WELDING PERFORMANCE			
2.1	What is the welding speed of the machine for different pipe sizes and schedules? Can you provide examples or typical metrics?		
2.2	How does the machine handle imperfect weld preparations, such as inconsistent gaps, bevels, or tacks?		
2.3	What is the maximum thickness the machine can handle in a single pass for pipes?		
2.4	Are there specific materials or grades that the machine performs better or worse with?		
3. QUALITY METRICS			
3.1	What is the typical defect or repair rate when using the equipment compared to manual welding?		
3.2	What types of defects are most commonly observed with this equipment, and how are they typically mitigated?		
3.3	Does the equipment include built-in quality monitoring systems, such as real-time defect detection?		
4. AUTOMATION AND FLEXIBILITY			
4.1	Is the machine capable of handling varied pipe diameters or geometries without extensive setup time?		
4.2	How adaptable is the equipment for other welding applications, such as structural or vessel welding?		
5. LIMITATIONS			
5.1	What are the key limitations of the machine in terms of environment, material compatibility, or performance?		
5.2	Are there specific operational conditions (e.g., outdoor use, extreme temperatures) that impact the machine's performance?		
6. CAPITAL EXPENDITURE			
6.1	What is the total cost of the equipment, including delivery, installation, and commissioning?		
6.2	Are there optional modules or upgrades, and what are their associated costs?		
7. OPERATING COSTS			
7.1	What are the typical running costs of the machine (e.g., power consumption, consumables, maintenance)?		
7.2	What is the estimated cost of consumables per meter of weld produced?		
8. RETURN ON INVESTMENT			
8.1	Can you provide any case studies or data on the typical payback period or IRR for this equipment?		
8.2	Do you offer assistance with business case development or ROI calculations?		
9. MAINTENANCE AND SUPPORT			
9.1	What is the expected maintenance schedule and cost of upkeep for the machine?		
9.2	Do you offer warranties or service agreements? If so, what do they include?		
9.3	What is the average downtime associated with maintenance or repairs?		
10. TRAINING AND SKILL REQUIREMENTS			
10.1	What level of skill or training is required for operators to use the equipment effectively?		
10.2	Do you offer training programs, and are they included in the purchase price?		
11. DELIVERY AND SETUP			
11.1	What is the expected lead time for delivery of the equipment?		
11.2	How long does installation and commissioning typically take?		
12. SCALABILITY AND UPGRADES			
12.1	Is the equipment scalable for future automation needs, or are there modular upgrades available?		
12.2	Can this system integrate with other automated systems, such as robotic material handling?		
13. ENVIRONMENTAL AND SAFETY CONSIDERATIONS			
13.1	Are there specific safety measures or protocols that must be followed when using this machine?		
14. GENERAL			
14.1	Based on your experience, what industries or applications have benefitted most from this equipment?		