DESIGNING A CONTINUOUS QUALITY IMPROVEMENT FRAMEWORK FOR IMPROVING ELECTROWINNING CURRENT EFFICIENCY

By

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Supervised by Dr. Michael Sony

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Declaration

I, Thomas Ehongo Moongo hereby declare that the work contained in the thesis, entitled designing a continuous quality improvement framework for improving electrowinning current efficiency is my own original work and that I have not previously in its entirety or in part submitted it at any university or other higher education institution for the award of a degree.

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I believe if one is to see farther, it is by standing on the shoulders of giants. The research report read today is a blossom of contributions and influence from various people and institutions. Without diminishing the contribution of many others, I would like to give my deepest gratitude to the following stakeholders:

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Above all, I give glory to God who, by Christ Jesus, makes all things work together for good.

***"I have fought a good fight, I have finished the race, I have kept the faith"* - 2 Timothy 4:7.**

"*When everything seems to be going against you, remember that the airplane takes off against the wind, not with it*" – Henry Ford

Abstract

Continuous quality improvement by applying statistical process control has been long recognized in the processing industry. Effectively monitoring and controlling of process variability can result in sustained process stability and maximized process efficiencies. The electrowinning process is an energy-intensive process, and the cost of electrical energy is ever increasing. The effectiveness of utilizing electrical energy in the electrowinning process is best measured by current efficiency. Although substantial research has been done to improve current efficiency, no evidence on improving current efficiency from a quality perspective or by applying statistical process control has been found in the reviewed literature. This identified knowledge/research gap needs to be filled.

This research project intends to contribute to the existing knowledge by filling the identified knowledge/research gap. The research aims to design a continuous quality improvement framework for improving electrowinning current efficiency. The objectives of the research are as follow: (i) to explore factors that influence current efficiency, (ii) to evaluate the factor that has the most significant effect on current efficiency, by applying statistical process control, and (iii) to develop a continuous quality improvement framework for improving current efficiency, by applying statistical process control.

A sequential mixed research methodology was applied in this research. In this case, a qualitative research approach was followed by a quantitative research approach. Questionnaires were utilized to establish factors influencing current efficiency and best practices for improving current efficiency. The quantitative research approach was accomplished by collecting and analyzing electrolyte samples and instrument data. This is in addition to gathering historical data from an instrument database and analytical laboratory database. The established research strategy includes exploring current efficiency factors, analyzing historical data, establishing current efficiency improvement best practice and finally designing a continuous quality improvement framework for improving electrowinning current efficiency.

The explored current efficiency factors were summarized into the following main subgroups: temperature, contacts and conductivity, reagent addition, electrodes (cathodes and anodes), electrolyte quality, rectifier current, and cathode weight. These main subgroups were further expanded by using a mind map. From the analysis of Shewhart control charts, it was concluded that metallurgical short-circuits (hotspots) had the most significant effect on current efficiency than all other factors. The same conclusion was also deduced from the qualitative research approach by using a Pareto chart.

Essentially, an out of control action plan for bringing metallurgical short-circuits (hotspots) under statistical control was developed and implemented. As a result, current efficiency improved from a minimum of 89.64 % to a maximum of 95.04 % (which translates to 5.40 % improvement). This converts to the production of approximately 74 metric tons of 99.999 % pure grade A copper cathode production over a period of 1.5 months. This research has contributed significantly to the bottom-line (profit) of the mine by improving current efficiency from a quality perspective, by applying statistical process control.

Consequently, and based on the achieved improvement methodology, a continuous quality improvement framework for improving electrowinning current efficiency was designed. This was done by considering current efficiency factors, normality test, transforming non-normal data, classifying data type, selecting suitable control charts, Pearson correlation analysis, out of control point alignment analysis, process capability analysis, root cause analysis, developing an out of control action plan, providing training and establishing a safe working procedure. By applying this framework, current efficiency can be improved from a quality perspective. In conclusion, the identified knowledge and/or research gap has been successfully filled by this research and all the objectives of the research were achieved.

Keywords

Quality, continuous improvement, continuous quality improvement, and current efficiency

Acronyms

AAS	Atomic absorption spectrometer
AE	Aqueous entrainment
CE	Current efficiency
CCF	Circulating electrolyte sample
CCE	Cathode current efficiency
CD	Current density
CUSUM	Cumulative sum
COP	Cost of production
DOE	Design of experiments
DSA	Dimensionally stable anodes
EC	Energy consumption
EW	Electrowinning
EWMA	Exponentially weighted moving average
HDC	High degrees committee
ISO	International organization for standardization
IR	Infrared
KPI	Key performance indicator
LIMS	Laboratory information management system
LCL	Lower control limit
LME	London metal exchange
L-SX-EW	Leaching - solvent extraction - electrowinning
MMF	Multi-media filters
OCAP	Out of control action plan
OOC	Out of control
OE	Organic entrainment
RCA	Root cause analysis
SEX	Spent electrolyte sample
SOP	Safe operating procedure
SX	Solvent extraction
SCADA	Supervisory control and data acquisition

SPC	Statistical process control
TQM	Total quality management
TSS	Total suspended solids
PCF	Advance electrolyte sample
PDT	Phase disengagement time
PPM	Parts per million
UCL	Upper control limit
WCL	Within control limit

Nomenclature

$\bar{x}$	Population estimator for mean/average
μ	Mean/average
I	Sample size
N	Number of samples
S	Sample standard deviation
H_0	Null hypothesis
H_1	Alternative hypothesis
T	Temperature
S	Distance between electrodes
J	Current density
A	Cathode surface area
Cu	Copper
Fe	Iron
H_2SO_4	Sulphuric acid
Co	Cobalt
Cl	Chlorine
Eh	Solution redox potential
Eh^o	Standard equilibrium potential
R	Gas constant
N	Charge number
F	Faraday’s constant
$[Fe^{3+}]$	Ferric concentration
$[Fe^{2+}]$	Ferrous concentration

Dedication

I dedicate this research project to God almighty, my departed father, my mother, my family and everyone who see potential in me. I dedicate it to them because they supported me during the time I was working on this project.

Table of Contents

List of tables

List of Figures

1. Introduction

1.1 Background

Quality control via statistical methods is central to success in the modern industry. The significance of Statistical Process Control (SPC) techniques in continuous quality improvement by reducing process variability and improving process stability has been long recognized in the industry. Although the Japanese have been successful in applying statistical methods to industrial quality control for many years and it has given them a significant advantage over many of their competitors, many organizations in the world are still not yet applying this powerful statistical quality control tool (Ben & Jiju, 2000; Helm, 2018). The increasing demands for achieving improvements in productivity, reduction of operating cost, business excellence and product quality has led to a heightened interest in the application of Total Quality Management (TQM) tools such as Statistical Process Control (SPC) (Mahanti & Evans, 2012).

The global nature of the modern industrial competition has forced quality control or statistical quality control to be a very crucial aspect of any engineer. It is enormously difficult, if not impossible to either maintain and/or achieve a competitive position in any industry without applying statistical quality control. With the increasing complexity of modern industrial chemical processes, it is essential to be able to monitor process variability and conformance to the specification standards to detect abnormal events quickly so that serious consequences can be prevented (Sanchez-Fernandez, Baldan, Sainz-Palmero, Benitez, & Fuente, 2018; Helm, 2018).

Statistical Process Control (SPC) was developed to effortlessly collect and analyze process data, permitting performance monitoring to achieve sustainable quality improvements which consequently result in increased profitability. This quality tool enables the process to be monitored, special causes of variation to be identified, and then coming up with an appropriate Out-of-Control Action Plan (OCAP) which ensures that the process remains under statistical control (Godina, Pimentel, Silver, & Joao, 2018).

Statistical process control makes use of statistics for controlling the process. It analyses historical data of a variable to identify process variations and deviations when the process statistically drifts from its usual variations (Mahammad, 2018). When applying SPC, control charts are used for providing visual signals when the process variable is out of control (Mahanti & Evans, 2012).

In electrowinning circuits, current efficiency also called faradaic efficiency or faradaic yield and coulombic efficiency can be simply defined as the ratio of the actual mass of the electrodeposited metal to the theoretical mass electrodeposited (based on Faraday's equation) from an electrolyte due to the passage of direct current through an electrolysis process (Hongdan, Wentang, Wenqiang, & Bingzhi, 2016).

There are a lot of process variables that have a direct and indirect effect on current efficiency, for example, electrolyte temperature, electrolyte acid concentration, concentration of additives such as cobalt sulfate and the cathode smoothing agent, concentration of impurities such as manganese, iron and lead, formation of metallurgical short-circuits (hotspots), electrode alignment (rat patrol), current density, electrode cleaning schedule and many other electrowinning process variables.

Some of these process variables may be considered as factors influencing current efficiency significantly than others. Statistical process control was used to monitor and control these process variables so that the process can remain in statistical control, to reduce process variability and maintain them within an acceptable/design standard limitation. Hence improving current efficiency from a quality perspective.

Unlike many other researchers, in this research current efficiency was improved by reducing process variability for the current efficiency factors. No literature was identified that addressed current efficiency improvement from a quality perspective. Noting that quality simply refers to conformance to specifications and reduced process variations (Joseph & Blanton, 1999).

In this case, current efficiency was improved by making sure current efficiency factors are conforming to their respective specification targets and the variation in the process was reduced. Thereafter, current efficiency was improved from a quality perspective by designing a continuous quality improvement framework for improving the current efficiency. This approach has other benefits such as cost-effective production of high-quality cathodes and reducing process variability in addition to improving current efficiency.

1.2 Problem statement

The traditional industrial electrowinning (EW) process is an electrical power-intensive process and the cost of electrical power is ever-increasing (Parada & Asselin, 2009). Over the years, there has been an increase in the unit cost of electrical power (Nampower, 2019; Eskom, 2019). Nampower has increased the power charge per unit from 121 c/kWh to 124 c/kWh for mines and the maximum demand from N$262/kW per month to N$267/kW per month for 2017/18 and 2018/19 respectively (Nampower, 2019).

In addition to that, Eskom’s system controllers have been struggling to supply the national grid with sufficient electrical energy to meet the demand. Hence, a load shedding decision was implemented (Eskom, 2019). However, the effectiveness of utilizing electrical energy and/or direct current in the electrowinning process is best measured by current efficiency (Hongdan, Wentang, Wenqiang, & Bingzhi, 2016). The electrowinning process efficiency should be emphasized because of the substantial energy savings that can potentially be achieved since it consumes from 60 - 80 % of the total energy of a typical mine (Gonzalez-Dominguez & Dreisinger, 1997). Therefore, there is a need to improve current efficiency.

Preliminary research conducted by the researcher has shown that there is no research identified yet that focused on improving current efficiency from a quality perspective and no researcher was identified who has improved current efficiency by enhancing or improving current efficiency factors by applying statistical process control.

Therefore, this research is aimed at filling this identified research/knowledge gap. The identified knowledge/research gap was addressed by designing a continuous quality improvement framework for improving current efficiency. The framework is an application of SPC to improve current efficiency from a quality perspective. The quality tool was applied to reduce the variability of current efficiency factors and hence improving current efficiency indirectly.

1.3 Research aim, objectives and questions

1.3.1 Research aim

Given the research/knowledge voids and gaps identified, this research aims to design a continuous quality improvement framework for improving electrowinning current efficiency.

1.3.2 Research objectives

1. To explore factors that influence current efficiency.

2. To evaluate the factor that has the most significant effect on current efficiency, by applying statistical process control.

3. To design a continuous quality improvement framework for improving current efficiency, by applying statistical process control.

1.3.3 Research questions

1. Which factors influence current efficiency?

2. Which factor has the most significant effect on current efficiency based on statistical process control?

3. What should be considered when designing a continuous quality improvement framework for improving current efficiency by applying statistical process control?

1.4 Research scope

1.4.1 Limitations

The most likely limitation of this research is the fact that the application of the Total Quality Management (TQM) tool, namely Statistical Process Control (SPC) on current efficiency factors will be done in a large scale electrowinning process at a copper refinery in Namibia which might not be at steady state. Only the normality assumption of control charts was fully addressed by transforming data so that it follows a normal distribution. This is the most important assumption unlike the homogeneity of variances and homogeneity of means. The last two assumptions were not addressed because it will interfere with the analysis of the control chart results. In addition to that, the conditions given by the mine management on the research will also limit the level of information disclosed. The conditions to research are given under ethical considerations below.

1.4.2 Delimitations

This research was conducted at a copper mine in Namibia since most and possibly all data needed was collected onsite. The research findings are not only applied to the copper electrowinning process. The findings apply to the electrowinning process of other metals also such as zinc, nickel, cobalt, and others. It should, however, be noted that the principle of electrowinning and current efficiency is the same for all the metals, but there may be a few design differences in the process design criteria. However, this report can still be used as a general guideline for improving current efficiency from a quality perspective.

1.5 Ethical consideration

Before executing this research project approval was given by the copper mine management in writing. The company was fully aware that the research is for academic purposes. In addition to that, no publication in any journal will be made without the mine management’s prior approval in writing. Furthermore, after the completion of this research, a copy of the report was provided to the mine.

An authorization to research and to publish the research findings was given, in writing, on the 11th of July 2019 by the processing manager. The three conditions attached to the research are as follows: The name of the mine should not be explicitly stated as the source of the material; no commercial information should be disclosed, even indirectly and the paper should not contain harmful information and/or information that may be commercially sensitive. These conditions have been met by this research and the research findings may even be published.

1.6 Significance/contribution of the research

The study aims to contribute to existing knowledge by designing a continuous quality improvement framework for improving electrowinning current efficiency by applying statistical process control. This study is significant because it is shifting researchers' mind-set towards considering improving current efficiency from a quality perspective by applying a Total Quality Management (TQM) tool, namely Statistical Process Control (SPC) on the current efficiency factors.

From the literature review done, it was concluded that substantial research has been done to improve electrowinning current efficiency. However, there was no evidence of research on improving current efficiency from a quality viewpoint and by applying Statistical Process Control (SPC) to be specific. This is the research gap that was identified, and this research intends to fill this knowledge gap. The application of Statistical Process Control (SPC) towards improved current efficiency will benefit all industrial electrowinning processes not only by improving current efficiency but also by minimizing the cost of production, improving product quality and maximizing productivity.

1.7 Research project schedule

The Gantt presented in Figure 1.1 depicts the schedule of this entire research project. The main tasks include drafting the research project proposal and reviewing it after every submission. It was submitted to the supervisor, submitted to the department, submitted to the faculty High Degrees Committee (HDC), submitted to the institutional HDC for approval and finally started working on the research project itself. All the chapters of the research project were submitted to the supervisor, reviewed and then the supervisor's recommendations were included in the final research project.

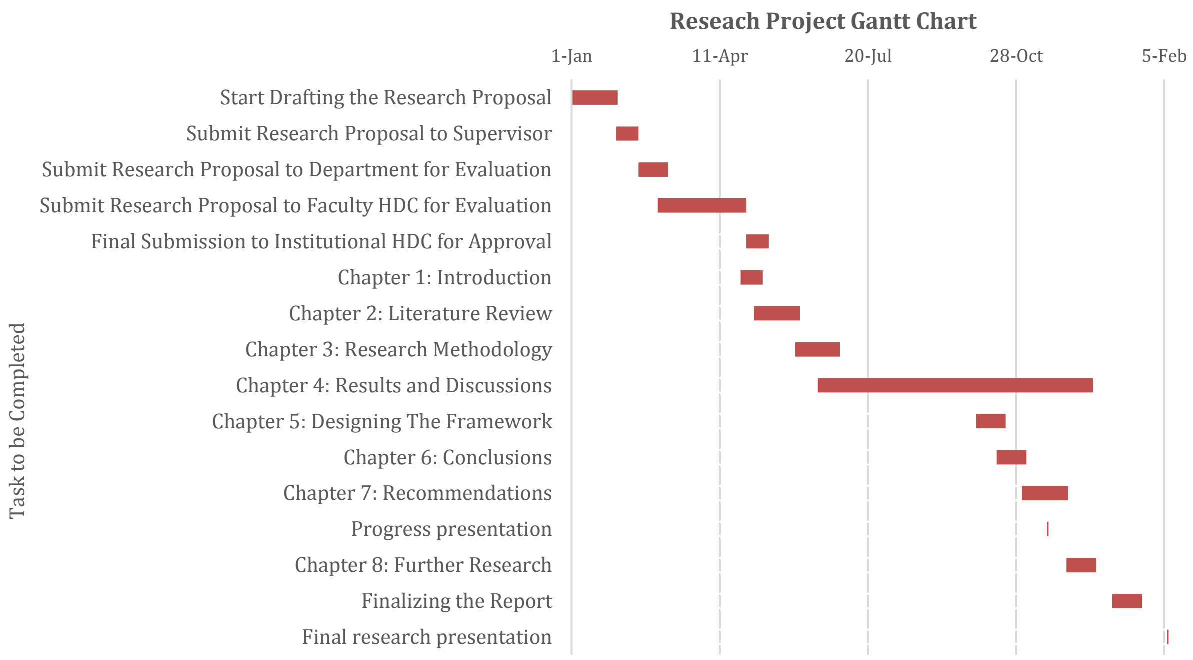


Figure 1.1: Research project Gantt chart (developed by the author)

1.8 Thesis structure

This thesis is comprised of six chapters and it highlights the focus of this research, its methodological approach, and its significance. The research thesis is structured as follow:

Chapter 1: Introduction

Chapter 2: Literature review

Chapter 3: Research methodology

Chapter 4: Results and discussions

Chapter 5: Designing the framework

Chapter 6: Conclusion, recommendations and further research

The thesis structure has been summarized in Figure 1.2 depicted below.

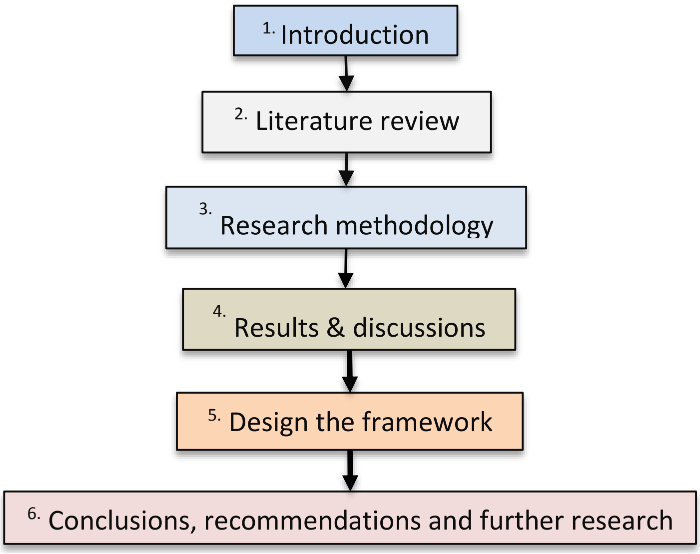


Figure 1.2: The structure of the thesis (designed by the author)

1.9 Summary

Improving current efficiency has attracted significant attention from researchers, practitioners, and academics from all over the world. Although considerable attention has been put in improving current efficiency, no evidence of improving current efficiency from a quality perspective was found in the literature. This is the research gap that was identified and this research intends to fill it by designing a continuous quality improvement framework for improving electrowinning current efficiency. A detailed review of the literature of this research will be presented in chapter 2.

2. Literature review

2.1 Introduction

The main objective of this chapter is to gain an understanding of how quality and current efficiency relate to each other. Thereafter, it is essential to get an insight into different types of process variability and the out-of-control action plan. Different types of control charts, rules for Shewhart control charts and the statistical basis of control charts were also discussed. The literature review then focused on the electrowinning process and current efficiency to be specific. It highlighted the identified research/knowledge gap that the research project intends to fill. The next section of the literature is focused on explaining how quality and current efficiency concepts are related. This was done by understanding the quality perspective of current efficiency. It was noted that not all definitions of quality can be directly applied to current efficiency. Which makes it hard to interconnect the two concepts.

2.2 Relating quality and current efficiency

It is crucial to understand how quality and current efficiency are interrelated. This is because this research intends to improve current efficiency from a quality viewpoint. The objective of the below sub-sections is to clarify how the two theoretical concepts are related. Without a thorough understanding of quality, it will be difficult to relate it to current efficiency. The relationship between quality and current efficiency was justified by focusing on understanding quality, relating the definitions of quality to current efficiency and finally explaining the quality perspective of current efficiency.

2.2.1 Understanding quality

For more than thirty years, defining quality has remained undoubtedly difficult and there is no universally agreed definition of quality because different definitions are appropriate under specific circumstances. Some authors asserted that quality cannot be defined nor quantified while others assert that quality is subjective, and it depends on the individual perspective. In addition to these and from the comprehensive literature review done, it was learned that there are a lot of narrow definitions of quality such as fitness for use, conformance to standards/specifications, excellence, reduced variability, etc. These definitions may be suitable under certain circumstances. However, they are not sufficiently comprehensive to give a good appreciation of the richness and complexity of the concept (Bobby, 2014; Ewell, 2010; Harvey, 2005; Harvey & Williams, 2010; Opre & Opre, 2006; Singh, 2010; Chandrupatla, 2018; Chandrupatla, 2018; Garvin, 1984; Reeves & Bednar, 1995).

After reviewing the literature, three challenges of defining quality were noted. The first challenge of defining quality is the fact that it depends on a wide variety of interpretations/viewpoints of the stakeholders. Four different stakeholders should be considered when defining quality, they are service or product providers, users of the product, users of the output and employees (Montgomery, 2009; Amitava, 2016). The second challenge is the fact that quality is a multidimensional concept (Green, 1994; Vlasceanu, Grunberg, & Parlea, 2007; Westerheijden, Stensaker, & Rosa, 2007; Schindler, Puls-Elvidge, Welzant, & Crawford, 2015; Montgomery, 2009; Amitava, 2016). The third challenge has something to do with the dynamic nature of quality, this is because quality is not static, but it is forever changing (Bobby, 2014; Ewell, 2010; Harvey, 2005; Harvey & Williams, 2010; Opre & Opre, 2006; Singh, 2010).

All these factors need to be considered when defining quality and thus reducing the definition of quality in a one-sentence definition is problematic. According to literature, most of the time a one-sentence definition of quality is one dimensional, it lacks meaning or specificity and sometimes it is too general to be operationalized. Some definitions are driven by pre-defined standards which are intended for excellence and exclusivity (Eagle & Brennan, 2007; Garvin, 1987). Therefore, it is a challenge to simply describe the quality perspective of current efficiency using a single sentence without first understanding the concept of quality in detail.

Garvin (1984) has managed to categorize the definition of quality into five categories, they are: user-based, product-based, manufacturing-based, value-based and transcendent. In addition to this, he also came up with eight dimensions/attributes from which quality can be described and evaluated, namely performance, reliability, durability, serviceability, aesthetics, features, perceived quality, and conformance to standards (Montgomery, 2009; Amitava, 2016; Ibrahim, 2012). Amongst these dimensions, performance and conformance to standards link current efficiency and quality.

2.2.2 Traditional definition of quality and current efficiency

According to literature, the traditional definition of quality is fitness for use and its basis is that the products and services must meet the requirements of the customers (Juran, 1974). There are two aspects of fitness for use, they are quality of design and quality of conformance (Montgomery, 2009; Pavol, 2015; Chandrupatla, 2018; Ibrahim, 2012; Graeme, 2011). Similarly, other researchers defined quality as features of products that provide satisfaction to customers by meeting their needs and/or expectations (Montgomery, 2009).

However, other researchers pointed out that this definition is one-dimensional because it is only considering that the success of the organization only depends on its ability to fulfill customer requirements or expectations, but customers are not the only stakeholders of the organization. The term quality should be defined by considering other stakeholders also. This was resolved by the International Organization for Standardization (ISO 9000:2005) that considered defining quality from a perspective of all interested parties instead of customers only (Ibrahim, 2012; Barrows & Powers, 2009; Hoyle, 2007; ISO9000, 2005:17).

According to literature, most designers and engineers lack formal education on quality engineering methodology (Juran & Godfrey, 1998). Therefore, recently the traditional definition is no more related to the quality of the design aspect, but to the conformance to specifications aspect. As a result, there is more focus of quality on the "*conformance-to-specifications*" as defined by Crosby (1979) and less focus on the customer viewpoint even if the product/service was "*fit-for-use*" or not by the customers. In addition to this, it is believed that quality improvement problems are solely addressed during manufacturing or production (Montgomery, 2009; Graeme, 2011). According to other authors, the generally accepted definition by many quality departments is "*conformance-to-specifications*" especially for the manufacturing or production industry (Juran & Godfrey, 1998; Amitava, 2016; Chandrupatla, 2018; Ibrahim, 2012; Graeme, 2011; Wild & Seber, 2017; Crosby, 1979).

Based on the above, the definition of quality shifts more towards the conformance to specifications and less on fitness for use and customer satisfaction. It is easier to relate quality and current efficiency by considering conformance to specifications than on fitness to use and customer satisfaction. This is because current efficiency can be improved by enhancing its factors and by making sure they are conforming to their specification standards. This definition presumes that there are specifications and requirements which are assigned and then the conformance to these specifications or requirements is then evaluated. If there is conformance then quality is deemed to be high. Specification ranges will be assigned to all the current efficiency factors and then their conformance to the assigned specification ranges will be evaluated, monitored and controlled. The framework for improving current efficiency was designed. Hence improving current efficiency from a quality perspective.

2.2.3 Modern definition of quality and current efficiency

On the other hand, the modern definition of quality is based on the fact that quality is inversely proportional to product variability. This means the less variability there is, the higher the quality of the product. The Japanese understood that reducing process variability will directly translate into lower cost of production (COP), reduced number of rework, reduced waste of time and reduced waste of resources (Montgomery, 2009). A product that is suitable for customer usage should be produced by a stable process, with an acceptable variability of stated quality indexes in terms of the specified target ranges. These processes can be improved on the basis that the variability of quality index values originated either from common or special causes (Pavol, 2015).

This definition brings in the variability component, which is a crucial feature of the product. Since in this case, current efficiency is not a product, process variability or copper cathode variability can be used instead of product variability. The current efficiency affects the quality of the copper cathodes produced. The cathode quality for example in terms of the chemical composition should not vary a lot. Current efficiency is an important key performance indicator (KPI) for the electrowinning process and any variations of current efficiency factors within the electrowinning process will affect current efficiency either by increasing and decreasing it. This is exactly how this research intends to improve current efficiency by focusing on the process variability of the current efficiency factors. Hence improving current efficiency from the quality perspective.

2.2.4 Quality perspective of current efficiency

The quality perspective of current efficiency can only be understood by having an insight into the electrowinning process and to understand current efficiency in detail one must first know the current efficiency factors. Amongst the definitions of quality from the reviewed literature, none of them can sorely describe the quality perspective of current efficiency. However, a combination of these definitions can describe it much better. The quality perspective of current efficiency can be described by considering the electrowinning process and quality as defined by Crosby (1979) that quality refers to "*conformance-to-specifications*", "*reduction in process variability*" as defined by Montgomery (2009) and "*fitness for use*" as proposed by Juran (1974).

For current efficiency, conformance to specifications can be interpreted in terms of how the current efficiency factors meet their specification standards. If the factors that have the biggest influence on current efficiency are not well monitored and controlled it is most likely that current efficiency will decrease. Therefore, they need to conform to the specification standards as set by the designers. When evaluating current efficiency factors using statistical process control (SPC), control charts are applied. On the process control chart, every current efficiency factor will have an upper control limit (UCL) and lower control limit (LCL) assigned to it. The current efficiency factors must be controlled within these control limits. If done well, the current efficiency is expected to improve. These explain the quality perspective of current efficiency.

In addition to this, the electroplated metal should also conform to the specification standards of the next process in terms of the chemical composition. The copper cathodes which are produced will be processed to manufacture copper wires and other products. But the copper cathodes must first meet the specification standard of these processes either in terms of the chemical composition and/or physical features. This means the produced cathodes should be fit for use in the manufacturing process, to manufacture a specific product that will, in turn, satisfy customer requirements. Current efficiency has a direct effect on the purity of the electroplated metal. If the electroplated metal is not of the required specification, it will not conform to the specifications of the manufacturing process.

The reduction of process variability is very important to the electrowinning process and current efficiency. The current efficiency factors play an important role and they should not be varied significantly to have consistency in current efficiency. The first step is to have all the current efficiency factors within their design specification ranges and then to ensure they remain there by monitoring them to minimize variability in current efficiency.

Quality was also defined as freedom from deficiencies or defect-free (Juran & Godfrey, 1998). This traditional definition is taken from the viewpoint of meeting customer requirements or expectations, but current efficiency is not necessarily focusing on customers directly. But it is focusing on the production of high-quality cathodes by utilizing direct current during electroplating. Either way, current efficiency will ensure that the customers will get a high-quality product (a very pure cathode electroplated) when the cathodic current efficiency is high unlike when current efficiency is low. This is another link between quality and current efficiency.

Current efficiency by itself is a measure of the effectiveness of the utilization of electrical current during electroplating. Therefore, it is an indication of the performance of the electrolysis process. On the other hand, conformance to specification standards best fit this research because the current efficiency factors should be improved to meet/conform to their specifications for current efficiency to be enhanced. Moreover, to improve current efficiency from a quality perspective by applying statistical process control it means current efficiency must be within the upper control limit (UCL) and the lower control limit (LCL). These are specification ranges within which it should be maintained and it makes sense to link quality and current efficiency by considering the specification limits.

It can also be argued that customer requirements or expectations may be met if current efficiency is high because the cathodes produced at high current efficiency will be of high quality. However, this explanation will bring in subjectivity because every customer has their requirements or expectations depending on what they will use the cathodes for. In this case organizations such as the London Metal Exchange (LME) have put up a standard of the chemical specifications of the copper cathodes (LME, 2020). London Metal Exchange (2020) claims that "*Grade A copper must conform to the chemical composition of one of the following standards: BS EN 1978: 1998 – Cu – CATH -1; GB/T 467 – 2010 – Cu – CATH – 1 and ASTM B115 – 10 – cathode Grade 1*".

The specified Grade A copper cathode chemical composition is shown in Figure 2.1 below. This is according to the special contract rules for copper Grade A content for LME. The quality specification stipulated below is based on "*Quality: GB/T 467-2010 Copper Cathode (High-Purity Copper Cathode (Cu-CATH-1)*". If the copper cathodes are produced at the lowest current efficiency, the presence of impurities can result in producing cathodes of a grade lower than grade A. This is because the chemical composition specification will not be complied with. As a result, the copper cathodes will be sold at a low price because they are regarded to be of low quality.

Element Group	**Impurity Element**	**Content, not more than**	**Total content of element group, not more than**	
1	Se	0.00020	0.00030	0.00030
	Te	0.00020		
	Bi	0.0020		
2	Cr	-	0.0015	
	Mn	-		
	Sb	0.0004		
	Cd	-		
	As	0.0005		
	P	-		
3	Pb	0.0005	0.0005	
4	S	0.0015	0.0015	
5	Sn	-	0.0020	
	Ni	-		
	Fe	0.0010		
	Si	-		
	Zn	-		
	Co	-		
6	Ag	0.0025	0.0025	
Where the total content of the impurity elements listed		**0.0065**		

Figure 2.1: Grade A quality copper cathode chemical composition specification (adopted from LME, 2020)

2.3 Statistical methods for quality control and improvement

2.3.1 Using statistical quality control methods

To improve current efficiency from the quality perspective, the variability of the current efficiency factors needs to be minimized. However, from literature, researchers suggest that process variability can only be described in statistical terms and statistical methods should be applied during quality improvement efforts. In this case, the data on quality characteristics are classified either as an attribute or variable data. The quality characteristics are then evaluated concerning the specification standards (Montgomery, 2009).

2.3.2 Statistical process control

The objective of Statistical Process Control (SPC) is to ensure that the production process is as stable (in control) as possible and the process variability has been reduced so that conformance to specification standards can guarantee product quality (Helm, 2018). According to literature, Total Quality Management (TQM) tools such as Statistical Process Control (SPC) is considered a powerful technique for managing, monitoring, analyzing and improving the performance of a process by using statistical methods (Mahanti & Evans, 2012).

Improving current efficiency from the quality perspective by using statistical methods implies that the electrowinning process must become stable. The process should be continuously monitored, controlled and improved as an action plan for reducing process variability (Montgomery, 2009). In the production industry, problems related to quality control are solved using the statistical process control toolbox. Amongst the statistical process control tools, only control charts will be applied in this research project because control charts are a very powerful tool in the field of statistical process control. The statistical process control toolbox contains tools such as (Helm, 2018):

- Control charts
- Cause-and-effect diagrams
- Pareto chart
- Histogram
- Defect-concentration diagrams
- Scatter diagrams
- Check sheets
- Experimental design methods

2.4 Causes of process variability

Variability is part of any process, no matter how sophisticated, so management and employees must understand it. Not all factors that influence process variability can be controlled, for example, environmental factors. However, factors such as people, materials, policies, equipment, and methods can be controlled (Amitava, 2016).

There are two types of process variations namely, a controlled process variation and an uncontrolled process variation. It is possible to predict the controlled variation because it occurs through probabilistic sense and there is a consistent pattern of the common cause or background noise. An uncontrolled variation, on the other hand, is unpredictable and there is no consistency because it is due to a special cause (SCME, 2017).

Statistical process control is mainly used for detecting the variability in the process as soon as possible so that an investigation of the root cause can be done and then an Out-of-Control Action Plan (OCAP) can be developed and implemented immediately (Montgomery, 2009; SCME, 2017). There are two main causes of variability in the process, namely random causes and special causes. Special causes should be eliminated so that control of a process can be achieved. On the other hand, to attain process improvement the common causes should be reduced (Amitava, 2016; Montgomery, 2009; Helm, 2018).

2.4.1 Special causes of process variability

Special or assignable causes of variability are not permanently part of the process and they do not have an influence on all components of the process, but they are a result of specific circumstances affecting the process temporarily (Pavol, 2015; Montgomery, 2009). Therefore, special causes are inherently not part of the process. A special cause is assumed whenever a quality characteristic point plot outside the control limit or a non-random pattern is displayed and the process is deemed to be out of control. It should also be noted that a special cause can also result in the quality control trend being above or below the centreline consistently. After identifying a special cause an Out-of-Control Action Plan (OCAP) should be developed and implemented so that the process stability can be restored (Amitava, 2016; Helm, 2018). A typical Out-of-Control Action Plan (OCAP) process is shown in Figure 2.2 below.

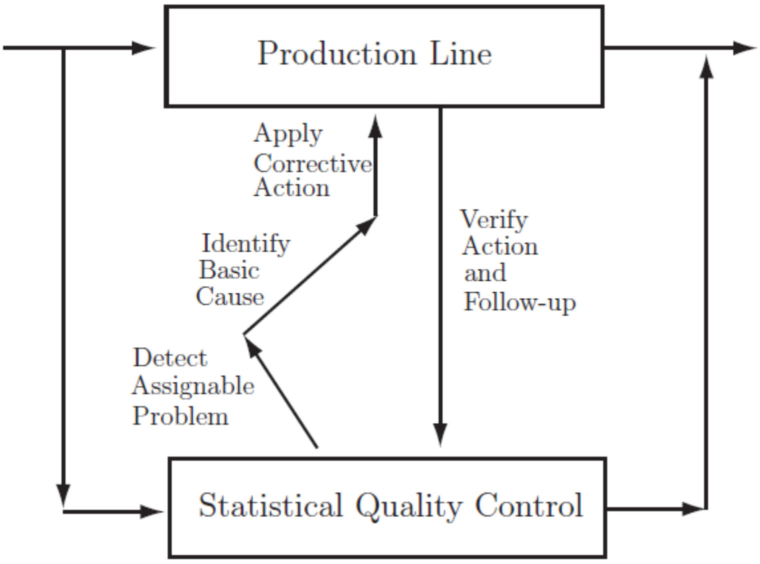


Figure 2.2: Correcting variation due to assignable causes (adopted from Helm, 2018)

2.4.2 Common causes of process variability

Common causes (also called random or chance causes) of variability are permanently part of the process and they influence all the components of the process. A common cause will always be present in the process if it is not changed. Chance causes are of low significance and they are technologically or economically impossible to eliminate even if they can be identified. Therefore, the process variability due to common causes is referred to as the natural variation in the process. The natural variation is an accumulation of small causes that are inherent within the process and they cannot be eliminated, that is why they are often referred to as background noise (Montgomery, 2009; Helm, 2018; SCME, 2017).

If the variation incurred is random, a stable system of common causes has been attained and the process is said to be in statistical control. This means if the process only has common causes of variability, it is said to be in "in control" or "in statistical control". Common causes are assumed to exist if the quality characteristic values are within the control limits and no non-random pattern is exhibited (Amitava, 2016; Helm, 2018).

Figure 2.3 shows that as the number of assignable causes increases, the process quality characteristic is negatively affected and the process is deemed to be out of control. The diagram also shows that the assignable cause has the biggest effect on the process. This is because a special cause is not permanently part of the process, meaning it causes instability in the process hence increasing variability. On the other hand, chance causes leave the process under statistical control. The main reason for this effect is because common causes are permanently part of the process, which means there will be consistency in the error and there will be low variability in the process since the variability is consistent.

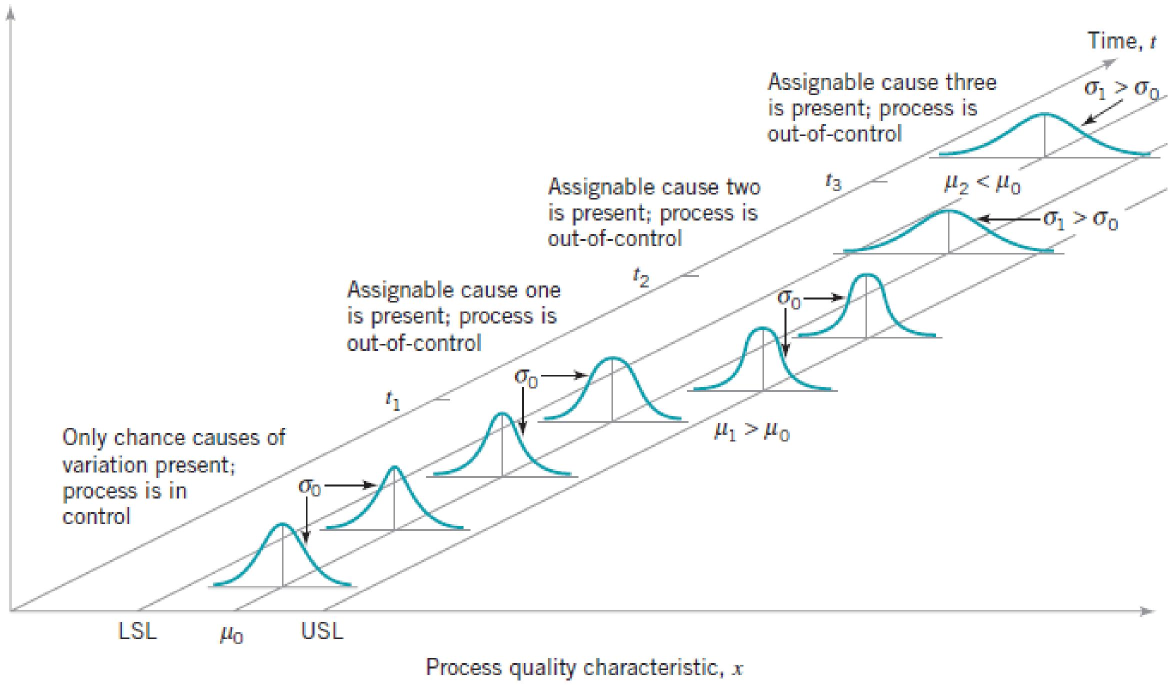


Figure 2.3: Chance and assignable causes of process variation (adopted from Montgomery, 2009)

2.5 Statistical basis for Shewhart control charts

Since the process is usually trying to conform to specification limits, the average tends to a specific quality characteristic figure. Therefore, most process data follow a normal or Gaussian distribution and with the basic understanding of statistical concepts such as average the variance and standard deviation can be calculated and applied for variability reduction. This can be used to show if the process is statistically stable or not as shown in Figure 2.4 above. These statistical concepts are used for the construction of control charts. The process control charts are also called the Shewhart control chart since Walter A. Shewhart developed the theory of control charts.

Statistical Process Control usually uses control charts for monitoring variability within a continuous process over time, for reducing process variability and for estimating process parameters. Control charts are effective because they can be used to keep the production process under control. Hence, avoiding wastage and unnecessary costs. They are used as a diagnostic tool since they can indicate where adjustments need to be made in the process and they provide information about the stability of the process. In short, control charts are a proactive approach to resolving process variability effects (Helm, 2018; Montgomery, 2009; SCME, 2017; Wild & Seber, 2017; Scott & James, 2015).

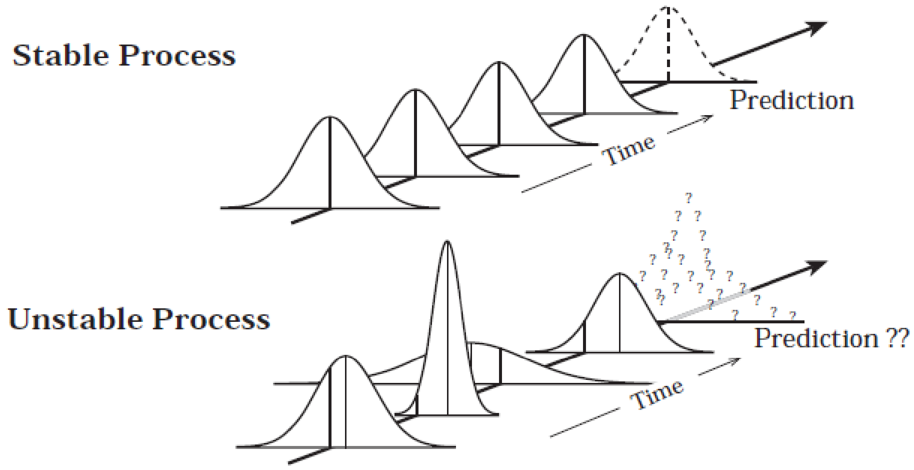


Figure 2.4: Process stability over time (adopted from SCME, 2017)

For this research control charts will graphically display quality characteristics that have been measured/sampled over some time. The quality characteristics represent the current efficiency factors that are normally plotted along the vertical axis and time or observations on the horizontal axis. A typical process control chart has three horizontal lines called Upper Control Limit (UCL), centreline (process average) and a Lower Control Limit (LCL) as shown in Figure 2.6 below.

The control limits are assumed to be ±3 standard deviation. The quality characteristic values plotted on the control charts are assumed to have an approximately normal distribution (also referred to as Gaussian Distribution) because it follows a bell-shaped pattern (see Figure 2.5). The central limit theorem holds if the sample sizes with a population distribution that is unimodal and close to symmetric (Montgomery, 2009; Anonymous, 2019; Amitava, 2016; SCME, 2017).

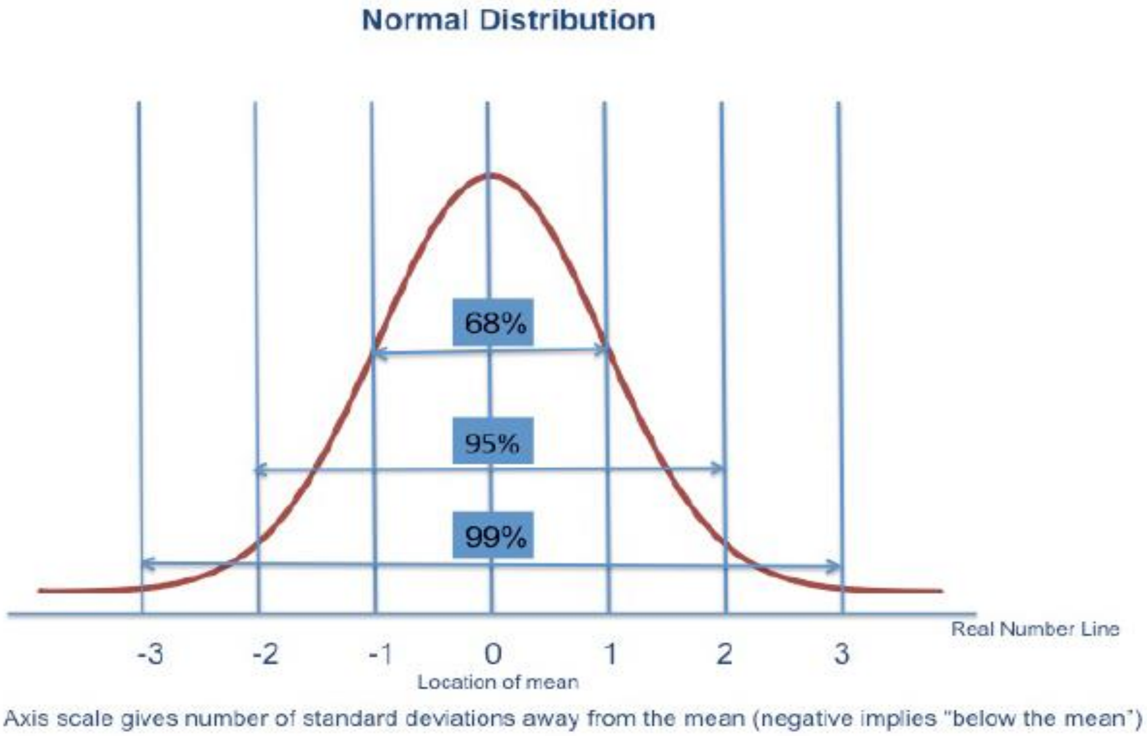


Figure 2.5: The bell-shaped pattern of the normal/Gaussian distribution (adopted from SCME, 2017)

The process is said to be in a state of statistical control if the quality characteristic points lie within the upper and lower control limits and they do not display any noticeable pattern/trend. Contrary, the process is said to be out of statistical control if a point plots outside the control limits or if there is a noticeable pattern within the control limits, for example, 10 points above the centreline. This simply means that if the process quality trend is between the limits it does not automatically mean that it is under statistical process control (Helm, 2018).

As such, there is a close connection between control charts and hypothesis testing. The process can either be under statistical process control or not in statistical process control and these can be turned into a hypothesis. Therefore, if a point lies within the control limits it means there is evidence that the process is in statistical control and the null hypothesis must be accepted.

However, the process still needs to be monitored further to fully conclude about the hypothesis, because if the points are above or below the centreline or they form a specific trend it means the process is statistically out of control. This is just an indicative truth (Helm, 2018). A hypothesis can be formulated as follow:

A null hypothesis (H_0): The process is in statistical control

An alternative hypothesis (H_1): The process is not in statistical control

As shown in Figure 2.6, it is possible to detect the causes of variability on the control chart. A single point outside the control limit signifies the special cause which does not affect the process permanently. On the other hand, a common cause can be detected as the process permanently start drifting away from the centreline. It will continue to do so until the problem is resolved (Sanchez-Fernandez, Baldan, Sainz-Palmero, Benitez, & Fuente, 2018; Montgomery, 2009; Anonymous, 2019; Amitava, 2016).

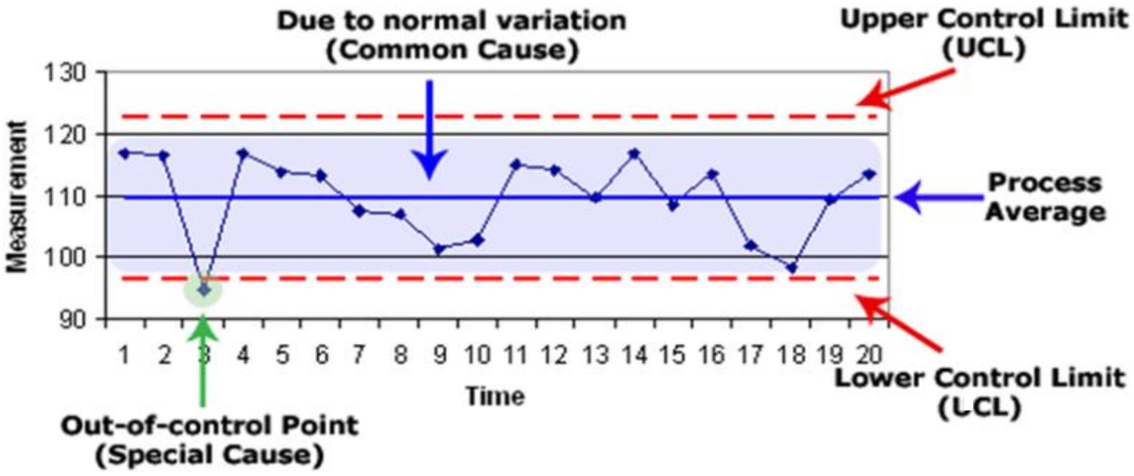


Figure 2.6: A typical process control chart (adopted from Anonymous, 2019)

A general model for the horizontal lines of a control chart is given by the following equations (Helm, 2018; Scott & James, 2015):

$$\text{Centreline} = \bar{x} \qquad 2.1$$

$$= \frac{\bar{x}_1+\bar{x}_2+\bar{x}_3+\cdots+\bar{x}_i}{n}$$

$$= \sum_{i=1}^{n} \frac{X_i}{n}$$

$$\text{Control limit} = \bar{x} \mp \frac{3s}{\sqrt{n}} \qquad 2.2$$

$$= \sum_{i=1}^{n} \frac{X_i}{n} \pm \frac{3\sqrt{\frac{\sum_{i=1}^{n}(X_i-\bar{X})^2}{n-1}}}{\sqrt{n}}$$

$$\text{Upper Control Limit (UCL)} = \bar{x} + \frac{3s}{\sqrt{n}} \qquad 2.3$$

$$= \sum_{i=1}^{n} \frac{X_i}{n} + \frac{3\sqrt{\frac{\sum_{i=1}^{n}(X_i-\bar{X})^2}{n-1}}}{\sqrt{n}}$$

$$\text{Upper Control Limit (UCL)} = \bar{x} - \frac{3s}{\sqrt{n}} \qquad 2.4$$

$$= \sum_{i=1}^{n} \frac{X_i}{n} - \frac{3\sqrt{\frac{\sum_{i=1}^{n}(X_i-\bar{X})^2}{n-1}}}{\sqrt{n}}$$

In which:

$\bar{x}$ = population estimator for mean/average (µ)

i = sample size

n = number of samples

s = standard deviation estimate for σ (the standard deviation of the population)

It is worth noting that the normal or Gaussian distribution bell-shaped curve in Figure 2.5 and the control chart in Figure 2.6 represent the same information. This is because a flipped normal/Gaussian distribution bell-shaped curve becomes a control chart as shown in Figure 2.7. This clearly shows the statistical basis for control charts.

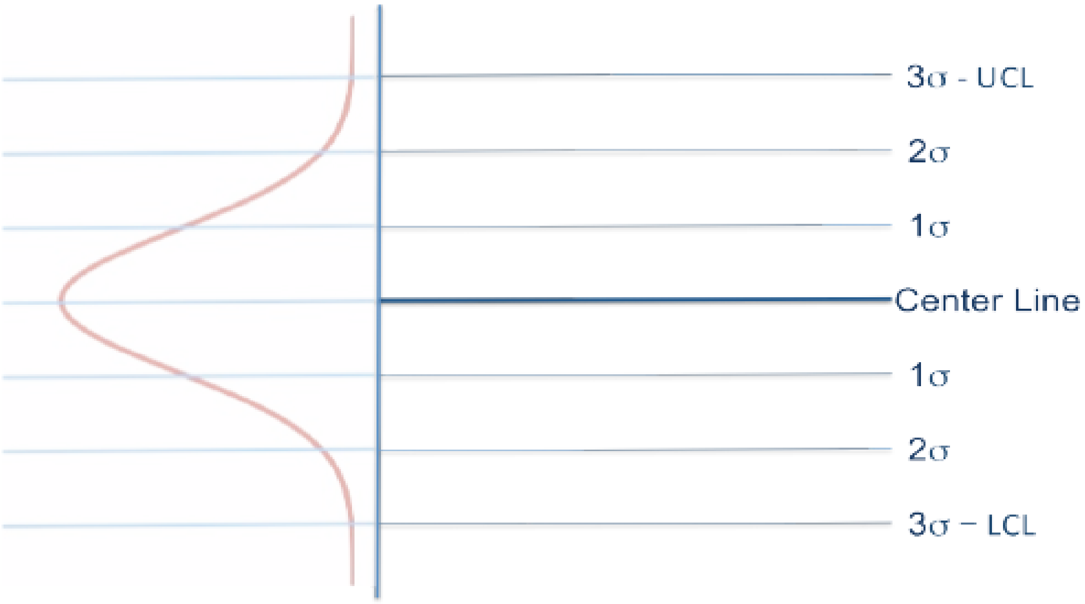


Figure 2.7: A flipped normal or Gaussian distribution bell-shaped curve becomes a control chart (adopted from SCME, 2017)

2.6 Out of control action plan (OCAP)

When monitoring process variability using control charts, decision rules are utilized to identify if the process is becoming unstable or going out of control. Control limits on the control chart are chosen in such a way that if the quality variables are within their range, it means the process is statistically under control. If the process operates outside these limits it means the process is statistically out of control and a Root Cause Analysis (RCA) needs to be completed to find an explanation of this abnormal process behavior. The crucial part associated with a control chart is referred to as the Out-of-Control-Action-Plan (OCAP) (Cheng & Tam, 1997; SCME, 2017).

This action plan is usually done in the form of a flow chart or text describing the sequence of events/activities that lead to the activating event. The OCAP consists of checkpoints (potential assignable causes) and the actions for eliminating the assignable causes. These actions are called terminators. The process for improving or eliminating process variability using an OCAP is summarized in Figure 2.8 (Montgomery, 2009). When putting back the process into statistical control a change in the process mean and standard deviation of the quality characteristic being tracked is expected to shift as shown in Figure 2.9 and Figure 2.10 (Amitava, 2016).

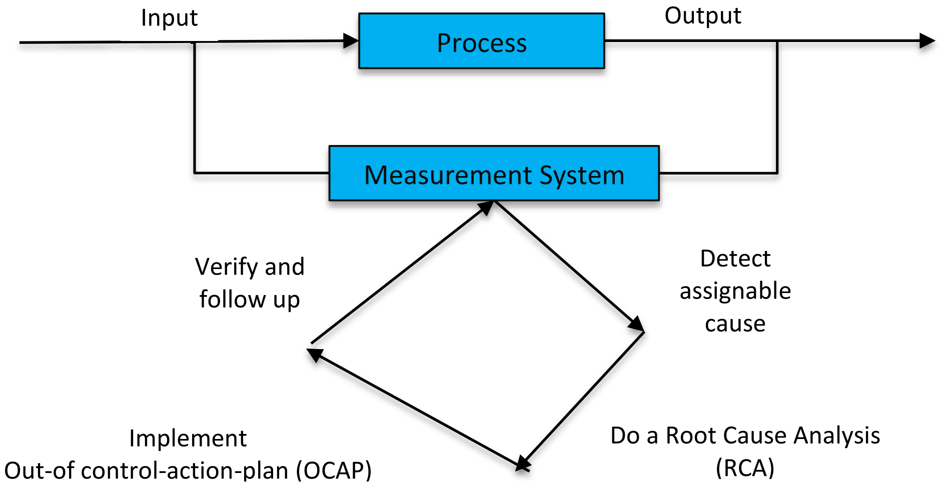


Figure 2.8: Process improvement using the out of control action plan (OCAP) (adopted from Amitava, 2016)

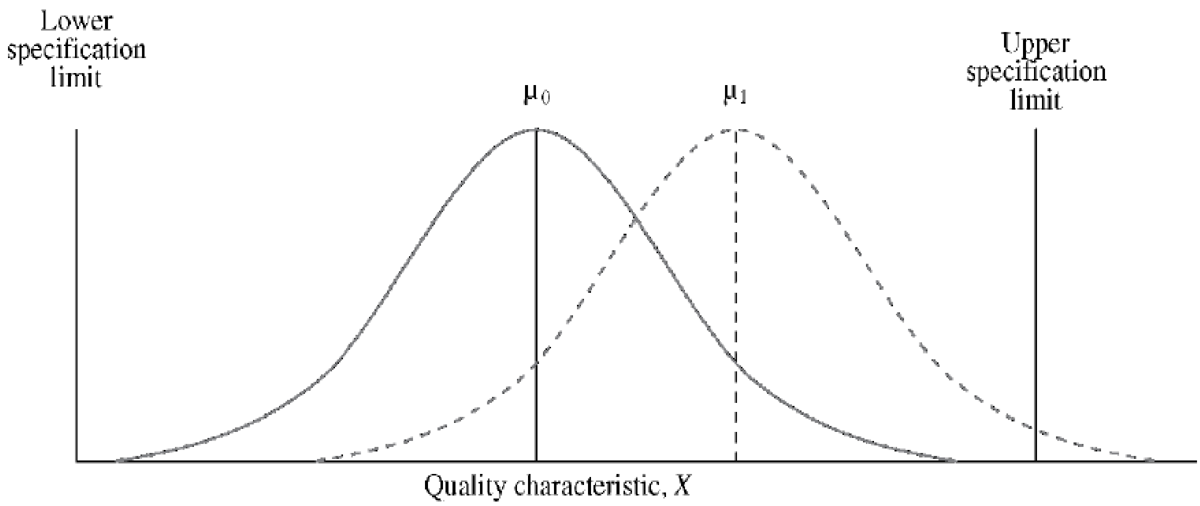


Figure 2.9: Change in the process average of a quality characteristic (adopted from Amitava, 2016)

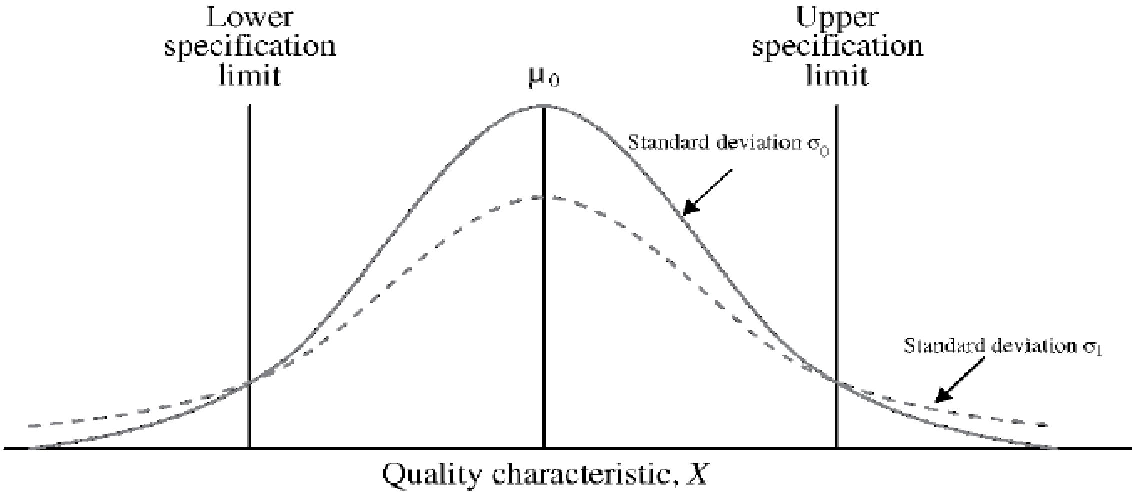


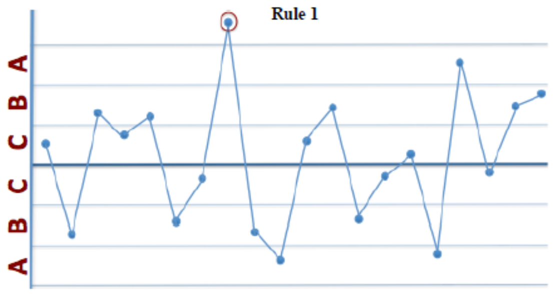
Figure 2.10: Change in the dispersion of a quality characteristic (adopted from Amitava, 2016)

2.7 Rules for Shewhart control charts

It is important to know when the process is out of control, it is for this reason that Walter Shewhart developed the eight Shewhart rules. The first four rules are also referred to as the Western Electric Rules. These rules are utilized as a signal that suggests that the quality characteristic data is not what is expected if the common causes were the only cause of process variation (natural variation).

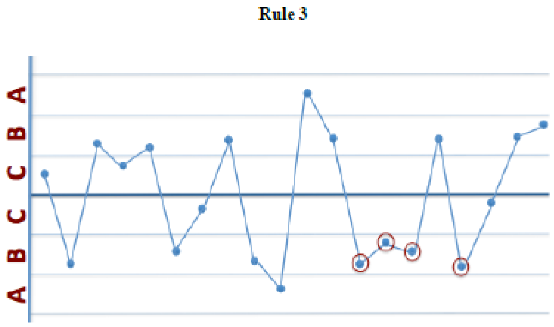
In short, the eight Shewhart Rules are the criteria for identifying that a special cause of variation is now affecting the process. It should, however, be noted that different companies use the rules depending on their process. Therefore, not all the rules are applied. It is crucial to understand why each one of them is an indicator of the special cause of variation (SCME, 2017; Montgomery, 2009). Table 2.1 summarizes the eight Shewhart rules by using the encircled points on the control chart.

Table 2.1: Shewhart rules for identifying special causes of variation on the control chart (adopted from SCME, 2017)

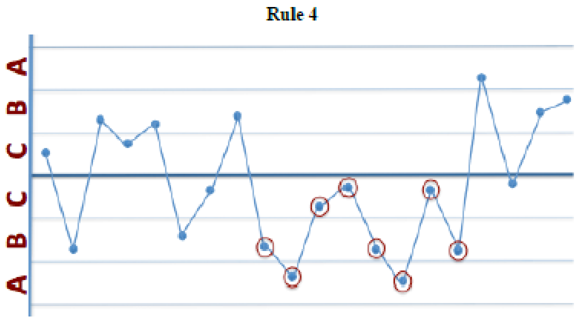


Rule 1: A point not in zone A, B, and C (outside the control limits). A single point outside the μ ± 3σ zones.

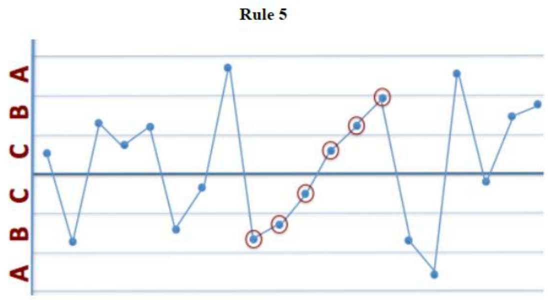
Rule 2: Two of the three successive points in zone A or beyond the mean. Two out of three consecutive points outside μ ± 2σ zones but still within the control limit.



Rule 3: Four out of five consecutive points in zone B outside μ ± 1σ zone.

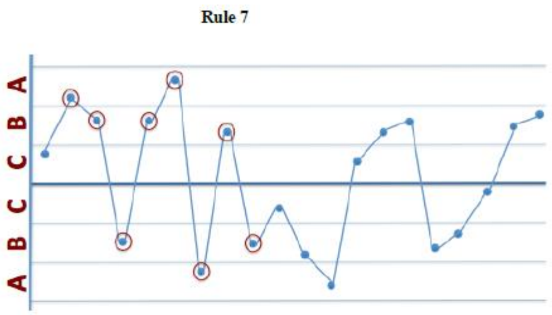


Rule 4: Eight or more successive points either strictly above or below the centreline or mean.



Rule 5: Six or more consecutive points displaying an uninterrupted increase or decrease trend.

Rule 6: Fourteen or more consecutive points that oscillate in size both above and below the centreline i.e. small, large, small, large, small, large, etc.



Rule 7: Eight or more consecutive points on both sides of the centreline that avoid or none of them are in zone C.

Rule 8: Fifteen successive points falling into zone C only, to either side of the centreline.

Should any of the above rules get contravened, the process is said to be Out of Control (OOC) and this should be followed by a Root Cause Analysis (RCA) and an Out of Control Action Plan (OCAP) for the identified special cause of variation until the process is back in statistical control (SCME, 2017).

2.8 Type I and type II errors of control charts

When it comes to processing control charts two types of errors exist, namely: Type I and Type II errors (SCME, 2017).

- Type I error happens if the decision rules (for example Shewhart rules) resulted in the researcher deciding that there is a special cause present in the process while in actual sense it does not exist. This is normally referred to as a false alarm.

- Type II error happens if the decision rules (such as Shewhart rules) resulted in the researcher deciding that there is no special cause of variation existing in the process. Hence the special cause of variation has been missed.

2.9 Types of control charts

In general, control charts can display either variable data or attribute data and they are mainly categorized into either of the two groups based on the type of data. A control chart displaying variable data shows measured values of the quality characteristic which is a continuous variable of the process. On the other hand, a control chart displaying attribute data of the quality characteristic which is not a continuous variable for the process, unlike variable data.

The attribute data normally result from counting the number of occurrences of items in a single category of similar items or occurrences such as pass/fail, yes/no, presence/absence of a defect (Woodruff, 2012). Other control chart types Cumulative Sum (CUSUM) control charts and multivariate control charts. The multivariate control charts are very crucial for monitoring multiple process variables especially when the process variables correlate (JMP, 2019).

Variable control charts

$\bar{X} - R$	Average and range	$\bar{X} - S$	Average and standard deviation
$\tilde{X} - R$	Median and range	$X - R_m$	Individual and moving range

Attributes control charts

p	Fraction nonconforming	c	Number of nonconformities
np	Number of nonconforming units	u	Number of nonconformities per unit

Multivariate control charts

- T-square partitioned multivariate control charts
- Change point detection multivariate control charts
- Principal components multivariate control charts

2.10 The electrowinning process

In the electrowinning (electrolytic process) a dissolved metal is recovered from the electrolyte by using an applied potential to drive the electrochemical reaction in a specific direction so that the metal can get electroplated on the surface of the cathode. This process is practiced widely in the metallurgical industry to produce high-quality copper, zinc, gold and other metals (Michael, 2013).

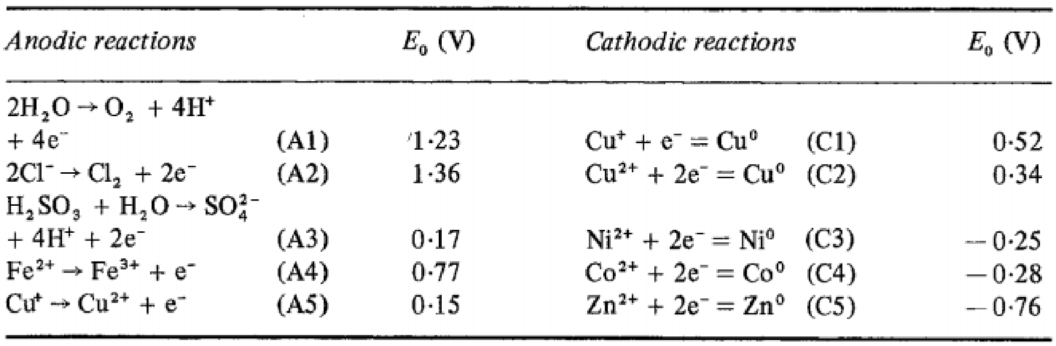
The performance of the electrowinning process is mainly measured by its current efficiency. In the case of copper electrowinning, nearly pure copper is electroplated on the blank cathodes. On the other hand, the dissociation of water occurs on the anode as shown by the electrochemical reactions below (Arman, Ersin, & Hac, 2016).

Cathodic half-cell reaction: $Cu^{2+} + 2e^{-} \rightarrow Cu^{0}$ $E^{0} = + 0.34$ V 2.5

Anodic half-cell reaction $H_2O \rightarrow \frac{1}{2}O_2 + H^{+} + 2e^{-}$ $E^{0} = - 1.23$ V 2.6

Overall reaction: $Cu^{2+} + H_2O \rightarrow Cu^{0} + \frac{1}{2}O_2 + H^{+}$ $E^{0} = - 0.89$ V 2.7

In practice, there are many possible anodic and cathodic electrochemical reactions as shown in Figure 2.11 below. The type and number of electrochemical reactions that will be experienced depending on the composition of the electrolyte solution.



Anodic reactions		E_0 (V)	*Cathodic reactions*		E_0 (V)
$2H_2O \rightarrow O_2 + 4H^{+} + 4e^{-}$	(A1)	1·23	$Cu^{+} + e^{-} = Cu^{0}$	(C1)	0·52
$2Cl^{-} \rightarrow Cl_2 + 2e^{-}$	(A2)	1·36	$Cu^{2+} + 2e^{-} = Cu^{0}$	(C2)	0·34
$H_2SO_3 + H_2O \rightarrow SO_4^{2-} + 4H^{+} + 2e^{-}$	(A3)	0·17	$Ni^{2+} + 2e^{-} = Ni^{0}$	(C3)	−0·25
$Fe^{2+} \rightarrow Fe^{3+} + e^{-}$	(A4)	0·77	$Co^{2+} + 2e^{-} = Co^{0}$	(C4)	−0·28
$Cu^{+} \rightarrow Cu^{2+} + e^{-}$	(A5)	0·15	$Zn^{2+} + 2e^{-} = Zn^{0}$	(C5)	−0·76

Figure 2.11: Possible anodic and cathodic electrochemical reactions at an electrowinning (adopted from Arman, Ersin, & Hac, 2016)

2.10.1 Current efficiency

There are many accepted definitions of current efficiency (CE) in literature. It can be referred to as the percentage of the total quantity of electrical energy consumed, which was effectively used for the intended electrochemical reaction (Natarajan, 1985). Current efficiency can also be defined as the fraction of the rectifier current that is utilized to electroplate the metal of interest (Joseph, 2017).

In other words, it is the ratio of the current that is electroplating the metal of interest to the total current applied to the electrolytic cells. However, in practice, it refers to the amount of metal electroplated divided by the amount of theoretical electroplated metal based on the applied current (Beukes & Badenhorst, 2009; Corby Anderson, 2017).

According to literature current efficiency or efficiency of deposition in modern electrowinning plants ranges from 90 % to 95 %, the unutilized current is usually wasted by the anode/cathode short-circuits, stray current to the ground and the reduction of Fe^{3+} to Fe^{2+} at the cathode and re-oxidation of Fe^{2+} to Fe^{3+} (Robinson, n.d.) and many other factors. The selected summary of electrowinning plant data showed that the copper electrowinning current efficiency normally ranges at > 92 % (Michael & Michael, 2007; Ntengwe, Mazana, & Samadi, 2010).

For a post Solvent Extraction (SX) electrowinning process current efficiency can be as high as 95 % (Beukes & Badenhorst, 2009). Another peer-reviewed article reported a current efficiency range from 82 % to 92 % for Cu electrowinning (Eduardo, Pablo, Guillermo, & Jorge, 2013) and 93 % to 95 % (Kordosky, 2002). Other studies show that attaining 100 % current efficiency is a realistic goal and in this case only the cell voltage is needed to force the process current to flow (Gonzalez-Dominguez & Dreisinger, 1997; Eduardo, Pablo, Guillermo, & Jorge, 2013). The theoretical plated metal is calculated based on Faraday's law. The formulas for current efficiency and Faraday's equation are given below:

$$\text{CE (\%)} = \frac{Mass\ of\ metal\ deposited\ or\ dissolved}{Ampere\ seconds\ (coulumbs)\ consumed\ \times electrochemical\ equivalent} \times 100 \qquad 2.8$$

$$= \frac{Current\ used\ by\ the\ half\ cell\ reaction}{Total\ current\ applied\ to\ the\ cells} \times 100 \qquad 2.9$$

$$= \frac{Actual\ amount\ of\ metal\ electroplated}{Theoretical\ amount\ of\ metal\ electroplated} \times 100 \qquad 2.10$$

$$= \frac{Change\ in\ weight\ after\ plating}{Theoretical\ weight\ of\ deposit} \times 100 \quad 2.11$$

$$= \frac{Amount\ of\ metal\ in\ head - Amount\ of\ metal\ in\ sample}{Amount\ of\ metal\ in\ head - Theoretical\ amount\ of\ metal\ in\ sample} \times 100 \quad 2.12$$

Theoretical mass of the metal electroplated onto the cathode blank =

$$\frac{Molecular\ weight\ of\ the\ metal\ (g/mol) \times Current\ (A) \times time\ (s)}{Number\ of\ electrons\ transferred \times Faraday's\ constant\ (C/mol)} \quad 2.13$$

2.10.2 Analysis of the literature

This section is aimed at highlighting a comprehensive review of peer-reviewed literature. This section is intended to achieve the following: (i) to establish the current knowledge on improving current efficiency, in general; (ii) to establish the knowledge gap on current efficiency by identifying a potential to contribute to the existing knowledge and to set a new dimension or mind-set on how current efficiency can be improved from a different angle.

Peer-reviewed publications literature survey on optimizing current efficiency from different databases such as Google Scholar, Science Direct, Emerald, IEEE, Pro-Quest dissertation and thesis was done by using keywords such as “current efficiency”, “current efficiency improvement”, “quality perspective of current efficiency”, “control charts used for current efficiency” and “current efficiency factors”. From the literature survey, it was clear that the research on current efficiency has been mainly focusing on improving current efficiency either by studying the effect of specific factors or the use of a specific technology for improving current efficiency. Therefore, no evidence of research done on improving current efficiency from the quality perspective by applying continuous quality improvement on current efficiency factors was found. This identified research gap was addressed by this research project.

The reviewed literature on improving current efficiency include but not limited to the development of technologies for improving energy efficiency in the electrowinning process such as electrode positioning capping boards and 3-D grids, segmented intercell bars, electrode spacers and the use of optibar intercell bars for avoiding electrode open circuits and minimizing contact resistance (Eduardo, Pablo, Guillermo, & Jorge, 2013); improving current efficiency through optimizing electrolyte flow in zinc electrowinning cell (Hongdan, Wentang, Wenqiang, & Bingzhi, 2016); contact system design to improve energy efficiency in copper electrowinning processes. This technology is aimed at increasing production, improving quality and reducing the electrolysis process operating costs by improving current density (CD) dispersion. The patented technology for electrical connection between electrochemical cells called the Walker connection (or Walker system) also resulted in improvements in the electrowinning process efficiency (Eduardo, Pablo, Guillermo, & Jorge, 2013).

In addition to that, other researchers focused on the effect of iron on energy consumption and current efficiency of zinc electrowinning from sulfate solutions (De Freitas, et al., 2010); Studies of micromorphology and current efficiency of zinc electrodeposited from flowing chloride electrolytes which highlighted the effect of electrolyte zinc concentration, effect of hydrogen ion, effect of flowrate, effect of substrate and effect of impurities on current efficiency (Mc Vay, Muller, & Tobias, 2011); a study of process parameters for zinc electrodeposition from a sulfate bath. This study concentrated on the effect of agitation, effect of current density, effect of pH and effect of temperature on cathodic current efficiency (Tuaweri, Adigio, & Jombo, 2013); Improving current efficiency by applying iron removal methods from the electrolyte such as solution precipitation, prior reduction of iron (III) by SO_2 or copper metal, increasing electrolyte bleed stream volume and utilizing a diaphragm cell (Beukes & Badenhorst, 2009).

Other researchers of current efficiency investigated into sustaining current efficiency by maintaining current density in the range of 280 A/m^2 to 320 A/m^2, ferrous iron to manganese ratio of >10, redox potential at < 600 mV and minimizing total iron tenor in the electrolyte to ~1 g/l (Joseph, 2017); effect of current, pH, $ZnCl_2$ concentration, Reynolds number, substrate and impurities on current efficiency (Vay, 2011); effect of temperature on current efficiency (Arman, Ersin, & Hac, 2016); the dependence of current efficiency on factors affecting the recovery of copper from solutions such as temperature, distance between electrodes, overvoltage, current, current density, concentration of the smoothing agent, electrolyte concentration and electrode-active surface area (Fereshteh, Naison, & Felix, 2010); increased current efficiency of zinc electrowinning in the presence of metal impurities by addition of organic inhibitors (Ivanov, 2003); a review of energy efficiency methods in metal electrowinning such as the use of Dimensionally Stable Anodes (DSA), maintaining current-density distribution on parallel electrodes as a function of electrochemical parameters of the electrode reactions, the ionic resistivity of the electrolyte and the internal electronic resistivity of the electrodes (Loufty & Leroy, 1978).

Further research on improving current efficiency focused on exploring the effect of Fe (III) during copper electrowinning at higher current density. From this study was found that current efficiency decreased with increased Fe (III) concentration at high electrolyte flowrate (Das & Gopala, 1995). Other researchers reported that current efficiency can be maximized by minimizing the wastage of current via anode or cathode short-circuits, stray current to the ground and minimizing the reduction of Fe^{3+} to Fe^{2+} and the re-oxidation of Fe^{2+} to Fe^{3+} (Robinson, n.d.); optimization of industrial copper electrowinning solution by focusing on solution flowrate, recycle ratio, reagent addition, addition of the acid mist depressing agent (Corby Anderson, 2017); the development of a “lower resistance” permanent cathode (ISA Cathode BR^{TM}) this upgraded technology was developed in response to the market demand because they reduce electrical power significantly and improve current efficiency (Webb & Weston, 2018). The analysis of the literature has been summarized in Table 2.2 shown below. Based on the literature review, a research gap was identified on improving current efficiency from a quality perspective because no evidence of it was established from the literature reviewed.

Table 2.2: Analysis of the literature on factors affecting current efficiency (developed by the author)

Authors name and year	Research gap to conduct the study and/or study topic	Research method used	Key findings identified from the article on electrowinning current efficiency	Future research direction / Things not considered	Knowledge gaps the present author intends to fill
N. T. Beukes and J Badenhorst (2009)	No sufficient coverage of theoretical and practical design considerations for copper electrowinning to ensure optimized cost, product quality, and high efficiency.	Quantitative method	1. Additional parasitic or side reactions have an effect on current efficiency. 2. The decomposition of water lowers current efficiency. 3. The cyclic oxidation and reduction of iron can affect current efficiency greatly. 4. Direct EW operation CE can be as low as 65 % and post SX EW operation CE can be as high as 95 %. 5. Optimum electrolyte conductivity is achieved by maintaining electrolyte temperatures ranging from 45 ℃ to 55 ℃ by using heat exchangers. This is essential for CE. 6. Cathode smoothing agents affect CE. The dosing rate ranges of glues and guar ranges from 150 g to 400 g per ton of Cu produced. Chloride concentration should be kept below 30 ppm by adding sufficient salt. 7. The presence of metallurgical short-circuits (hotspots) results in reduced current efficiency. Attention should be given to the electrode furniture to ensure that all anodes have five insulators and all electrodes are straight. 8. The design and condition of the busbar and the intercell busbar can result in heat losses and reduced CE. 9. The cell potential is related to half-reaction potential, additional side reactions, losses via the electrolyte and busbars. Its effects on CE and it normally ranges from 1.9 V to 2.3 V. 10. The electrolyte filtration is essential for preventing organic entrainment (OE) and total suspended solids (TSS) from going to EW via the electrolyte solution. The organic and suspended solids result in impurities transfer to EW and reduced CE.	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).
S.R. Natarajan (1985) and P. Radhakrishnamurty (199)	Most calculations of CE only consider a single metal electroplated. A formula for calculating CE of a ternary alloy metal plated was developed.	Quantitative method	1. Electrowinning bath conditions such as temperature and current density should be chosen so that CE can be maximized. 2. An extension of a single metal CE calculation formulas is essential when calculating CE for electrolytic alloy deposition. This will result in the summation of individual current efficiencies when a binary or ternary alloy metal is electroplated. 3. CE is the sum of individual CE of individual metals electroplated.	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).

K. Joseph (2017)	There is no procedure for copper EW circuit equipment sizing and copper electrolyte flowrate simulation (design aspect).	Quantitative method	1. The CE fraction that is not used for plating copper is due to metallurgical short-circuits and also cyclic reduction and oxidation of iron. 2. It is possible to give a mathematical expression that relates to CE and the reduction of Fe^{3+} ions only. 3. CE increases with an increase in operating current density, iron boundary thickness and decreasing iron concentration in the electrolyte. 4. The operating rectifier current should be maintained in the range of 280 A/m^2 to 320 A/m^2. While the electrolyte iron concentration should be controlled below 2 g/l. This can ensure CE ranging from 88 % to 92 %. 5. For copper electrolysis, the electrolyte iron tenor is controlled by bleeding off the electrolyte. It is best for the electrolyte iron tenor to be maintained at around 1 g/l. 6. High manganese in the electrolyte gets oxidized to permanganate which degrades the organic at solvent extraction (SX). This causes high phase disengagement time (PDT) and increased organic entrainment (OE) which carry impurities to EW. The impurities reduce CE. 7. Manganese to iron ratio should be kept greater than 10 for manganese oxidation control.	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).
V. de Freltas, R. Abelha, M. das Merces, M. Maciel, L. Lanza, C. Robert and T. Matencio (2010)	Effect of iron on energy consumption and current efficiency of zinc electrowinning from sulfate solutions by using electrochemical techniques such as galvanostatic deposition and cyclic voltammetry.	Quantitative method	1. High iron concentration in the electrolyte decreases current efficiency and it increases energy consumption. 2. High CE was obtained using electrolyte without sulphuric acid addition than when acid has been added.	Further work needs to be done on the effect of impurities such as antimony, nickel, cadmium, and iron by making use of cyclic voltammetry and electrochemical impedance spectroscopy.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).
S. Sandoval, N. Goel, A. Luzanga and O, Tshifungat (2016)	Improvements in copper electrowinning at Tenke Fungurume Mining Company.	Quantitative method	1. Operating at a current density of 430 A/m^2 resulted in the production of fine crystalline copper cathodes at a CE of 98 %. 2. A demonstration cell selected at EW was operated by changing cathode and anode insulators showed an improvement in CE from 77 % to 89 % at a current density of 400 A/m^2. This occurred when using a three-side cathode edge strip, A-style anode insulators, and better cell furniture design causing an increase in CE by 12 %.	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).

			3. The main parameters for good CE include electrode straightness, electrode alignment, electrolyte distribution, electrode contact system, and good current distribution. 4. The electrolyte for the operation concerned was unique. It is composed of 43 g/l Cu, 1 g/l Co and 1 g/l Fe. The produced cathodes had good morphology and the current efficiency was reported to be 98 %. 5. The bench-cell showed remarkable current efficiency, exceptional cathode quality, and superb lead anode performance. 6. A dramatic improvement in CE and Cu quality was experienced solely by the optimization of cathode and anode insulator geometry and also the cell furniture.		
A. Ehsani, E. Yazici and H. Deveci (2016)	Study the effect of temperature on copper electrolysis.	Quantitative method	1. Increased temperature results in increased current density and rate of copper deposition. 2. High temperature reduces the resistance of the electrolyte solution hence causing an increased rate of copper electrodeposition. 3. Elevated temperature improves the electrodeposition kinetics, reduces cell potential roughly by 0.09 V with an additional ~10 % reduction in energy consumption. 4. Copper electrolysis is conducted from 35 ℃ to 65 ℃ because there is no ideal temperature for the process and the optimum temperature depends on other operating parameters. 5. The physicochemical properties and mass transfer parameters of the electrolyte are affected by the electrolyte temperature. 6. Temperature affects the electrolyte speciation with the concentration of H^+ and Fe^{3+}. These ions are inversely proportional to temperature. 7. The electrolyte viscosity decreases with an increase in temperature. This improves mass transfer and hence advances current efficiency. 8. The limiting current density, diffusion coefficient, and current efficiency increase with temperature. 9. Current efficiency can be improved by increasing temperature, maintaining high electrolyte Cu tenor and low electrolyte impurity concentration especially Fe^{3+}. 10. If the electrolyte Fe^{3+} tenor is high, increased temperature will result in an increased Fe^{3+} diffusion coefficient which will cause a decrease in current efficiency.	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).

			11. It was noted that there is an interaction between high temperature ranging from 40 °C to 60 °C, high electrolyte Cu concentration of 65 g/l and no presence of Fe^{3+} in the electrolyte. This interaction resulted in low current efficiency. 12. A model showed that increased Cu concentration and high current density tends to improve CE. 13. Increased temperature causes improved diffusion of Cu ions and accelerated rate of Cu deposition onto the cathode blank. 14. Increasing temperature from 20 °C to 50 °C contributed to an approximately 10 % reduction in energy consumption from 1.94 kWh/kg to 1.69 kWh/kg. 15. The CE increased by ~2 % after increasing the temperature from 20 °C to 50 °C. 16. Increased temperature causes dendritic cathode structure because there is no sufficient time to develop the crystal structure. After all, the electrochemical reaction and diffusion rate of ions is accelerated by increased temperature. 17. Increased rate of deposition is associated with an increased number of high energy collisions that resulted from high temperatures. 18. It is essential to strike a balance between deposit quality and improvement in the copper deposition rate, CE and energy consumption.		
F. Ntengwe, N. Mazana and F. Samadi (2010)	To establish the effect or dependence of current efficiency on different factors that affect the recovery of copper from solution.	Quantitative method	1. CE varies with the levels factors such as temperature, the concentration of electrolyte and cathode smoothening agent, the distance between electrodes, the potential across the reactor, electrode-active area and current density. Interactions between these factors resulted in different CE values. 2. The presence of dissolved impurities will result in their ions participating in the chemical reaction and reducing CE. 3. The potential across the reactor and current density are the main driving forces for the electrochemical reactions. If kept too low they will not be effective and if maintained too high they can cause nodulation, passivity and rough cathode surface hence affecting the morphology. 4. Increased cathode surface area would result in lowering the distribution of current over the surface area of the cathode. This will consequently cause low current density that has the potential to result in nodulation or passivity. 5. The effect of temperature was studied at 24 °C, 39 °C and 60 °C. It was noted that increased temperature increased the limiting current density. However, for most temperature values there was no effect observed. All temperature values had little effect on current efficiency. 6. Increased current density increased the rate of deposition but it had little effect on CE.	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).

			7. High electrolyte copper and smoother concentration resulted in increased CE. 8. The distance between the electrodes had little effect on CE. 9. An increase in the electrode surface area resulted in a decrease in current density, reduction in the mass of deposited copper and low CE. The surface area was noted to have a linear relation with CE but with a negative slope and it is proportional to the current density. 10. Increased temperature improves the conductivity of ions in the electrolyte. It also enhances properties of cathode smoothing agents, electrolyte viscosity and density which makes the conditions conducive for the recovery of copper. 11. The copper concentration in the electrolyte contributes to the increase in current density. However, CE varies with the distance between the electrodes.		
S. Das and G. Krishna (1995)	The effect of Fe (III) during Cu EW at higher current density by using an open channel cell on current efficiency, power consumption and cathode quality.	Quantitative method	1. High Fe (III) concentration in electrolyte causes CE to decrease and it contributes to poor quality copper cathodes. 2. CE decreases with an increase in the electrolyte Fe (III) concentration as the electrolyte flow rate increases. 3. Power consumption increases with an increase in the electrolyte Fe (III) concentration as the electrolyte flow rate increases. 4. A CE of ≥ 90 % can be achieved by maintaining a Fe (III)/Fe (II) ratio of ≤ 1.00. 5. The addition of Fe (II) may be done when controlling the Fe (III)/Fe (II) ratio and it also improves the cathode quality. 6. Increased temperature contributes significantly to increasing the limiting current density. 7. The diffusion of Cu (II) and Fe (III) increases with an increase in temperature. It was noted that the diffusion coefficient of ions in the solution increases at a rate of 2 %/°C. Fe (III) ion reduction is limited by its diffusion on the cathode surface and Fe (III) gets reduced first compared to copper because it has a higher reduction potential. It will then consume all the current. Therefore, the high voltage should be applied so that copper can electroplate. 8. The current keeps increasing until Fe (III) reaches its limiting current. At any current density, the CE for copper deposition is governed by the limiting current of Fe (III) ion reduction. 9. Increased bath temperature improves cathode quality. However, does not change CE significantly. High temperature up to 40 °C is sufficient to improve the cathode surface quality by keeping it smooth. 10. The marginal increase in CE was observed after increasing the electrolyte copper concentration within the 17 g/l to 37 g/l range and temperature range of 30 °C to 50 °C. The most likely reason for the increase in CE stems from the fact	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).

			that at high Cu (II) tenor, the viscosity of the solution increases which also impedes the distribution of Fe (III) over the cathode surface. 11. Power consumption and electrolyte copper tenor are inversely proportional. But power consumption is directly proportional to the electrolyte Fe (III). 12. The electrolyte sulphuric acid concentration only has an effect on CE at high temperatures and low Fe (III) concentration. 13. Power consumption was reported to increase with increased acid concentration as the Fe (III) concentration was also increased. 14. Increased electrolyte circulation rate and hydrodynamics improve the mass transfer conditions in the cells. At high circulation flowrate and low Fe (III), the CE fell by ~4 %. However, at high circulation flowrate and high Fe (III), the CE fell by ~15 %. Unlike for CE, these conditions had a worse effect on power consumption. The temperature had a negligible effect on CE and cathode morphology at a lower circulation flow rate. 15. The recent trend is to operate at a relatively high current density. Many copper operations are doing it and it is advisable. 16. An outstanding cathode quality was observed after increasing current density and bath temperature. A cathode deposit of high quality can be achieved at higher Fe (III) concentration if both temperature and current density have been increased.		
T. Robinson (n.d.)	An overview of copper electrowinning	Quantitative method	1. The rate of copper plating increases with increasing current density. 2. Excessive current density consequently results in the formation of rough, nodular cathode deposits and decreased copper cathode purity. Therefore, when choosing an operating current density a balance between all these parameters should be considered. 3. After a plating period of ~7 days, 30 % of the cathodes should be harvested. This maintains the adherent corrosion product layer on the lead alloy anode thereby minimizing contamination of the electroplated copper cathodes. 4. The chemical composition of the anodes is contributing to the quality of the cathodes produced and CE. Most anodes are cold-rolled Pb-Sn-Ca alloyed anodes. They are normally composed of 98.4 % Pb, 1.5 % Sn and 0.1 % Ca. Sn is added for cathode quality and CE improvement corrosion resistance and corrosion layer conductivity. 5. Additives such as guar result in the production of dense, smooth copper deposits with minimum impurity entrainment. The addition of cobalt protects the anodes from corrosion and minimizes cathode contamination because it promotes	The author suggested potential future developments by suggesting the use of truly inert anodes. The Pb-alloy anodes currently used corrode slowly and they contaminate the cathode purity and affect CE. However, if they were made from iridium,	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).

			the evolution of O_2 rather than Pb oxidation on the anode. Chloride ions added either as NaCl or HCl causes the production of dense, fine grain and low impurity copper deposits. 6. It is essential to maintain a steady rectifier current supply to the EW process so that an adherent anode corrosion layer is maintained. 7. High electrolyte manganese causes speedy Pb corrosion and the formation of flaky corrosion products that can compromise cathode quality and reduce CE. 8. Electrolyte supplied from SX should be free from solids and organic because they can host impurities. 9. Cell cleaning or cell sludge removal should be done frequently to ensure that cathode contamination is minimized. 10. The electrolyte flow regime should not be turbulent. 11. Metallurgical short-circuits should be minimized. 12. Electrolyte iron concentration should be at its minimum so that the reduction of Fe^{3+} to Fe^{2+} and the re-oxidation of Fe^{2+} to Fe^{3+} can be minimal.	titanium and lead they will minimize Pb contamination, reduce the need for cell cleaning and a 0.3 V to a 0.4 V decrease in oxygen overpotential. This can reduce energy consumption and decrease the need for Co addition. However, it will be expensive.	
S. S. Xue, M. J. Gula, J. T. Harvey and E. P. Howitz (2000)	Application of the newly developed monophosphonic or sulphonic acid resin to control iron in electrolyte streams	Quantitative method	1. Monophosphonic or sulphonic acid resin can strongly and selectively extraction ferric ions over copper and cobalt ions from the electrolyte. Applications of this resin for iron control can result in improved CE and power consumption.	Monophosphonic or sulphonic acid resin was only tested in a simulated electrolyte. It should also be tested in a large scale process to fully benefit from it.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).
W. Webb and J. Weston (2017)	The development of lower resistance permanent cathodes by ISA Process Technology	Quantitative method	1. The development of the lower resistance permanent cathodes has resulted in the introduction of operating current densities up to 350 A/m^2 and current efficiencies of more than 98 %. 2. This technology ensures that the London Metal Exchange (LME) grade A quality copper cathodes are produced. 3. The low resistance electrode ISA process cathode plates have the potential to reduce power costs significantly. 4. The ISA process cathodes were reported to operate at 2 % higher CE than the conventional solid copper hanger bars. 5. The ISA Cathode BR^{TM} cathodes were designed considering both CE and conductivity making them the most efficient cathodes.	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).

			6. The low resistance ISA Cathode BR^{TM} cathodes have been electroplated with 15 mm of copper to plate down onto the blade thereby ensuring even flow of current into the blade and even initiation of copper deposition. The electroplated copper result in significantly reduced resistance within the cathode.		
T.J. Tuaweri, E.M. Adigio and P.P. Jombo (2013)	Analysis of zinc electrodeposition from a sulfate bath	Quantitative method	1. Electrolyte bath agitation resulted in reduced CE. It was assumed that agitation will improve the mass transport and hence the rate of deposition but the experiments proofed otherwise. 2. Current efficiency was reported to increase with an increase in electrolyte pH. 3. A linear relationship was observed between temperature and CE. 4. Current density, agitation, and temperature of the bath affected CE and deposit thickness.	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).
E. P. Wiechmann, A. S. Morales and P. Aqueveque (2009)	Application of optibar intercell bars and reduction of the distance between electrodes to improve productivity and energy efficiency in Cu EW plants.	Quantitative method	1. For copper EW plant, CE normally ranges from 82 % to 92 %. 2. During operating conditions of EW, the rectifier current gets wasted though metallurgical short-circuits, stray current, the formation of by-products due to parasitic or side reactions and the re-oxidation of cathodes. 3. Cell voltage and current density have the biggest influence on energy losses and CE. 4. Metallurgical short-circuits and contact resistances account for up to 30 % of the energy losses. 5. It is important to reduce current dispersion among the anode-cathode pairs and/or the resistance of the process. 6. The metallurgical short-circuit phenomenon increases cathodic current by 1500 A. Thereby reducing the neighboring cathode current and affecting the overall cell dynamics. During metallurgical short-circuits an overcurrent of 1200 A is normally concentrated at a small area for instance 1 cm^2 of 1 m^2 total surface area for a long period. 7. There are a lot of factors that affect cell voltage at EW such as thermodynamic equilibrium potential of the electrodes (also referred to as cell reaction voltage), kinetic overvoltage and ohmic resistance of the bath and at the contacts. For electrolysis to work a higher potential should be applied thereby overcoming these resistances at every cathode-anode pair. 8. The electrolyte has the highest resistance and it depends on factors such as electrolyte resistivity due to electrolyte composition and temperature. Therefore, only changing the electrolyte composition is not sufficient to reduce the resistance. It should be coupled with reducing the distance between the electrodes which is effective at reducing energy losses.	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).

			9. The intensity and occurrence of metallurgical short-circuits and current dispersion need to be monitored and controlled. 10. Energy efficiency is affected by factors such as positioning and distance between electrodes, bath temperature, electrolyte conductivity, electrolyte impurity concentration, reagents addition, DC high current system efficiency, frequency of short-circuits occurrence, the dispersion of current density and contact resistance between electrodes and intercell bars. 10. Ideally, a 100 % energy efficient EW plant should have 100 % CE and no ohmic losses. In this case only the reaction cell potential ($\sim 1.45\ V$) is required to force the process to electroplate copper. However, in practice, an overvoltage of ~ 0.55 V is required for the electrolysis process to occur. 11. Significant cathode weight differences result from current imbalances that exist in the process. 12. The segmented optibar technology force rectifier current to balance thereby assisting with compensating for geometrical asymmetries, contact resistances, misalignments, and electrolyte dispersion. 13. The application of optibar intercell bars connects the anode-cathode pairs of contiguous cells in series. Hence generating the preferred electrical paths or current channels thereby producing equivalent resistances and current balances. 14. To compensate for contact resistances and electrode alignment slight overvoltage differences should be allowed. The optibar connection is featured by high short-circuit resistances (Thévenin resistance) which avoids high overcurrents. This improves CE and energy savings. 15. Replacing conventional intercell bars with optibar resulted in an energy saving of + 1.5 % and cell electrical energy efficiency increased by + 3.0 %. 16. The optibar intercell bars can increase the operating current density by + 6.2 % without affecting copper quality. The use of optibar intercell bars ensured a homogeneous copper cathode in terms of weight and quality. 17. The optibar intercell bars create current channels that have the potential to decrease cathode current density dispersion by 43.8 % and the metallurgical short-circuit by 67 %. This technology allows for the reduction of the distance between electrodes, electrical resistance reduction, and associated energy losses. This allows for extra cathodes to be inserted into the cells.		
J. M. Werner (2017)	To develop improved predictions of EW	Quantitative method	1. Current efficiency is mainly affected by impurity concentration, current density, metallurgical short-circuits (hotspots), bath temperature, electrode condition, and the incubation period.	Future research direction was not provided.	Improving CE from a quality perspective

	performance by using advanced modelling techniques.		2. CE factors can be categorized into two groups namely electrochemical and geometrical. The concentration of iron has the biggest influence amongst electrochemical factors. On the other hand, short-circuiting contributes significantly to CE because it allows an alternative path for the current which is not used for cathode plating.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	by using methods such as Statistical Process Control (SPC).
F. Parada and E. Asselin (2009)	Reducing electrowinning power consumption	Quantitative method	1. Current efficiency increases as the concentration of the electroplated metal increases. 2. High acid concentration causes the conductivity of the electrolyte to increase hence improving current efficiency. 3. The effect of temperature is not clear. The high temperature was reported to increase CE at a laboratory scale but different results were obtained in a large scale pilot plant.	It is hoped that future research focuses on EW practices which are not dependent on the current process. Impurity control and anode design present good opportunities for improvement in the future.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).
G. A. Kordosky (2002)	Copper recovery using L-SX-EW technology: 40 years of innovation and 2.2 million tons of Cu annually	Quantitative method	1. Flotation cells can be installed to remove entrained organic from advance electrolyte thereby improving copper quality and current efficiency. Electrolyte filters may also be utilized for the removal of total suspended solids (TSS) and organic entrainment (OE). 2. The addition of cobalt into the electrolyte reduces the lead anode corrosion thereby minimizing chances of cathode contamination by lead. 3. The use of a dimensionally stable anode (DSA) presents good performance. However, rolled anodes of Pb-Ca and Pb-Sr-Sn are currently the best anodes of choice due to their dimensional stability, a lower rate of corrosion and decreased anode-cathode spacing which is less than when using cast anodes. 4. To improve copper cathode quality and current efficiency plating should be done on stainless steel blanks. 5. The use of manifold assists with evenly distributing the electrolyte to every cathode in the cell. This technique was the key factor that contributed to Magma Copper producing LME Grade A quality copper at current densities up to 320 A/m^2.	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).
Y. Khouraibchia and M.S. Moats (2015)	To develop statistical models that describe the effect of Cu EW parameters on CE and	Quantitative method	1. Current efficiency was reported to increase with increasing electrolyte copper concentration at any applied current density until 42 g/l of copper. 2. Current efficiency is directly proportional to current density.	Future research direction was not provided. Improving CE from a quality perspective by	Improving CE from a quality perspective by using methods such as Statistical

	energy consumption using surface response methodology		3. For every 1 g/l of Fe^{2+} in the electrolyte, the current efficiency decreases by 2.5 g/l. 4. If the electrolyte copper tenor ranges from 35 g/l to 45 g/l, current efficiency ranging of more than 95 % may be attained while the ferric tenor is maintained below 1 g/l and a current density greater than 320 A/m^2. 5. Ferric concentration, copper concentration, current density, and their interactions were found to have a significant effect on current efficiency. Amongst other parameters, these three parameters have the most significant effect on current efficiency hence a CE model was developed in terms of these three factors. 6. Stray current and short-circuits also have a significant negative effect on current efficiency. 7. An increase in electrolyte copper concentration increases current efficiency. 8. The operating current density depends on the set rate of copper cathode production and maximum energy consumption allowed. However, the higher the current density the higher the current efficiency. 9. High electrolyte temperature was found to lower current efficiency. 10. Statistical analysis showed that there is an interaction between electrolyte copper concentration and ferric concentration has a significant effect on energy consumption.	using methods such as Statistical Process Control (SPC) was not considered. However, statistical analysis was considered for developing the empirical models for CE and EC in terms of ferric tenor, electrolyte concentration and current density. MINITAB was used for statistical analysis and the R^2-value for the model was 98.25 %.	Process Control (SPC).
S. Chaoran (2017)	The effect of lead impurity and manganese addition on the main operating parameters of Zn EW.	Quantitative method	1. High bath temperature causes the overpotential to decrease and it results in increased cathodic current efficiency. The increase in current efficiency is related to the increase in the diffusion rate of the ions plated because the electrolyte viscosity has decreased. High temperature also increases electrolyte conductivity which reduces cell voltage and energy required. 2. Increase the metal of interest concentration in the spent electrolyte was reported to increase current efficiency. 3. Increasing current density increased cathodic potential and also current efficiency.	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).
A. Shukla (2013)	Modelling and measuring electrodeposition parameters near electrode surfaces to enhance EW performance and optimization.	Quantitative method	1. Operating at high current efficiency is crucial because it maximizes the metal plating rate and decreases electrical energy consumption. 2. Poor current efficiency is usually a consequence of metallurgical short-circuits, the stray current into the ground and the reduction of Fe^{3+} to Fe^{2+} at the cathode and re-oxidation of Fe^{2+} to Fe^{3+} at the anode. 3. The main reasons for metallurgical short-circuit (hotspot) formation are the misalignment of electrodes, bent cathodes, and longer nodules or dendritic growths on the plated copper.	Future research direction was not provided. Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC) was not considered.	Improving CE from a quality perspective by using methods such as Statistical Process Control (SPC).

			4. The misalignment of electrodes results in uneven current distribution, current density distribution and current efficiency for individual cathodes within the cells. 5. The use of optibar intercell bar and bypass-backup connection systems are promising technologies for improving current efficiency and the electrowinning process in general. 6. Increasing copper tenor contributes to increased current efficiency. High copper concentration increases the electrolyte viscosity which impedes the distribution of Fe^{3+} over the cathode surface. 7. The optimum operating temperature depends on other operating parameters and they are specific for each plant. Increased temperature ranging from 35 °C to 65 °C results in increased current efficiency. However, high temperature causes the formation of fine-grained cathodes. 8. The addition of cobalt sulfate into the electrolyte stimulates the evolution of oxygen at the anodes rather than lead oxidation. This minimizes anode corrosion ensuring no cathode contamination from lead occurs and also improving current efficiency. 9. Current density affects current efficiency and the quality of the electroplated metal. The optimum current density in the industry ranges from 280 A/m^2 to 340 A/m^2. 10. With a Fe^{3+}/Fe^{2+} ratio of at least 1.0 a current efficiency of 90 %. A high reduction in current efficiency occurs at a high electrolyte flow rate and high Fe^{3+} concentration.		

2.11. Summary

Chapter 2 focused on the literature review. The objective of this chapter is to gain an understanding of how quality and current efficiency relate to each other. This was done by linking the definitions of quality that suites application onto current efficiency. The most suitable definitions were "*conformance-to-specifications*", "*reduction in process variability*" as defined by Montgomery (2009) and "*fitness for use*" as suggested by Juran (1974). These definitions allow for the improvement of current efficiency factors from a quality perspective to translate into improved current efficiency. In this way, current efficiency may be improved from a quality perspective.

Thereafter, the statistical methods for quality control and improvement were discussed. The discussion included statistical process control (SPC), causes of process variability, statistical basis for Shewhart control charts, out of control action plan (OCAP), rules for Shewhart control charts and types of control charts. The reviewed literature then focused on the electrowinning process and current efficiency to be specific. Different formulas for calculating current efficiency and the famous Faraday's equation for electrolysis was given. Moreover, an analysis of the literature on current efficiency was done. It was concluded that there is no evidence of improving current efficiency from a quality perspective and/or by applying statistical process control from the reviewed literature.

Chapter 3 below will be covering the research methodology. It will indicate the research approach utilized, the methodology for establishing current efficiency factors, how the data was collected, how the data was analyzed, a description of the analysis tools and the research strategy that was applied.

3. Research methodology

3.1 Introduction

The research methodology chapter intends to describe the roadmap or strategy on how the researcher planned to achieve the aim of the research. This chapter is organized as follows: It started with the research approach, followed by the methodology for exploring current efficiency factors, thereafter data collection, followed by data analysis, after that a description of the data analysis tools and finally a research strategy.

3.2 Research approach

A sequential mixed research methodology was applied to this research. In this case, a qualitative research approach was followed by a quantitative research approach. This is because most of the factors that affect electrowinning current efficiency can easily be quantified (except a few factors) and the actual values can be compared with the targets. In addition to that, current efficiency variables are significantly affected by the operators and technical people working at the electrowinning plant. Therefore, a survey will be done to get suggestions from the production and technical team. The qualitative research approach will also be utilized to get suggestions about the current efficiency factors, the current efficiency improvement best practices. Before the framework is designed, what needs to be considered when developing the framework will be discussed and how it should be implemented.

3.3 Methodology for exploring current efficiency factors

Before any attempt is made to collect data, the current efficiency factors first need to be identified. The main approaches for identifying the factors that will be used are an intensive literature review and a questionnaire-based survey (qualitative research approach). The literature review will be utilized to establish the effects of the factors on current efficiency and also for assigning specification ranges to them. A questionnaire will be used to collect more operational factors that affect current efficiency. These factors will be ranked depending on the number of people that mentioned that specific factor. The above-mentioned methodology for establishing current efficiency factors has been displayed in Figure 3.1 below.

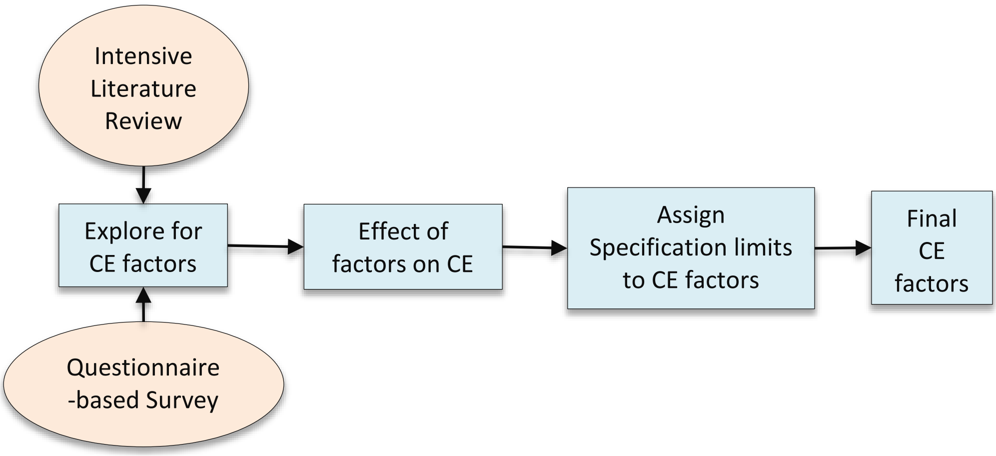


Figure 3.1: A strategy for establishing current efficiency factors (designed by the author)

3.4 Data collection

The factors influencing current efficiency were established from an intensive literature review and from the questionnaires that were filled in by current efficiency experts. Thereafter, depending on the current efficiency factors identified sample sizes and population sizes were developed. Most of the current efficiency factors are based on the chemical composition of the electrolyte at the electrowinning process. Therefore, the electrolyte samples of 250 ml each were collected and analyzed at the analytical laboratory.

This is the minimum solution volume that can be analyzed by the atomic absorption spectrometer (AAS) and there will still be sufficient solution volume left for re-analysis should it be required. For this research, the sample sizes and population sizes are 6516 samples (or 1629 L) and 185 000 L of electrolyte solution respectively during 6 months of the study. It should be noted that the sample population is the total electrolyte inventory for the advanced tank, spent electrolyte tank and circulating electrolyte tank were the electrolyte samples will be taken. Information regarding sampling is summarized in Table 3.1 below and the following calculations were used:

Population size = Advance tank volume + Spent tank volume + Circulating tank volume

= 73 000 L + 55 000 L + 57 000 L

= 185 000 L

Total sampling days = January days + February days + March days + April days + May days + June days

= 31 days + 28 days + 31 days + 30 days + 31 days + 30 days

= 181 days

Total number of samples = Total sampling days × Sampling frequency × Sampling points

= 181 days × 12 sample/days × 3

= 2172 samples × 3

= 6516 samples

Total sample volume = Advance electrolyte + Spent electrolyte + Circulating electrolyte

= 2172 samples×250 ml + 2172 samples×250 ml + 2172 samples×250 ml

= 543 000 ml + 543 000 ml + 543 000 ml

= 1629 000 ml

Table 3.1: Sample sizes and population sizes over 6 months (developed by the author)

Electrolyte Name	**Sampling days**	**Sampling frequency**	**Total samples**	**Sample volume**	**Total sample volume**	**Population Size**
Advance	181 days	Every 2 hours	2172	250 ml	543 000 ml	73 000 L
Spent	181 days	Every 2 hours	2172	250 ml	543 000 ml	55 000 L
Circulating	181 days	Every 2 hours	2172	250 ml	543 000 ml	57 000 L
Total	**181 days**	**Every 2 hours**	**6516**	**750 ml**	**1629 000 ml**	**185 000 L**

In addition to data collected from the collected samples for chemical analysis. Instruments automatically measure and record process variables such as current, voltage, temperature, tank levels, etc and the data is stored in the historian server. These data will also be retrieved for daily monitoring and control purposes for the 6 months during the study. The data sources are the cathode mass calculator, historian or Supervisory Control and Data Acquisition (SCADA) database, Laboratory Information Management System (LIMS) database and also from the daily KPI report.

3.5 Data analysis

Statistical Process Control (SPC) techniques such as control charts were applied to analyze current efficiency factors. Some of the control chart types that will be used are the I–MR chart, Xbar-R chart, Xbar- S chart, P chart, and the U chart. The type of control chart constructed depends on the data type and also on the number of subgroups.

The data were first tested to see if it follows a normal distribution or not. The non-normal data was transformed by using Johnson transform and/or Box-Cox transform so that it follows a normal distribution. This was done after doing an Anderson Darlington normality test by using Minitab17. Hence, the appropriate control chart was contrasted and analyzed by checking if the variable is conforming to the specification limit set-point. This was done by monitoring if the actual values are within the average/centreline, Lower Control Limit (LCL) and Upper Control Limit (UCL).

Should none conformance to specification set-point be observed, a Root Cause Analysis (RCA) is executed. This analysis was done carefully after making sure all the data follows a normal distribution. If not, the data was transformed by using Johnson or Box-Cox transformation. Otherwise, conclusions will be misleading. The results of the surveys determine if the operations and technical team have a concrete understanding of the current efficiency factors. The data was also used to rank the factors according to their influence on current efficiency. An out of control action plan (OCAP) was also established to address the issues that were identified. All the steps which are necessary for current efficiency improvement by using continuous quality improvement were then included in the continuous quality improvement framework for current efficiency.

3.6 Data analysis tools

The main data analysis tool used for this research is a statistical software package called Minitab. The version of the software used was Minitab 17. The data analysis software was fused for conducting the Anderson Darlington normality test, for transforming non-normal data by making use of Johnson transformation and Box-Cox transformation, for creating control charts and also for process capability analysis. The software gives a report for the points which are out of control based on the Shewhart rules after constructing a control chart.

The Anderson Darlington normality test in Minitab results in the calculation of the Anderson Darlington statistic. If it is less than 0.05 then the data does not follow a normal distribution and vice-versa. Johnson transformation transforms non-normal data by making use of the Johnson distribution system which then gives an equation that models the transformed data.

3.7 Research strategy

This research project was executed based on the research strategy depicted in Figure 3.2. For simplicity's sake, the current efficiency (CE) factors were established from an intensive literature review and also from the questionnaire-based survey. Thereafter, historical data for the identified CE factors were analyzed using Minitab statistical software package by testing for normality, transforming non-normal data, developing process control charts and analyzing process capability. Samples were collected over 6 months as indicated above.

From this analysis, the current efficiency best practice was established from the questionnaires and also the actual current efficiency improvement campaign completed in the electrowinning plant. The current efficiency improvement best practices were then embedded into daily operational activities by developing a standard operating procedure (SOP). It was decided to give current efficiency training to the employees also. However, there was no sufficient time to train everyone. All the above-mentioned aspects were then considered when designing the current efficiency continuous quality improvement framework. Finally, the continuous quality improvement framework was designed.

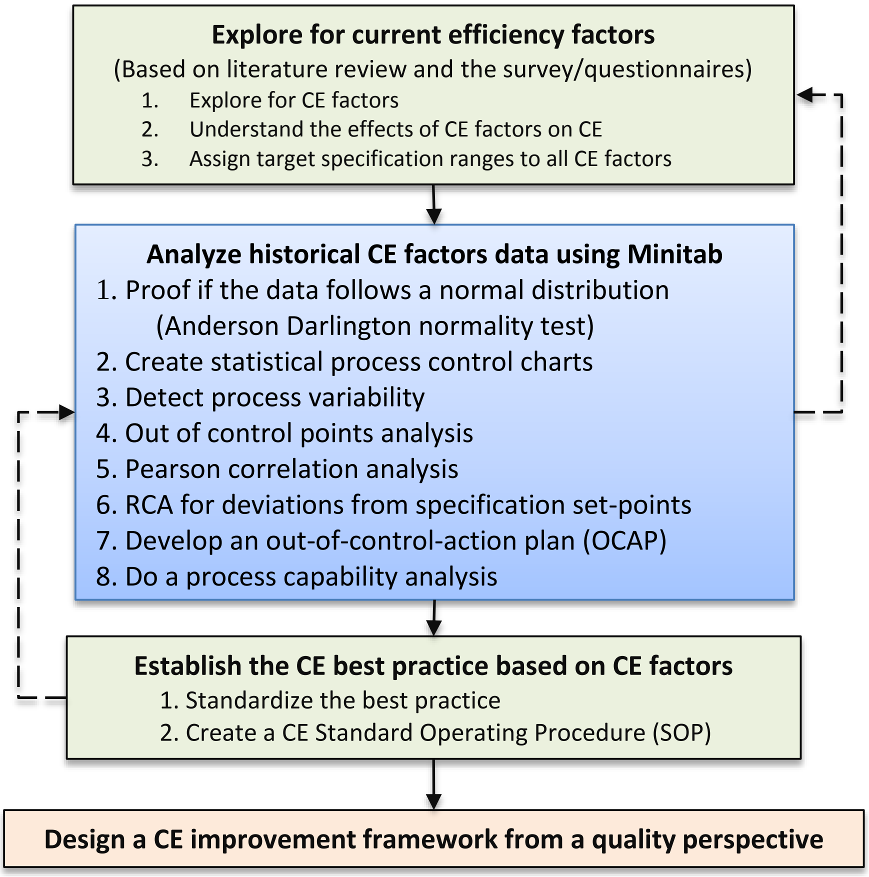


Figure 3.2: A summary of the research project strategy (designed by the author)

3.8 Summary

The research methodology chapter was first introduced. Thereafter, it commenced by explaining the research approach that was applied. This was followed by a discussion on the methodology for exploring current efficiency factors. Thereafter, the collection of data and subsequent analysis were discussed. A discussion on the data analysis tools used followed. Finally, the last discussion on the research methodology was the research strategy that is presented in Figure 3.2 above. The next chapter will focus on the results and discussions.

4. Results and discussions

Results and discussions chapter commenced by exploring the factors that influence current efficiency. This was done by conducting a questionnaire-based survey and also by doing an intensive literature review. On the one hand, all the factors explored from an intensive literature review were summarised by using a mind map. On the other hand, the questionnaire-based survey current efficiency factors were analyzed further by making use of the Pareto chart (applying the 80-20 rule). The objectives of this chapter are based on the research sub-objectives. They are as follow:

1. To explore factors that influence current efficiency.

2. To evaluate the factor that has the most significant effect on current efficiency by applying statistical process control.

3. To develop a continuous quality improvement framework for improving current efficiency factors by applying statistical process control.

It is worth noting that the raw data for this entire research project has been uploaded onto the Mendeley web site for easy access by anyone who is interested. The raw data can be accessed by following the link below:
https://data.mendeley.com/datasets/r3hf2n9tf9/draft?a=37999064-7ddb-4ad1-b89d-437b02dfd355

4.1. Exploring current efficiency factors

In this case, current efficiency factors were established from an intensive literature review and also from the questionnaire-based survey. The questionnaires were given to the technical and operational employees that work in the electrowinning process. The findings from the two methods were combined to conclude on the factors that have a significant effect on current efficiency. The current efficiency factors with a significant effect on current efficiency were analyzed further by using the actual electrowinning process data.

4.1.1 Exploring current efficiency factors from an intensive literature review

Current efficiency factors that have been established from an intensive literature review been summarized in Table 4.1 below. The current efficiency factors have been identified and then discussed in depth. This is essential so that one can understand how they affect current efficiency. It also assists with understanding the potential interaction between the current efficiency factors.

Table 4.1: Current efficiency factors established from an internsive literature review (developed by the author)

Current efficiency factors	Effect on electrowinning and on current efficiency	Ranges
1. Electrolyte temperature	It has been reported that high temperature increases current density, reduces electrolyte solution electrical resistance resulting in greater conductivity of ions in the electrolyte solution and improved rate of electrodeposition. It positively affects the quality of the cathodes produced, improves kinetics of the electrolysis process, high-temperature increases limiting current density, it can potentially result in reduced cell potential by approximately 0.09 V thereby contributing roughly 10 % reduction in energy consumption and it affects the efficiency of the electrochemical process by affecting the physicochemical properties of the electrolyte solution (Arman, Ersin, & Hac, 2016; Ntengwe, Mazana, & Samadi, 2010; Beukes & Badenhorst, 2009; Eduardo, Pablo, Guillermo, & Jorge, 2013). Moreover, temperature affects electrolyte speciation with the concentration of H$^+$ and Fe^{3+} decreases which decreases with high temperature because of the formation of complex species (Casas, Crisostomo, & Cifuentes, 2005). According to the reviewed literature high temperature reduces the viscosity of the electrolyte thereby facilitating the mass transfer and improving current efficiency. Elevated temperature increases the diffusion coefficient of ions in the electrolyte solution. If Fe^{3+} concentration is high in the electrolyte, increasing temperature increases the Fe^{3+} diffusion coefficient which then results in decreased current efficiency (Arman, Ersin, & Hac, 2016). The elevated temperature was also reported to play a role in maintaining fine-grained copper cathodes, which means the higher the temperature the higher the cathode quality. At increased temperatures, a more crystalline and compact cathode deposit is achieved (Robinson, n.d.; Das & Gopala, 1995). An increase in current efficiency by ∼2 % and a reduction in energy consumption by 10 % was reported after increasing the electrolyte temperature from 20 °C to 50 °C this was associated with high energy collisions due to high temperature. However, very high-temperature also results in increased surface roughness hence a balance between improvement in deposition rate, current efficiency, and energy consumption and the deposit surface quality needs to be maintained (Arman, Ersin, & Hac, 2016). Although the temperature has an effect on current efficiency, some studies reported that it was evident that it had little effect on current efficiency (Ntengwe, Mazana, & Samadi, 2010). The electrolyte temperature is normally controlled by making use of cooling towers and/or heat exchangers. Since heat is already generated within the cells, spent electrolyte temperature should maintain < 40 °C to prevent the degeneration or degradation of the organic. (Sandoval, Luzanga, & Tshifungat, 2015; Beukes & Badenhorst, 2009). Other researchers reported that a linear relationship exists between temperature and electrowinning cathode current efficiency. This was confirmed after increasing the bath temperature from 30°C, 35°C and 40°C which contributed to an increase in cathode current efficiency (CCE) from 96.1 %, 96.6 % and 97.4 % respectively	Copper EW is accomplished in a range of 25-65 °C (Arman, Ersin, & Hac, 2016); the condition for copper electroplating was found to be more encouraging at temperature values of > 24 °C and < 60 °C (Ntengwe, Mazana, & Samadi, 2010). Other researchers proposed that the optimum temperature of the electrolyte solution when using a heat exchanger ranges from 45 °C to 55 °C (Beukes & Badenhorst, 2009). On the other hand, to get pure fine-grained copper cathode deposits an operating electrolyte temperature of 45 °C to 50 °C was commended (Robinson, n.d.). Similarly, other studies recommended an operating temperature target of 45 °C because elevated temperatures of 50 °C cause a high chance of copper cathode nodulation. Unless nodule avoidance additives such as cathode

	(Tuaweri, Adigio, & Jombo, 2013). These findings were also confirmed by another research where the bath temperature was changed from 25 ℃ to 50 ℃ consequently resulting in an increase in electrowinning cathode current efficiency from 94.0 % to 97.7 % respectively and a rapid decrease in specific energy consumption from 2960 kW/t to 2700 kW/t was experienced at a temperature of 25 ℃ and 50 ℃ respectively. This is due to an increase in cathode current efficiency was a result of a decrease in cell voltage (from 3.39 V to 3.21 V at 25 ℃ and 45 ℃ respectively) after the bath temperature was increased. The rate constants of both cathodic reactions increases at elevated temperature. Hence, a low driving force is required (Scott, Pitblado, Barton, & Ault, 1988).	smoothing agents are used (Scott, Pitblado, Barton, & Ault, 1988).
2. Iron concentration	According to the reviewed literature, iron is leached simultaneously with copper and then it builds-up in the electrowinning closed circuit. Current efficiency is intensely influenced by additional side reactions that occur in the cells. The presence of iron in the electrolyte solution results in the cyclic oxidation of Fe^{2+} to Fe^{3+} and the reduction of Fe^{3+} to Fe^{2+}. These cyclic reactions reduce cathode current efficiency significantly and it results in poor electrowinning cathode quality production (Beukes & Badenhorst, 2009; Robinson, n.d.; McLean, 1996; Parada & Asselin, 2009; Das & Gopala, 1995). In addition to that, impurities that get continually reduced at the cathode and also oxidized at the anode can decrease cathode current efficiency. This is the outcome of the soluble redox couple such as Fe^{3+}/Fe^{2+} (Peter, 2017). Similarly, it was reported that elevated iron concentration in the electrolyte solution decreases cathode current efficiency and also increases energy consumption (De Freitas, et al., 2010; Joshua, 2017). Therefore, cathode current efficiency may be increased by elevating the iron boundary thickness and by decreasing the iron concentration in the electrolyte solution (Joseph, 2017). A number of approaches for reducing or removing iron from the electrolyte solution have been established. They include methods such as electrolyte solution precipitation, prior reduction of iron (III) by SO_2 or copper metal, elevating the electrolyte bleed stream volumetric flow rate and using the diaphragm cell (Beukes & Badenhorst, 2009). Even though high iron concentration results in reduced cathode current efficiency, decreased electrolyte solution iron concentration is essential for copper cathode quality and for controlling the oxidation of impurity elements such as manganese. The effect of increased electrolyte iron concentration on cathode current efficiency may be mitigated by introducing a separator into the electrolytic cell, thereby preventing the cycling oxidation of electrolyte iron from Fe^{2+} to Fe^{3+} at the anode and also the reduction of electrolyte iron from Fe^{3+} to Fe^{2+} (Peter, 2017). Some studies have reported that current efficiency decreases by as high as 7 % due to an increase in the electrolyte iron concentration from 1 g/l to 2.5 g/l (Ozdag, Bozkurt, Ipek, & Bilir, 2012). Other studies concluded that cathode current efficiency decreases with 2.5 % for each 1 g/l increase in electrolyte solution ferric tenor (Khouraibchia & Moats, 2016). Another study showed that beyond a ferric iron (Fe^{3+}) concentration of 1.0 g/l, current efficiency commences decreasing drastically. The electrowinning current efficiency of about 90 % may be attained if the ferric to the ferrous ratio (Fe^{3+}/Fe^{2+} ratio) is sustained roughly at ≤ 1.0 (Das & Gopala, 1995).	For copper electrowinning maintaining an electrolyte solution iron at a maximum concentration of ~1 g/l can consequently result in cathode current efficiency ranging from 88 % to 92 % (Joseph, 2017).
3. Cathode center to center spacing	It was observed that the electrode alignment (rat patrol) has an impact on the design current density. Therefore, if the electrodes are not well spaced or aligned the high chance (risk probability) of the formation of metallurgical short-circuits (hotspots) due to nodular growths or protrusions is increased. Metallurgical short-circuits (hotspots) causes' high current to be consumed for heating instead of using it for electroplating copper cathodes (Beukes & Badenhorst, 2009).	Electrode alignment is normally a routine task that is executed on a daily basis.

4. Current density	It has been reported that an increase in current density resulted in an increase in the deposition/plating rate but it has a minor effect on current efficiency depending on the other factors that affect current efficiency such as bath temperature (Ntengwe, Mazana, & Samadi, 2010). Nonetheless, under normal circumstances, copper electrowinning current density normally ranges from 200 A/m^2 to 375 A/m^2. Researchers highlighted that elevated current density translates into the production of cathodes with a high-quality morphology/surface feature especially when multimedia coalescing filters are utilized effectively (Beukes & Badenhorst, 2009). It has been noted that, if the current density is too high, it may cause the formation of poor quality cathodes which are rough, nodular cathode deposits and also poor copper purity which makes the product unfavorable for some customers depending on the application. Therefore, the operating current density should be chosen by balancing all these effects (Robinson, n.d.).	When SX and multimedia filters are part of the operation process engineers are comfortable operating in the current density region of 250 A/m^2 to 300 A/m^2. Conventional electrolytic cells have a maximum current density ranging from 350 A/m^2 to 400 A/m^2 (Beukes & Badenhorst, 2009). Other researchers reported an operating copper current density range of 280 A/m^2 to 340 A/m^2 (Robinson, n.d.). At the copper refinery under consideration, the nominal and maximum current densities are 325 A/m^2 and 350 A/m^2 respectively. Other authors claim that the current density range for the production of compact structure copper cathodes ranges from as low as 270 A/m^2 to as high as 350 A/m^2 (Joseph, 2017).
5. Cell potential/voltage	Studies report that the electrolytic cell potential depends on the electrolysis half-cell reaction potentials, losses through the busbars, electrolyte and the competing side-reactions due to the presence of impurities in the electrolyte. The cell potential is usually lower for the purer leach-SX-EW processes unlike for direct electrowinning operations. The cathode current efficiency for direct electrowinning processes is normally as low as 65 % while for leach-SX-EW operations can be as high as 93 % on average. It should however, be noted that the cell potential and current efficiency depend on the electrolyte solution iron concentration, how good	The cell potential normally ranges from 1.9 V to 2.3 V (Beukes & Badenhorst, 2009). At the copper refinery under review, the nominal

	the electrical contact is between the electrode hanger bars and the triangular busbars and many other factors. This is because there is an interaction between the factors (Beukes & Badenhorst, 2009).	and maximum cell voltage is 2.2 V and 2.3 V respectively.
6. Busbar design and condition	Researchers claim that the busbar design and condition has an effect on cathode current efficiency. This is because it affects heat losses and cathode current density through it. In industry, electrowinning operations are usually conservative since they prefer not to operate $\leq$ 1.0 A/m^2. On the other hand, the busbar design companies design busbars at a current density of 1.2 A/m^2. It is therefore crucial for the parallel busbars to have a gap between them that allows for heat reduction by air cooling. This is achieved by the Ruashi busbar designs that are dimensioned as follows: 450 mm × 20 mm with an air gap of 20 mm between them (Beukes & Badenhorst, 2009).	The busbar installed is normally permanently installed, they are usually sprayed with water to keep the dirt off.
7. Equipotential intercell busbar design and condition	According to literature, the equipotential intercell busbar design and condition affect current efficiency similar to the main equipotential intercell busbar as described above. In industry, there are two main designs of the equipotential intercell busbars, namely the conventional dog-bone type of design and the triangular equipotential intercell busbars. The conventional dog-bone equipotential intercell busbars are more expensive than the cheap and more viable triangular equipotential intercell busbars. The triangular equipotential intercell busbars do not need a larger amount of copper contact metal because of their triangular shape and they make good conduct between the cathode and anode hanger bars compared to the conventional dog-bone type equipotential intercell busbar designs. The good contacts result in upgraded cathode current efficiency for the triangular equipotential intercell busbars (Beukes & Badenhorst, 2009).	Triangular equipotential intercell bars are used at the copper refinery where the study was done.
8. Electrode features	Currently, the most employed anode types are referred to as cold-rolled lead anodes that result in superior dimensional stability. The anode life expectancy usually ranges from 7 to 9 years or for 5+ years depending on the operating conditions. The composition of the anodes also play a major role, a fraction of calcium (0.05 % to 0.08 %) and tin (1.2 % to 1.5 %) is normally added when manufacturing lead anodes alloys. All these factors give a substantial contribution to the performance of the anodes and hence to current efficiency indirectly (Beukes & Badenhorst, 2009; Robinson, n.d.). The electrowinning anodes are usually cold-rolled Pb-Sn-Ca alloys that contain roughly around 98.4 % Pb (oxygen scavenged before alloying), 1.5 % Sn and 0.1 % Ca. The function of calcium and cold rolling is to add strength to the anode. While tin is added to offer corrosion resistance and corrosion layer conductivity. These alloy forms an adherent corrosion layer that inhibits lead contamination and prolongs the anode life expectancy. The electrolytic cells should be cleaned regularly for the removal of anode sludge found at the bottom of the cells. The cold-rolled anodes are normally having the following dimensions: 1.1 m (long) × 0.9 m (wide) × 0.006 m (thick). Most copper electrowinning operations utilize the re-usable 316L stainless steel blank cathodes and they have the following dimensions: 1.2 m (long) × 1.0 m (wide) × 0.003 m (thick) (Robinson, n.d.). To ensure good cathode quality, the cathodes are normally washed in the heated dip tanks and/or they pass through a heat water spray system or chamber (Beukes & Badenhorst, 2009; Robinson, n.d.).	The copper refinery studied is employing cold-rolled Pb-Sn-Ca-Al anodes which are composed of 0.05 % - 0.1 % Ca, 1.25 % - 1.75 % Sn, 0.005 % - 0.02 % Al and the balance is Pb. The cathodes have an active surface area of 1.1 m^2. The surface area plays a role when it comes to current density which affects current efficiency. There are 49 anodes and 48 cathodes per cell.

9. Electrode furniture	The anodes are normally having either three or five anode buttons or insulators (also referred to as polymer spacer knobs) that inhibits the development of metallurgical short-circuits if the anode and a cathode get into contact. The anode buttons are usually located at the bottom and top corners of the anodes. The fifth anode button or insulator is usually positioned at the center of the anode. On the other hand, the cathode insulator is normally located on the edges of the stainless steel cathodes as side strips that ensure that the sides/edges of the cathodes do not get intergrown. There are different types of edge/side strips on the stainless steel cathodes available in the industry for example operations in Zambia and other electrowinning operations employ the Rehau ‘cross-slot’ configuration of edge strips. They should be designed to end well above the liquid level because the electrolyte between the side strip and the cathode will result in the metal plating between them and hence damaging the edge strips (Beukes & Badenhorst, 2009).	The anodes should always have five insulators and the cathodes should have side strips.
10. Reagent addition	A number of reagents are added into the electrolytic cells for different reasons. There is a lot of commercially viable cathode smoothing agents such as glues, guars and synthetic products. Normally the cathode smoothing agent test work is carried out at research facilities such as Mintek to determine the effect of the cathode smoothing agent on current efficiency and also on the quality of the cathode surface or morphology (Beukes & Badenhorst, 2009). Most zinc electrolytic processes control acid mist using liquorice which has an effect on current efficiency. However, for copper electrowinning hollow polyethylene balls are utilized and they have no effect on current efficiency (Robinson, n.d.). Salt is added to the copper electrowinning cells because of low chloride concentration in the electrolyte solution ranging from 20 ppm to 25 ppm result in the formation of high-quality cathodes by affecting crystal growth and discoloration of copper cathodes. Other electrowinning operations add HCl for the same reason (Beukes & Badenhorst, 2009; Robinson, n.d.). Cobalt sulfate is added into the electrolyte to promote O_2 evolution at the anode rather than Pb oxidation thereby decreasing Pb contamination, extending anode life, improving current efficiency and also the cathode quality (Robinson, n.d.).	The addition of the cathode smoothing agent usually ranges from 150 g to 400 g of the cathode smoothing agent per ton of copper produced. The chloride concentration in the electrolyte should be kept below 30 ppm in order to prevent stainless steel Cl_2 induced pitting corrosion that causes cathodes to become sticky (Beukes & Badenhorst, 2009; Robinson, n.d.). Electrolyte Co^{2+} concentration is usually controlled at approximately 150 ppm. However, at the copper refinery under review, it is maintained at 130 ppm (Robinson, n.d.).
11. Electrolyte filtration	In order to reduce the need to clean cells, Scheibler filters are employed on the circulating electrolyte. The filter normally reduces Total Suspended Solids (TSS) and Organic Entrainment (OE) before they go to the electrowinning cells. If the electrolyte is not filtered it will result in suspected solids getting occluded into the cathodes and also impurities transferred with the organic. Hence affecting cathode current efficiency and cathode quality simultaneously (Beukes & Badenhorst, 2009; Robinson, n.d.). Normally, filtration is done by making use of activated carbon and sand/garnet.	Most electrowinning processes that make use of Multi-Media Filters (MMF) reduces Total Suspended Solids (TSS) from 50 ppm to 5 ppm, and the

		Organic Entrainment (OE) is reduced from 50 ppm to 2ppm.
12. Incubation periods	From the reviewed literature, the incubation period and/or harvest cycle depends on the operating current density, cathode active surface area, and current efficiency. A copper cathode thickness target of ~ 5 mm and cathode weight ranging from 40kg to 60kg makes the stripping machine to perform well (Joseph, 2017).	The incubation period depends on the size of the electrowinning plant. Unlike for zinc electrowinning were the incubation period is 48 hours, copper electrowinning requires almost 7 days of plating (Joseph, 2017). At the electrowinning process studied the incubation period is 6 days.
13. Electrolyte copper concentration	Current efficiency was reported to rise with an increase in the electrolyte copper concentration. This effect was experienced until the electrolyte copper concentration of 42 g/l. In addition to that, current efficiency may increase to ≥ 95 % if the copper concentration ranges from 35 g/l to 45 g/l when the ferric concentration is maintained < 1 g/l and 320 A/m^2 current density. In this study, the researcher noted the interactions that exist between ferric and copper and also between ferric and current density that has an effect on current efficiency (Khouraibchia & Moats, 2016).	The electrolyte copper concentration should be maintained at 37 ± 2 g/l. However, it is sometimes reduced to 35 ± 2 g/l especially at the end of the month when chasing after production target.
13. Others	Other factors that affect current efficiency including but not limited to the calculation method, crane operation, crane/scale calibration, electrolyte sulfate balance, overpotential, rectifier efficiency, and measurement.	These factors vary depending on the electrolytic process design and the control instrument in place.

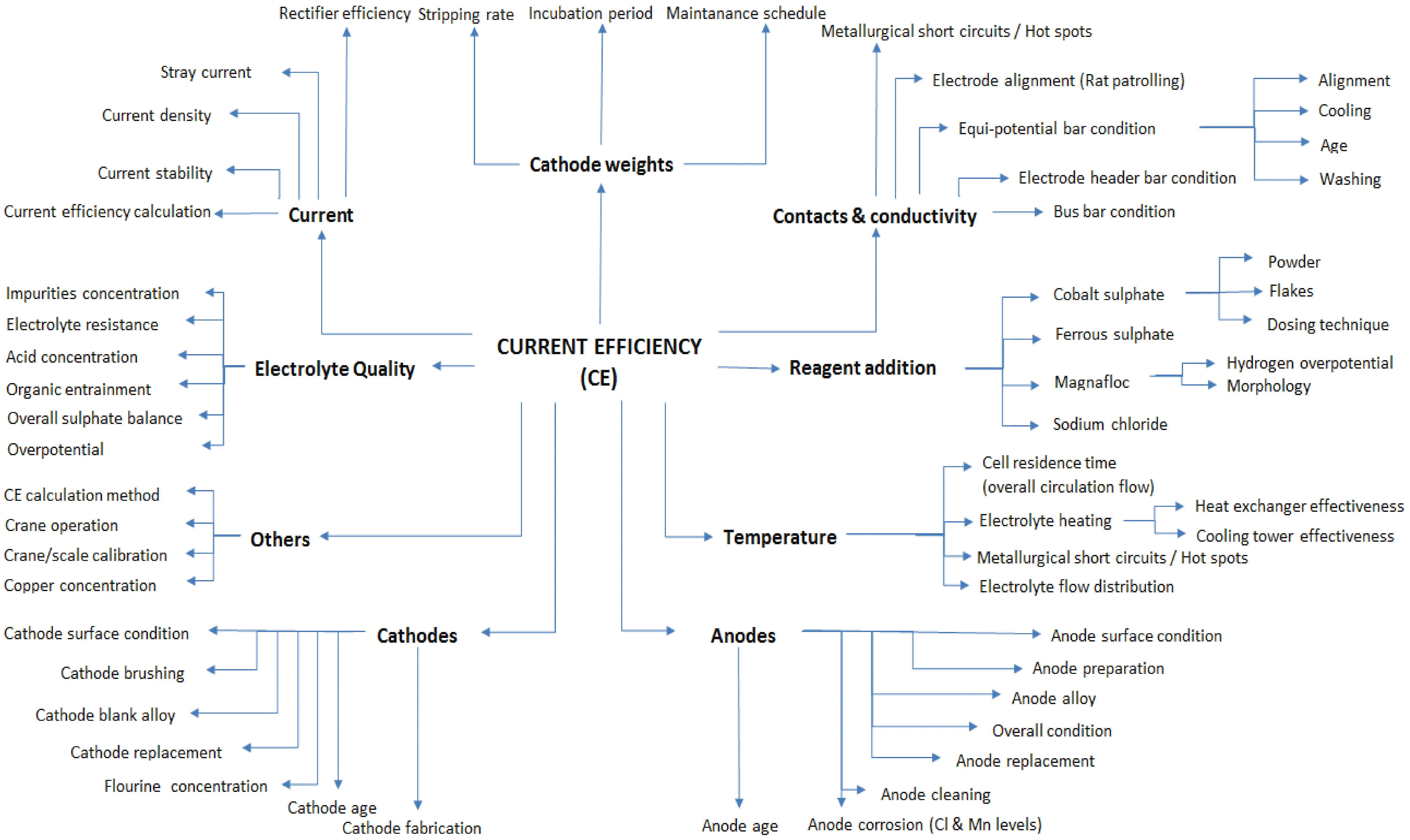


Figure 4.1: A mind map of current efficiency factors (designed by the author)

4.1.2 Discussing a mind map of current efficiency factors

Current efficiency factors were explored and they are summarised on a mind map shown in Figure 4.1. The major factors are electrolyte quality, temperature, electrodes (cathodes and anodes), cathode weight, current, reagent addition, contacts, conductivity, and others. Due to the complexity of the actual industrial electrowinning process, the factors have interactions amongst each other that result in a decrease or increase in CE. The factors can be categorized into chemical and physical factors. It should be noted that it is almost impossible to rank the CE factors. This is because any of the factors can have the biggest influence depending on the conditions of that specific electrolysis process. The next section will summarize the current efficiency factors and best improvement practice that was obtained from the questionnaires. The questionnaires were part of the qualitative research aimed at obtaining information from the operations and technical people who are familiar with the electrowinning process.

4.1.3 Exploring current efficiency factors from questionnaires

Qualitative research approach results from the questionnaires focusing on exploring current efficiency factors and current efficiency improvement best practices. The raw data obtained from questionnaires are shown in Table 8.1 and Table 8.2 in appendix A.

4.1.3.1 Exploring current efficiency factors from a qualitative approach

The top five most frequently suggested current efficiency factors from the questionnaires are metallurgical short-circuits (hotspots), electrolyte impurities example iron, electrode condition (including replacement), electrode alignment (rat patrol) and the condition of the contacts (see Table 4.2 below). A lot of other current efficiency factors were suggested. Factors that are similar were put under the same title and the rest of the factors which were only suggested once have been put under the title others. The frequency of the suggestions was added up to form a cumulative number of suggestions and these were then converted into a cumulative percentage. The data was used to construct a Pareto chart in order to show 20 % of the factors that have a significant influence on current efficiency (based on the 80-20 rule) as shown in Figure 4.2 below.

Table 4.2: Current efficiency factors established from the questionnaires (compiled by the author)

CE factors suggested	Frequency of suggestion	Cumulative Suggestion	Cumulative Percent
Hotspots	48	48	19.7 %
Impurities	31	79	32.4 %
Electrode condition	27	106	43.4 %
Rat patrol	26	132	54.1 %
Contacts	26	158	64.8 %
Temperature	17	175	71.7 %
Reagent addition	14	189	77.5 %
Acid content	10	199	81.6 %
Current density	7	206	84.4 %
Rectifier current	7	213	87.3 %
Rectifier efficiency	7	220	90.2 %
Electrode insulators	6	226	92.6 %
Nodules	6	232	95.1 %
Electrolyte conductivity	4	236	96.7 %
Copper tenor	4	240	98.4 %
Flowrate	3	243	99.6 %
Others	1	244	100.0 %

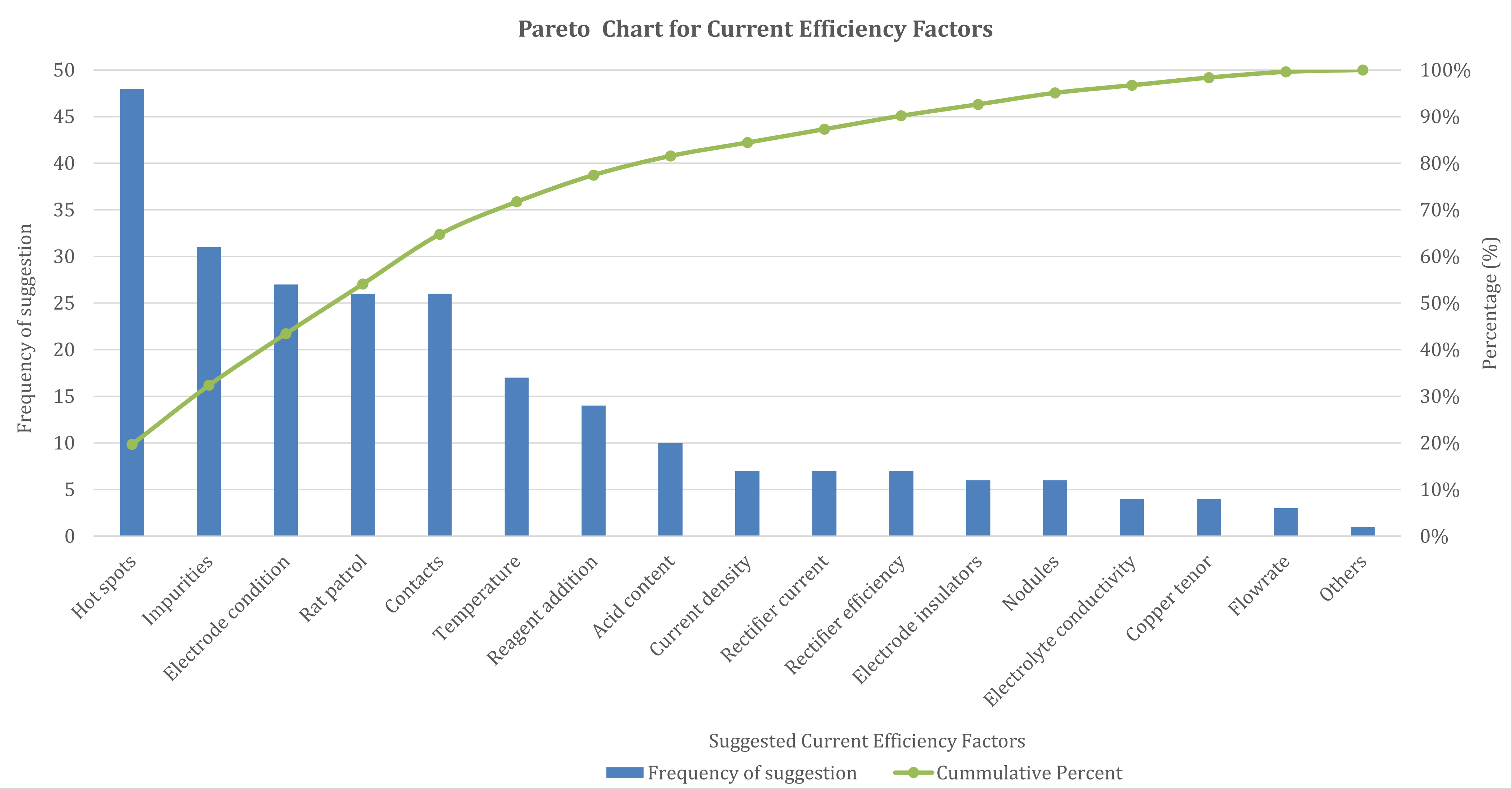


Figure 4.2: Pareto chart for current efficiency factors from the questionnaires (created by the author)

Discussion of the current efficiency factors Pareto chart

Based on the Pareto principle, in this case, the 80-20 rule can be explained by considering the fact that 80 % of the effects on current efficiency are due to 20 % of the factors. From the Pareto chart in Figure 4.2 above, it can be seen that 20 % of the CE factors that contribute 80 % effect on current efficiency are metallurgical short-circuits (hotspots), electrolyte impurities, electrode condition, electrode alignment (rat patrol), contacts condition, electrolyte temperature, reagent addition, and the electrolyte acid concentration. The 80-20 rule is very crucial for downsizing the number of CE factors. Thereby making it easier to apply statistical process control.

By understanding how these factors affect CE, it is possible to improve it. It is worth noting that the factors with the most significant effects also depend on the type of electrolysis process, for example, copper, zinc, and cobalt electrowinning operations. It also depends on the designs and types of equipment/instruments put in place. Therefore, it best to investigate a few extra other factors in addition to 20 % of the factors mentioned above. This is just to make sure if there are special causes of process variability they will be picked up and addressed accordingly.

4.1.3.2 Exploring current efficiency improvement best practice from a qualitative approach

Table 4.3 below shows a summary of CE improvement best practices obtained from the questionnaires. Suggested best practices which are similar were put under the same title. The raw data for the best practices can be found in appendix A in Table 8.2. The best practice suggestions were not expected to be addressing every single factor. This is because some of the factors are either too expensive to resolve or the plant design cannot be changed or their contribution is not significant.

From the questionnaires, the top five most frequent best practices are metallurgical short-circuit (hotspot) identification and rectification, CE training, enforcing CE procedure, electrolyte impurity control and electrode alignment (rat patrol). These factors are the most frequently suggested CE improvement best practices. The cumulative best practice suggestion and cumulative percentage were also computed. This enabled the construction of a Pareto chart shown below.

Table 4.3: Current efficiency improvement best practice obtained from questionnaires (compiled by the author)

Best practice	Frequency of best practice suggestion	Cumulative best practice suggestions	Cumulative percent
Hotspot rectification	48	48	16 %
CE training	45	93	31 %
Enforce CE procedure	43	136	46 %
Impurity control	29	165	56 %
Regular rat patrol	26	191	65 %
Regular electrode maintenance	26	217	73 %
Regular contacts cleaning	20	237	80 %
Reagent addition control	16	253	85 %
Regular cell maintenance	10	263	89 %
Regular temperature control	8	271	92 %
Replace missing insulators	7	278	94 %
Acid tenor control	6	284	96 %
Control current density	4	288	97 %
Heat exchanger control	3	291	98 %
Review CE calculations	2	293	99 %
Control copper tenor	2	295	100 %
Others	1	296	100 %

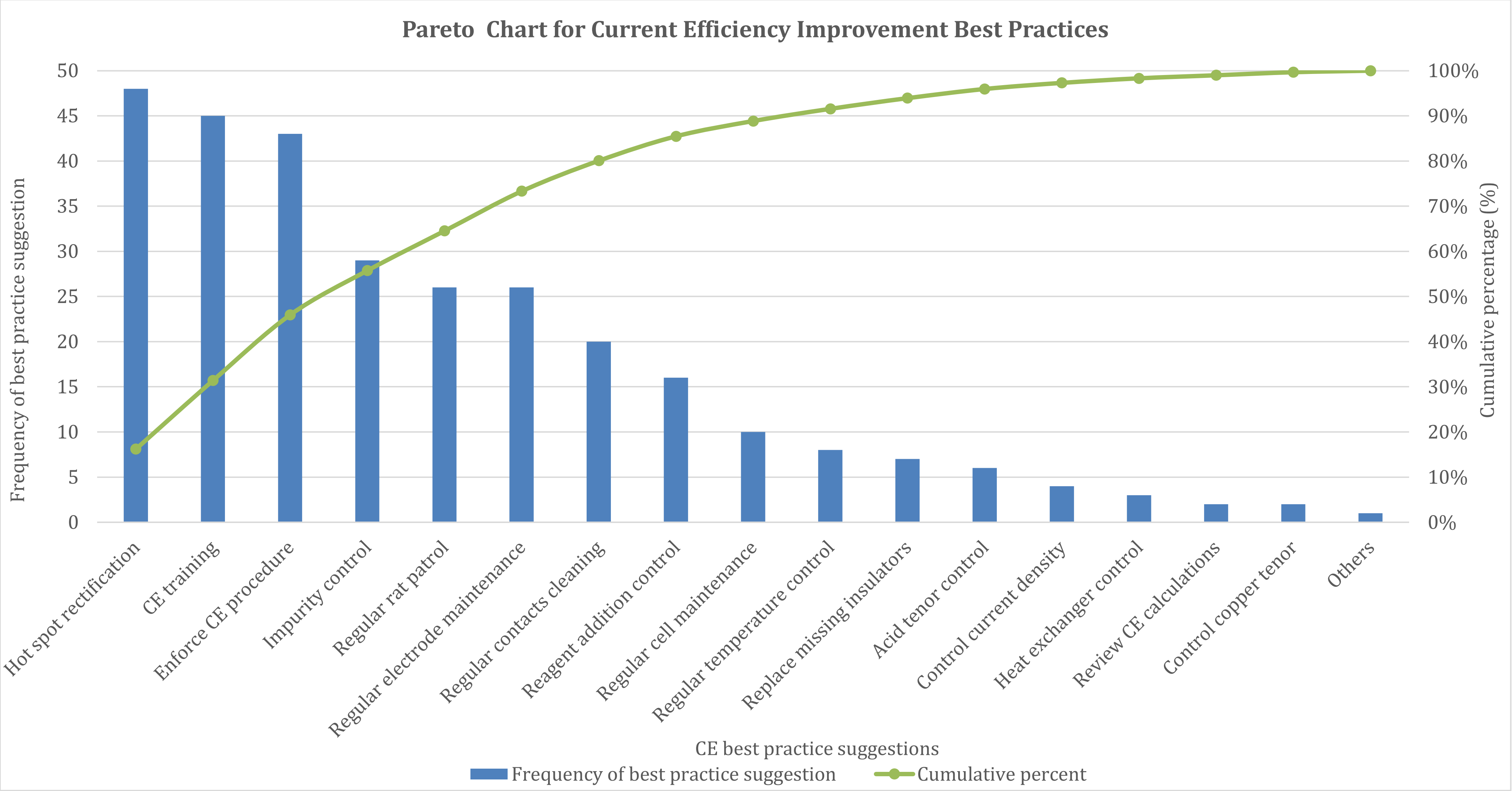


Figure 4.3: Pareto chart for current efficiency best practices obtained from the questionnaires (made by the author)

Discussing CE improvement best practices from a Pareto chart

A Pareto chart for current efficiency improvement best practice is displayed in Figure 4.3 above. By making use of the 80-20 rule it is possible to deduce the best practices that will have the most significant effect on improving current efficiency. The best practices that have a significant effect on current efficiency improvement are metallurgical short-circuits (hotspots) identification and rectification, current efficiency training, enforcing a current efficiency improvement procedure, electrolyte impurity monitoring and control, regular electrode alignment (rat patrol), regular electrode maintenance which includes electrode replacement, anode cleaning and straightening bend electrodes and the last best practice falling within 20 % range is regular electrode contacts cleaning.

Implementing all these 7 best practices effectively may potentially result in improved current efficiency. The improvement might also depend on the special cause of a decrease in current efficiency and on that specific electrowinning operational and design issues. Although the qualitative findings show the above mentioned current efficiency factors and improvement best practices, it is best to study many other factors as mentioned above. Just to make sure statistical process control is applied and it has proven which factors have the most significant effect. This will be first executed, by testing if the data follows a normal distribution.

4.2 Current efficiency continuous factors normal distribution test

As discussed in the literature review chapter, the data for which statistical process control need to be applied must follow a normal distribution. It should be noted that not all factor data follows the normal distribution because of process variability and/or special causes. Therefore, a normality test was first done and if the data does not follow a normal distribution it is transformed by either using Johnson transform and/or Box-Cox transform. The figures below display Minitab output for current efficiency. From both figures, it can be seen that the P-value is <0.005 which is <0.05. Therefore, current efficiency data does not follow the normal distribution. The historical data used was collected as from 1st January 2019 06:00 am to 1st July 2019 06:00 am.

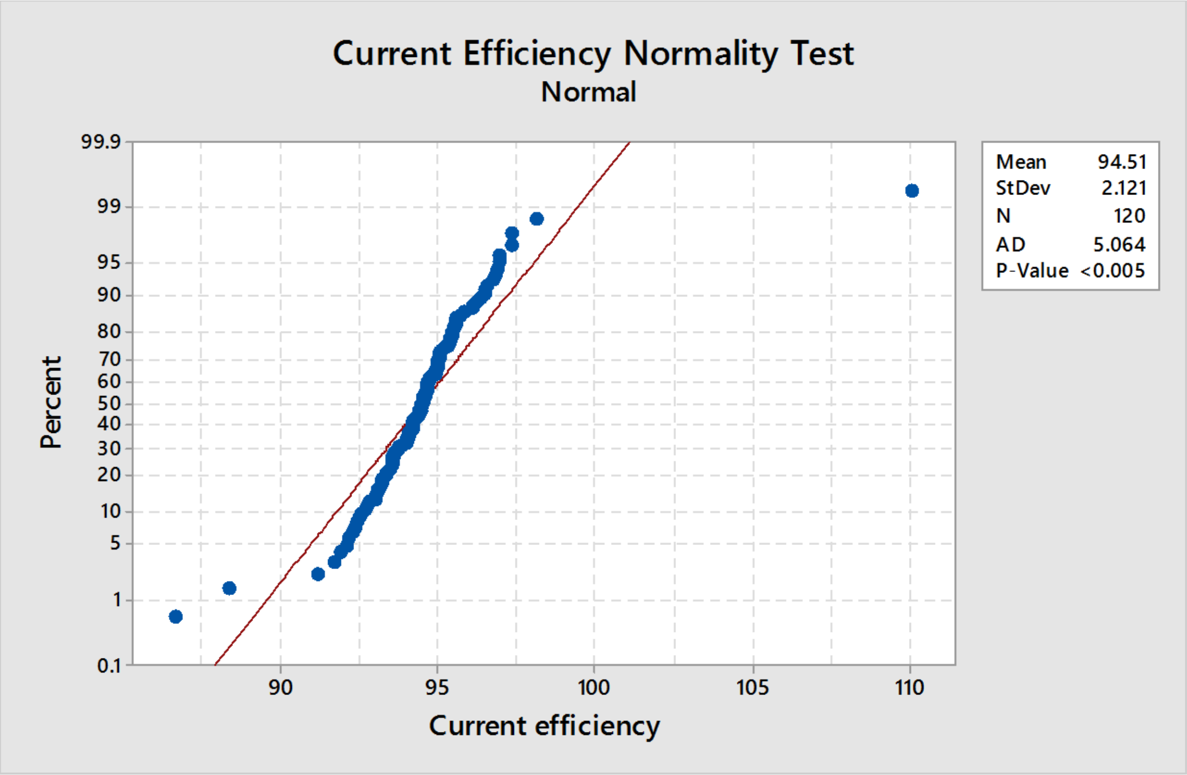


Figure 4.4: Normality test output for CE before transforming data (created by the author)

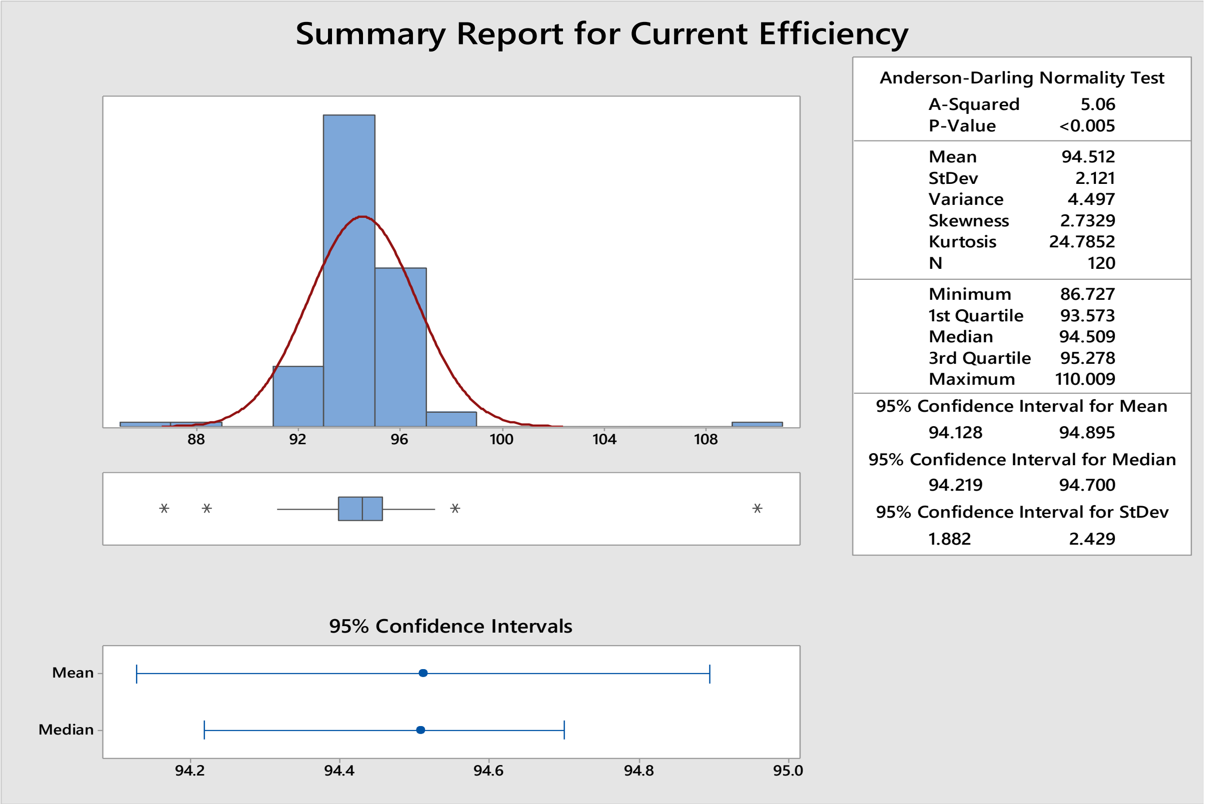


Figure 4.5: Graphical summary output for CE before transforming data (created by the author)

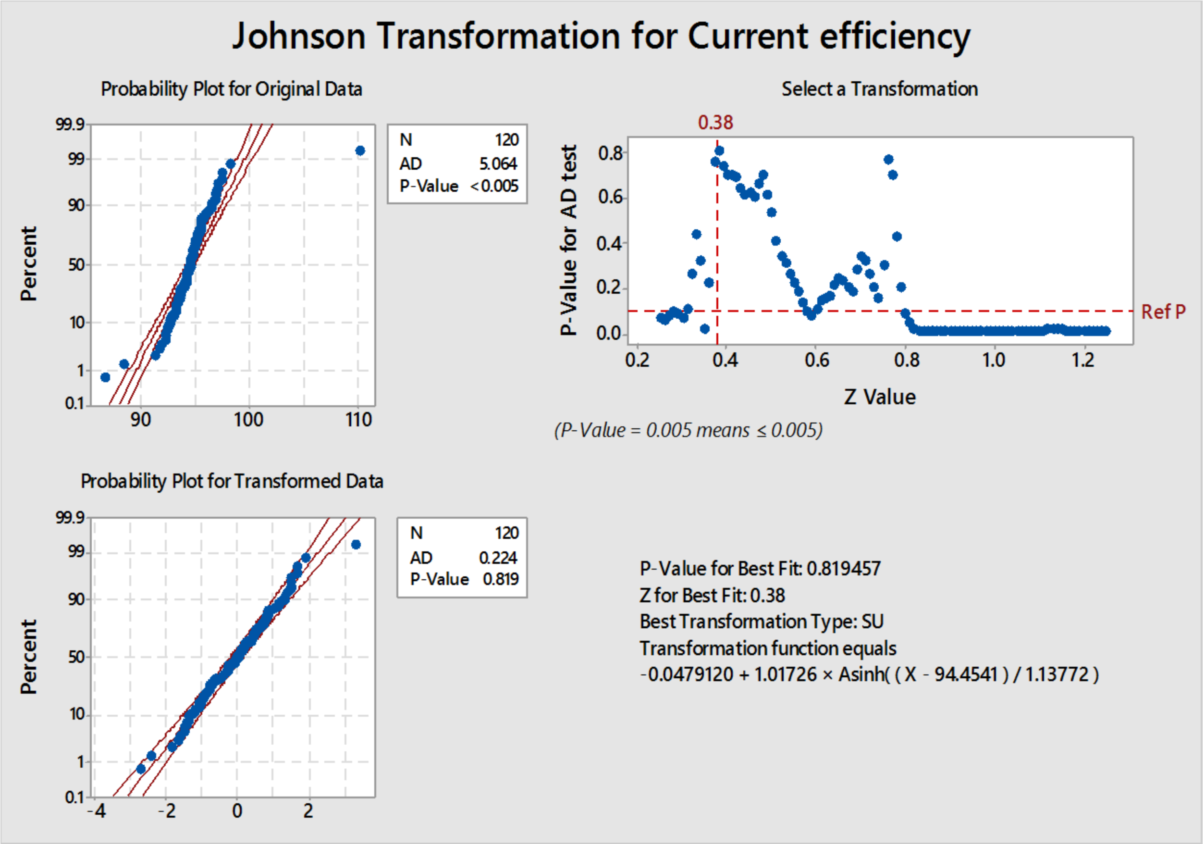


Figure 4.6: Johnson transformation output for transforming CE data (created by the author)

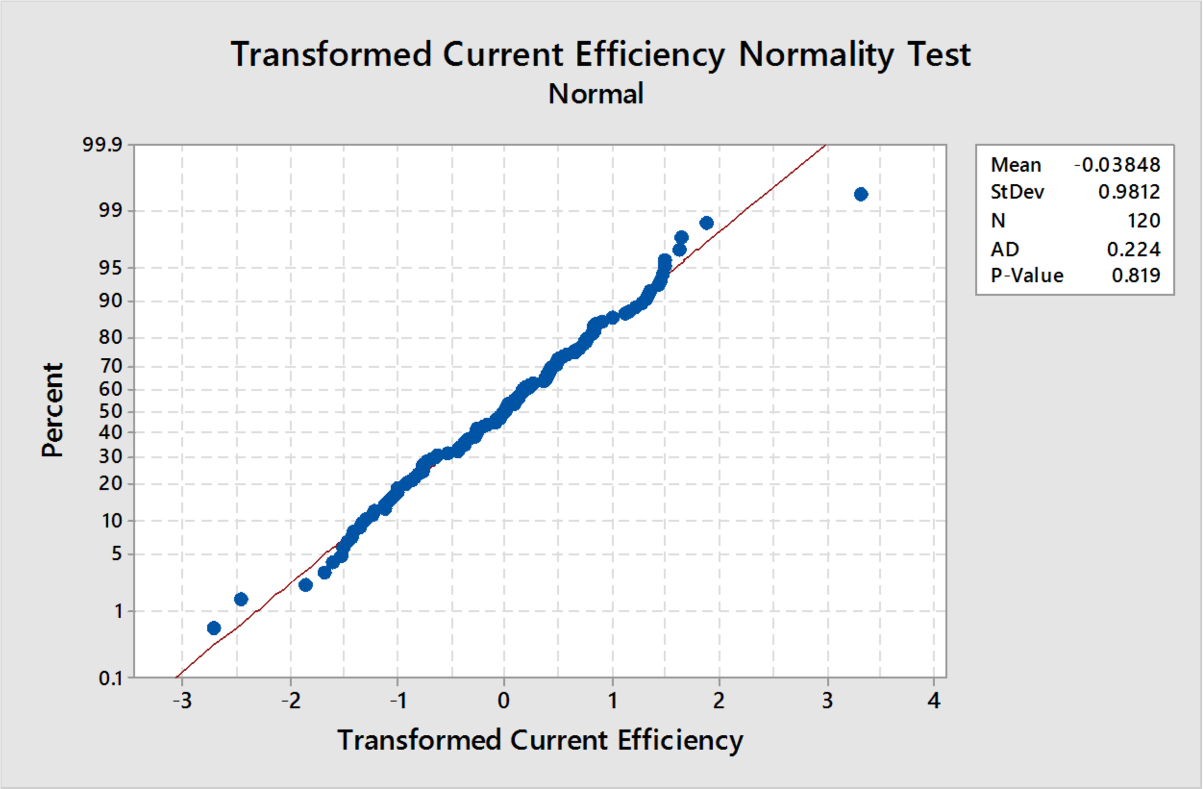


Figure 4.7: Normality test output for CE transformed data(created by the author)

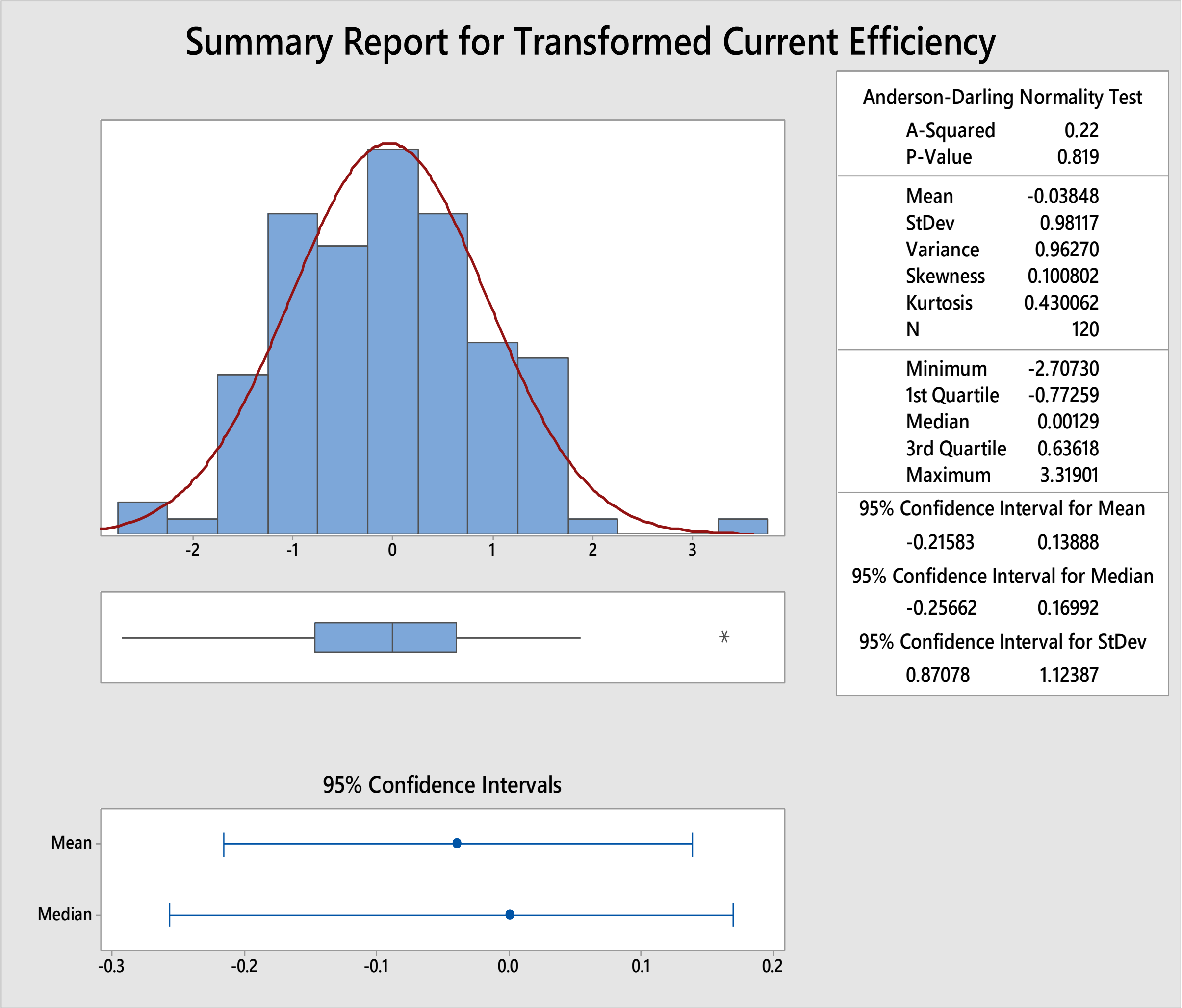


Figure 4.8: Graphical summary output for CE transformed data (created by the author)

The above analysis was applied to all the current efficiency factors. The results of the normality test are depicted below. Appendix B depicts the Anderson Darlington normality test results for all the factors (see Figure 8.1). The transformed data for the non-normal factors done by using Johnson and Box-Cox transformation is shown in Appendix C (see Figure 8.2) and the statistical summary of current efficiency factors is displayed in Appendix E (see Figure 8.4). It should be noted that the data only follows the normal distribution if the p-value is greater than 0.05. The decision is made with respect to the following hypothesis:

A null hypothesis (H_O): p-value >0.05 – the data follows a normal distribution.

An alternative hypothesis (H_a): p-value <0.05 – the data does not follow a normal distribution.

Table 4.4: Current efficiency factors normal distribution hypothesis testing results (compiled by the author)

Factor	P-value	Hypothesis decision	Transformation Used
1. PCF_Cu concentration (g/l)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
2. SEX_Cu concentration (g/l)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
3. CCF_Cu concentration (g/l)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
4. PCF_H_2SO_4 concentration (g/l)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
5. SEX_H_2SO_4 concentration (g/l)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
6. CCF_H_2SO_4 concentration (g/l)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
7. PCF_Total Fe concentration (ppm)	<0.005	Reject null hypothesis (Not normally distributed)	Box-Cox Transformation
8. SEX_Total Fe concentration (ppm)	<0.005	Reject null hypothesis (Not normally distributed)	Box-Cox Transformation
9. CCF_Total Fe concentration (ppm)	<0.005	Reject null hypothesis (Not normally distributed)	Box-Cox Transformation
10. PCF_Co concentration (ppm)	<0.005	Reject null hypothesis (Not normally distributed)	Box-Cox Transformation
11. SEX_Co concentration (ppm)	<0.005	Reject null hypothesis (Not normally distributed)	Box-Cox Transformation
12. CCF_Co concentration (ppm)	<0.005	Reject null hypothesis (Not normally distributed)	Box-Cox Transformation
13. PCF_Cl concentration (ppm)	<0.005	Reject null hypothesis (Not normally distributed)	Box-Cox Transformation
14. SEX_Cl concentration (ppm)	<0.005	Reject null hypothesis (Not normally distributed)	Box-Cox Transformation
15. CCF_Cl concentration (ppm)	<0.005	Reject null hypothesis (Not normally distributed)	Box-Cox Transformation
16. PCF_Eh (mV)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
17. SEX_Eh (mV)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
18. CCF_Eh (mV)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
19. Rectifier Current (kA)	<0.005	Reject null hypothesis (Not normally distributed)	Box-Cox Transformation
20. Current density (A/m^2)	<0.005	Reject null hypothesis (Not normally distributed)	Box-Cox Transformation
21. Advance temperature (°C)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
22. Polishing cells temperature (°C)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
23. Commercial cells temperature (°C)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
24. Circulation flowrate (m^3/h)	<0.005	Reject null hypothesis (Not normally distributed)	Johnson Transformation
25. Advance flowrate (m^3/h)	<0.005	Reject null hypothesis (Not normally distributed)	Box-Cox Transformation

Discussing normal distribution test results

The normality test results in Table 4.4 shows that none of the current efficiency factors follows a normal distribution. As a result, all the data was transformed to follow a normal distribution. This was done by using Johnson and/or Box-Cox Transformation. If the data do not follow a normal distribution it does not necessarily mean the factors do not affect current efficiency. The Anderson Darlington normality test charts for these factors is depicted in Appendix D (Figure 8.3). It only means the data does not tend toward an average but it is rather more scattered. The data that follows a normal distribution is expected to have low variability comparatively. It is worth noting that current efficiency does not follow a normal distribution also.

4.3 Applying statistical process control on current efficiency factors data

4.3.1 Justification for the control charts to be applied

Current efficiency factors data was collected from 1st January 2019 at 06:00 am to 1st July 2019 at 06:00 am. Depending on the current efficiency factor, the data was collected every 2 hours and every 12 hours. The data is continuous and the subgroup was determined per day. That is a subgroup of 12 samples and 2 samples every day. Figure 4.9 below the most appropriate control chart to be used is the Xbar-R chart and Xbar-S chart for the respective subgroups. Current efficiency values are individual values per day. Which means current efficiency only has a single subgroup. Therefore, the best control chart type for it would be the individual control chart called the I-MR chart as shown in Figure 4.9 below.

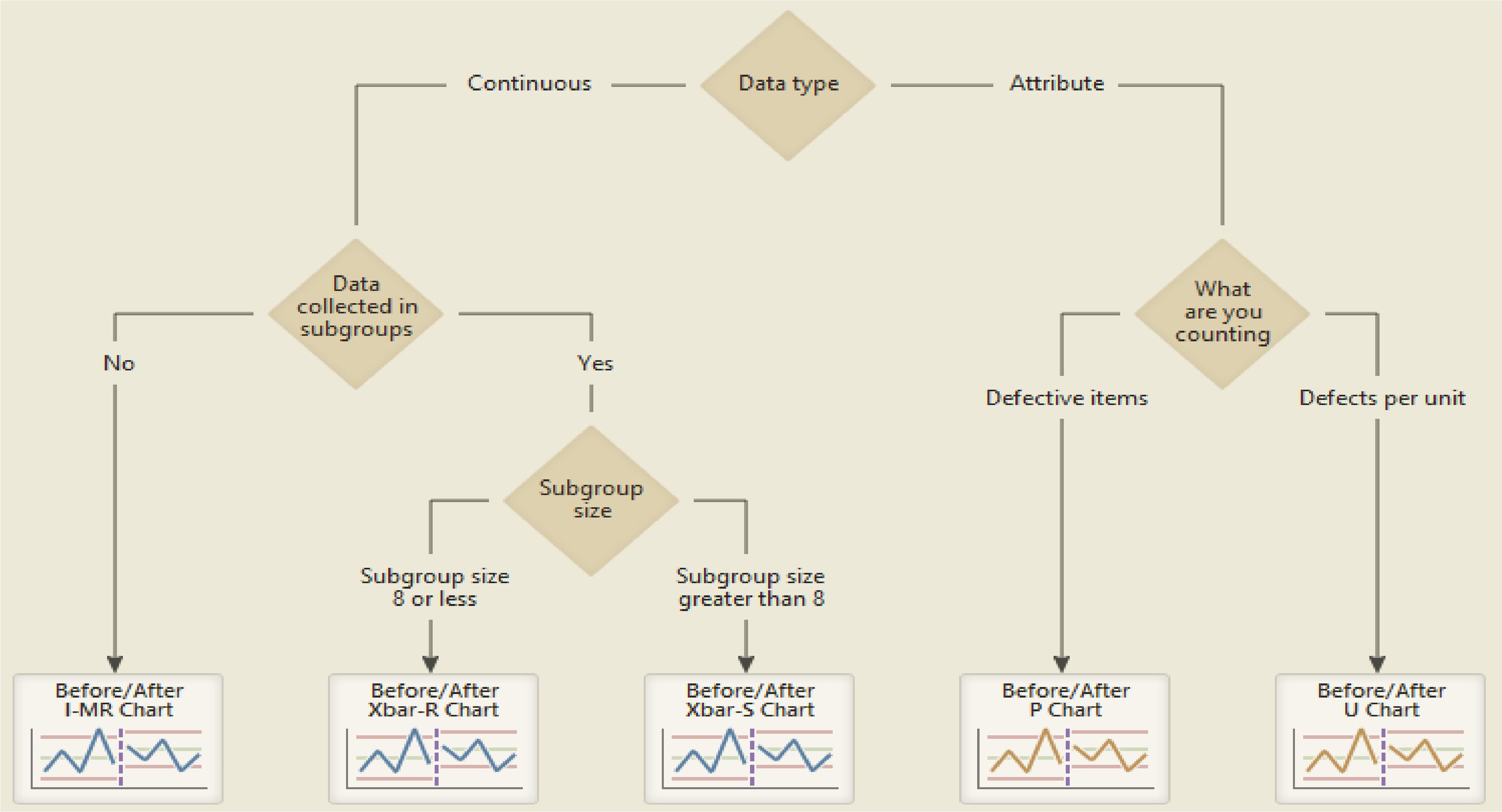


Figure 4.9: A decision tree for choosing the type of control chart to be applied (adopted from Minitab, 2019)

Table 4.5: Justification for the control charts applied (compiled by the author)

Factor	Subgroup sizes	Appropriate control chart	Justification
a. Current efficiency	1	I-MR control chart	Individual values
1. PCF_Cu concentration (g/l)	12	Xbar-S control chart	Subgroup size > 8
2. SEX_Cu concentration (g/l)	12	Xbar-S control chart	Subgroup size > 8
3. CCF_Cu concentration (g/l)	12	Xbar-S control chart	Subgroup size > 8
4. PCF_H2SO4 concentration (g/l)	2	Xbar-R control chart	Subgroup size ≤ 8
5. SEX_H2SO4 concentration (g/l)	2	Xbar-R control chart	Subgroup size ≤ 8
6. CCF_H2SO4 concentration (g/l)	2	Xbar-R control chart	Subgroup size ≤ 8
7. PCF_Total Fe concentration (ppm)	2	Xbar-R control chart	Subgroup size ≤ 8
8. SEX_Total Fe concentration (ppm)	2	Xbar-R control chart	Subgroup size ≤ 8
9. CCF_Total Fe concentration (ppm)	2	Xbar-R control chart	Subgroup size ≤ 8
10. SEX_Co concentration (ppm)	2	Xbar-R control chart	Subgroup size ≤ 8
11. CCF_Co concentration (ppm)	2	Xbar-R control chart	Subgroup size ≤ 8
12. PCF_Cl concentration (ppm)	2	Xbar-R control chart	Subgroup size ≤ 8
13. SEX_Cl concentration (ppm)	2	Xbar-R control chart	Subgroup size ≤ 8
14. CCF_Cl concentration (ppm)	2	Xbar-R control chart	Subgroup size ≤ 8
15. PCF_Eh (mV)	2	Xbar-R control chart	Subgroup size ≤ 8
16. SEX_Eh (mV)	2	Xbar-R control chart	Subgroup size ≤ 8
17. CCF_Eh (mV)	2	Xbar-R control chart	Subgroup size ≤ 8
18. Rectifier Current (kA)	12	Xbar-S control chart	Subgroup size > 8
19. Current density (A/m2)	12	Xbar-S control chart	Subgroup size > 8
20. Advance temperature (°C)	12	Xbar-S control chart	Subgroup size > 8
21. Polishing cells temperature (°C)	12	Xbar-S control chart	Subgroup size > 8
22. Commercial cells temperature (°C)	12	Xbar-S control chart	Subgroup size > 8
23. Circulation flowrate (m3/h)	12	Xbar-S control chart	Subgroup size > 8
24. Advance flowrate (m3/h)	12	Xbar-S control chart	Subgroup size > 8

4.3.2 Creating an I-MR control chart for current efficiency

The figure below shows an I-MR control chart for current efficiency data. Only the first test of the Shewhart rules for control charts was considered due to the complex nature of the electrowinning process. The control chart average was found by calculating the average of the Johnson Transformed current efficiency data and then solving for 'X' in the Johnson Transformation model shown in Figure 4.6. This was done as follow: The Johnson Transformation function for current efficiency in Figure 4.6 is given as follow:

$$Y = -0.0479120 + 1.01726 \times \text{Asinh}\left(\frac{X-94.4541}{1.13772}\right)$$

In which:

Y = Johnson Transformed current efficiency value
X = Actual current efficiency
Asinh(X) = Inverse hyperbolic sine for each element of X

Solving for X was done as follow:

$$Y + 0.0479120 = 1.01726 \times \text{Asinh}\left(\frac{X-94.4541}{1.13772}\right)$$

$$\frac{Y + 0.0479120}{1.01726} = \text{Asinh}\left(\frac{X-94.4541}{1.13772}\right)$$

$$\text{Sinh}\left(\frac{Y + 0.0479120}{1.01726}\right) = \frac{X-94.4541}{1.13772}$$

$$1.13772 \times \text{Sinh}\left(\frac{Y + 0.0479120}{1.01726}\right) = X - 94.4541$$

$$\therefore X = 94.4541 + 1.13772 \times \text{Sinh}\left(\frac{Y + 0.0479120}{1.01726}\right)$$

$$= 94.4541 + 1.13772 \times \text{Sinh}\left(\frac{-0.03848 + 0.0479120}{1.01726}\right)$$

$$= \underline{94.46}$$

In this case, X is the average actual current efficiency and Y is the Johnson Transformed current efficiency average value. The calculated average (X) was used in Minitab when creating an I-MR chart for current efficiency. In addition to that, the upper and lower control limits can also be calculated using Minitab by applying one standard deviation from the mean. The final Minitab output for the I-MR control chart is displayed in Figure 4.10 below.

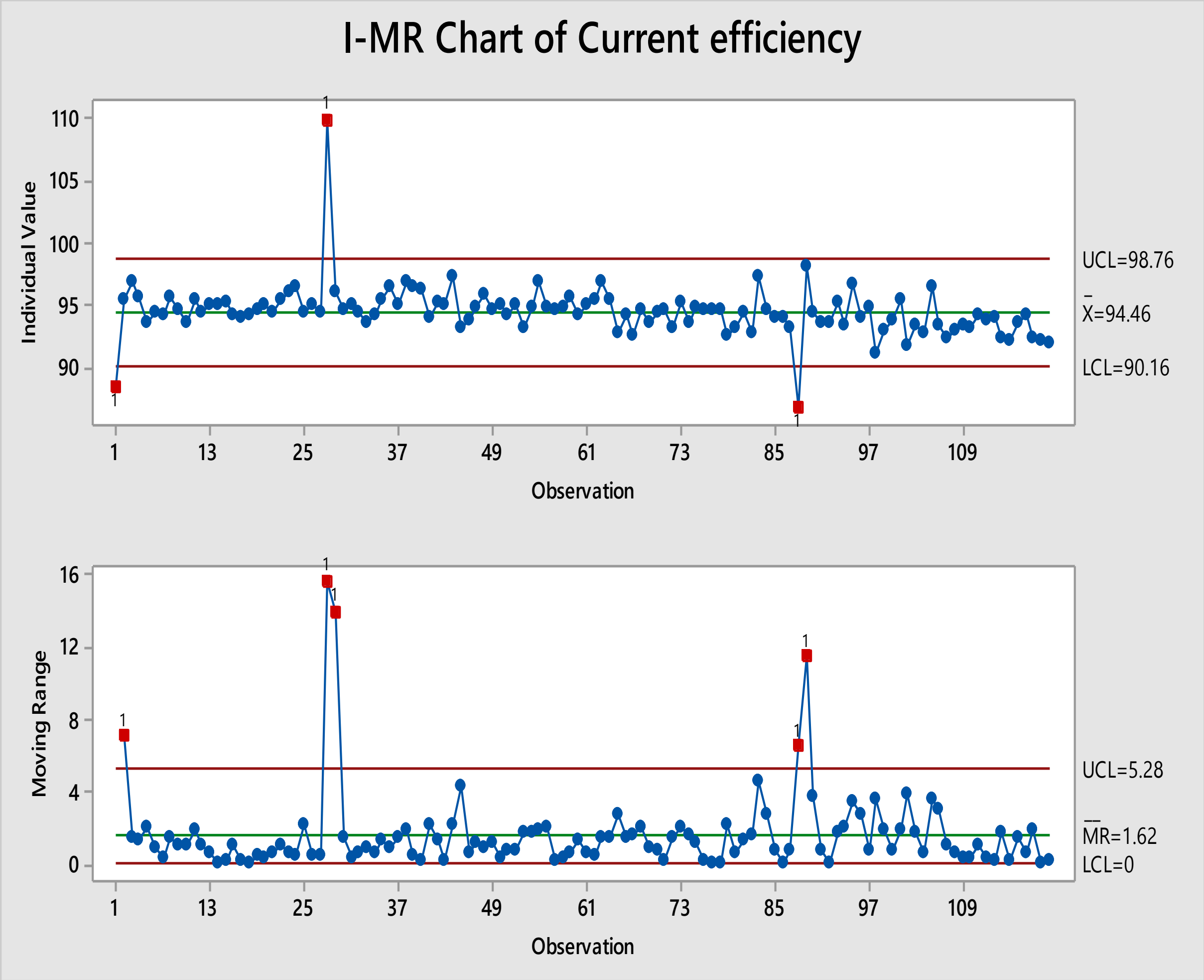


Figure 4.10: Current efficiency I-MR control chart (created by the author)

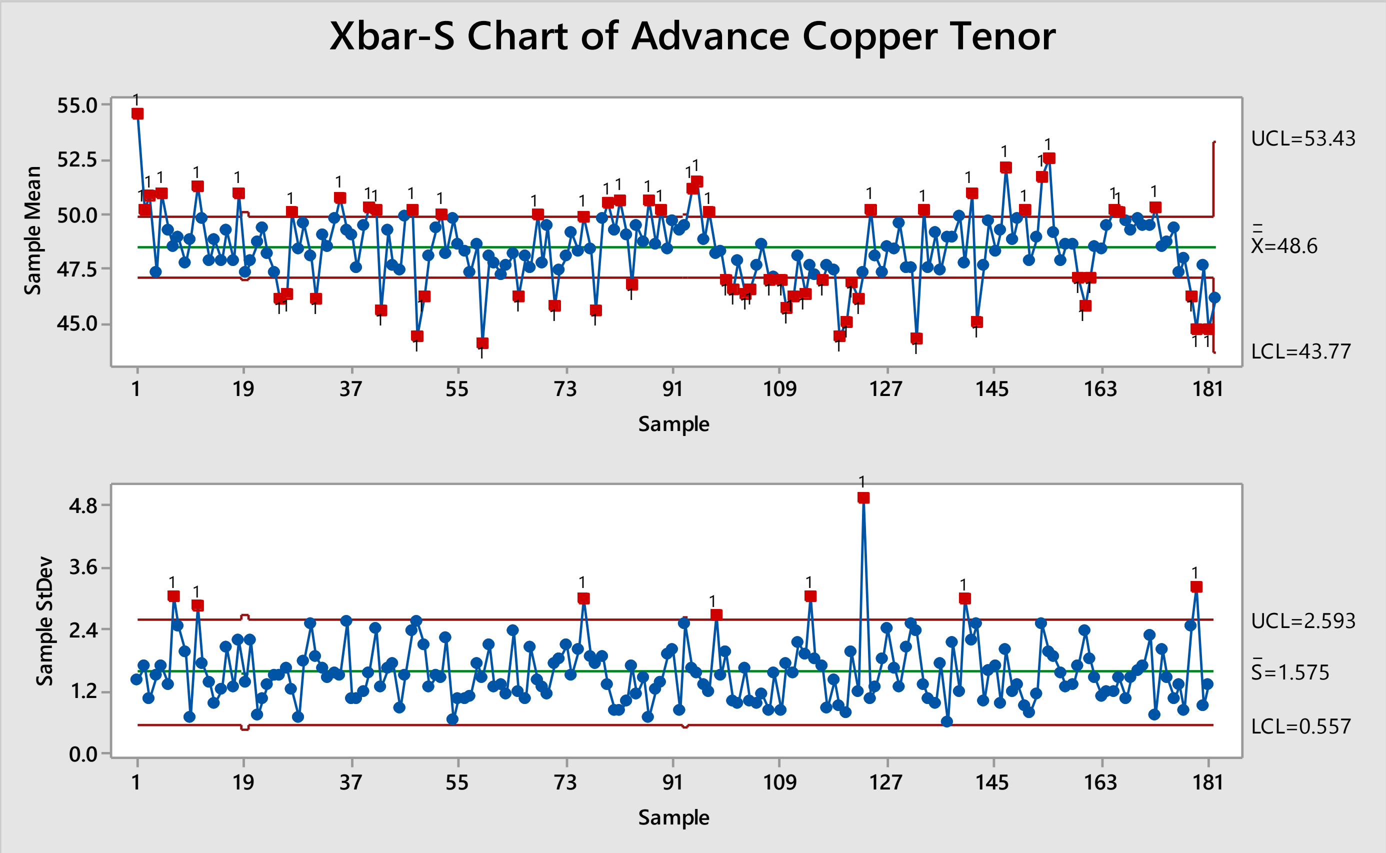
Discussing current efficiency control chart

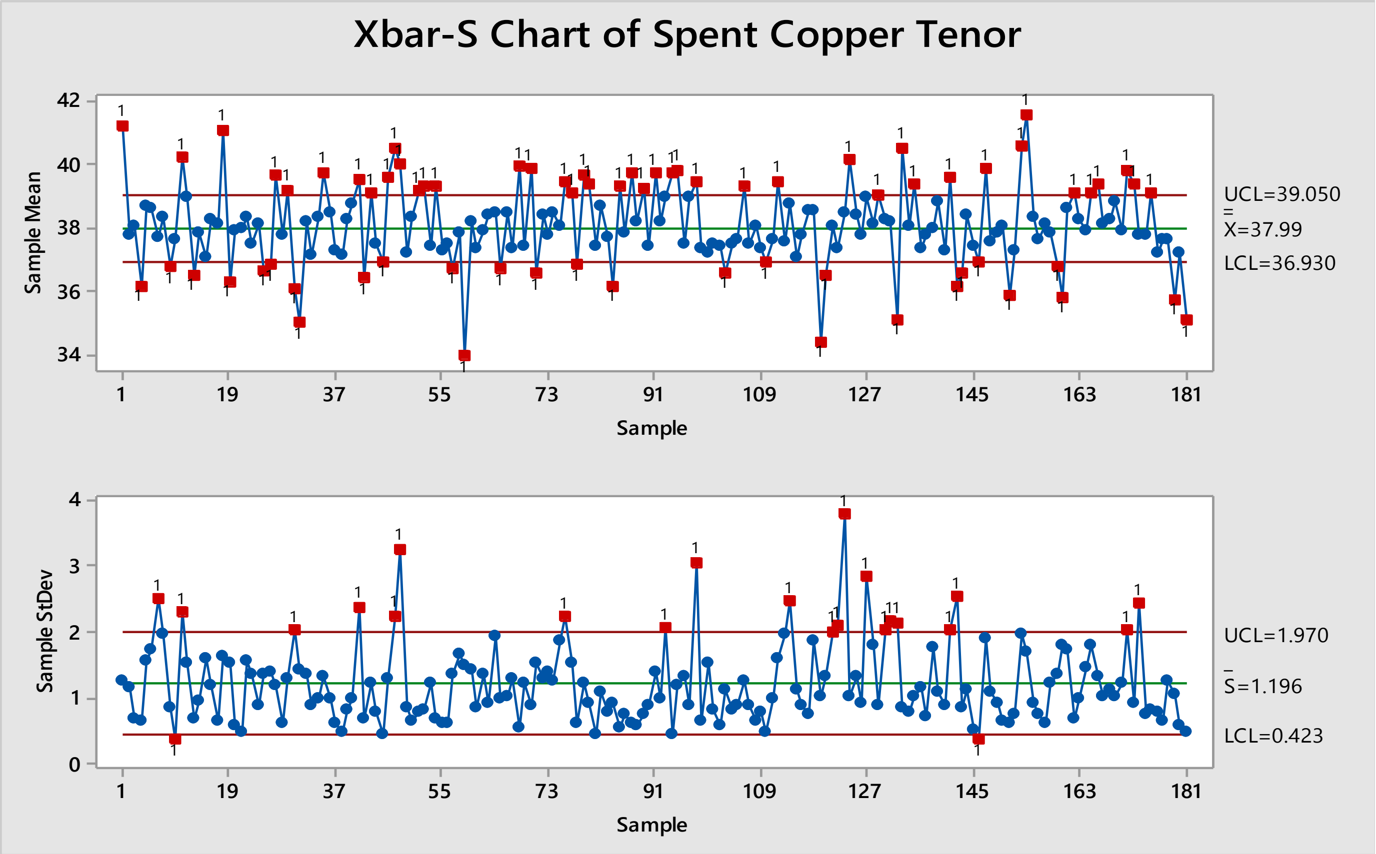
The current efficiency I-MR control chart shows that current efficiency has been out of control over the 6 month period under study. The individual control chart shows a total of 7 out of control points. Amongst these points, 3 of the 7 points are below the lower control limit and 4 of the 7 points are above the upper control limit. Interestingly one of the out of control points shows a CE of 110 %. It is believed that there might have been a typing error when entering the time the cathodes were returned back into the cells. This is due to human intervention in the calculation of current efficiency. All the out of control points will be better understood after creating control charts for the factors.

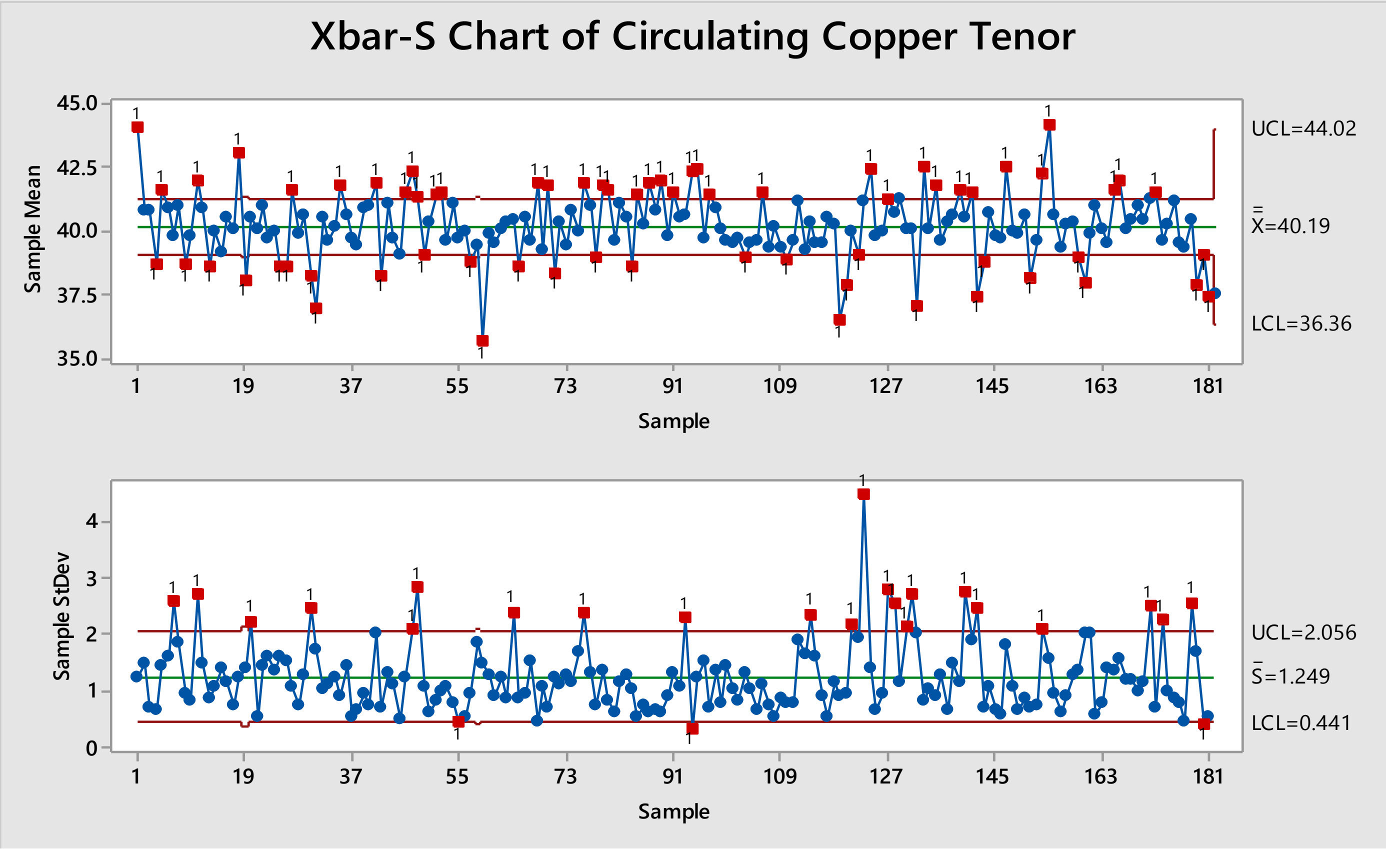
On the other hand, the moving range control chart shows that there are 9 points that are out of control. All the 9 points are above the upper control limit. This is because of the increase or decrease in current efficiency by more than 3.69 %. These points are clearly due to the change reflected in the individual control chart. The immediate change in current efficiency by more than 3.69 % is really a big change and it is a sign of a special cause. Again, these changes can only be understood well by creating the control charts for the factors.

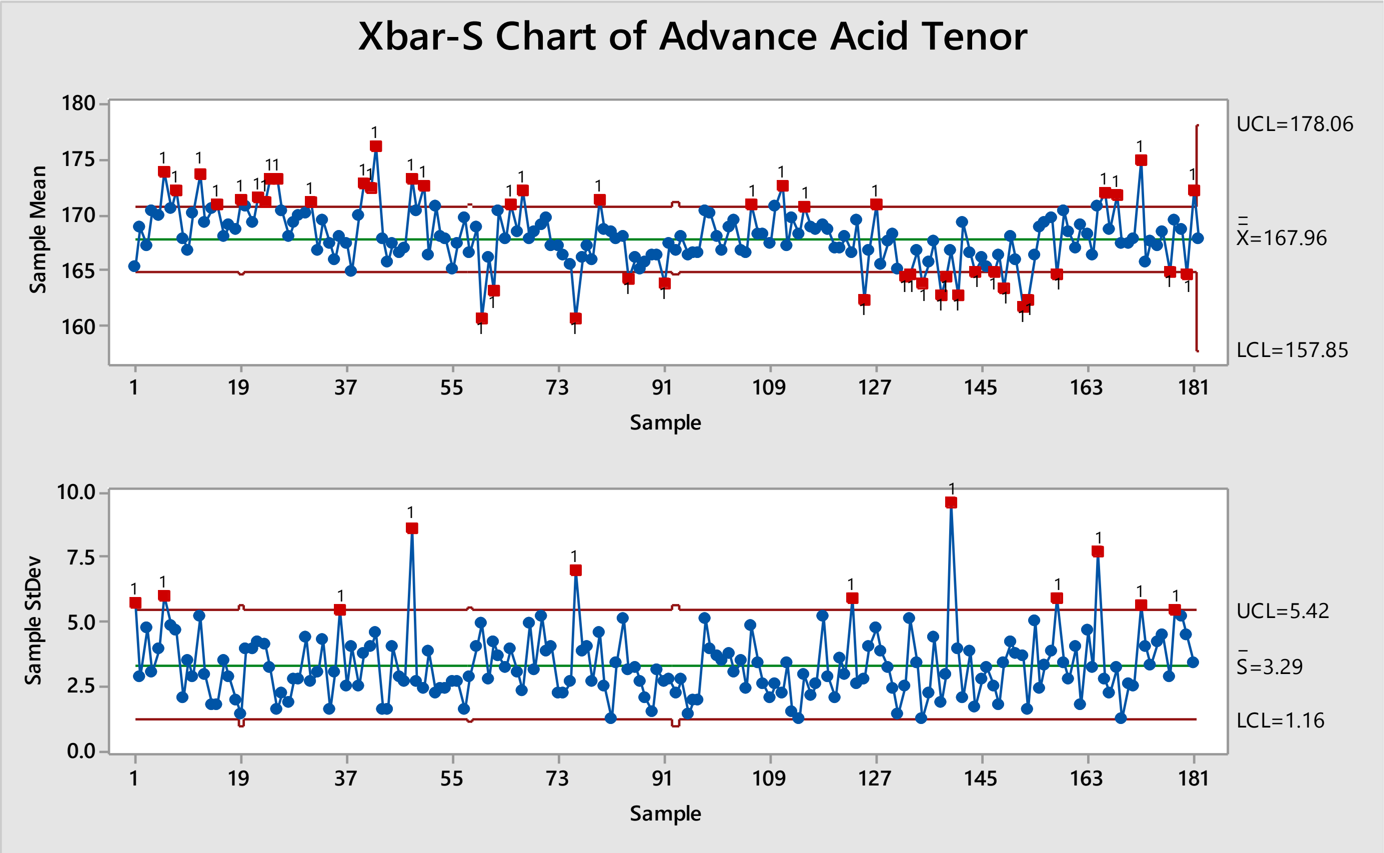
4.3.3 Creating Xbar-R and Xbar-S control charts for CE factors

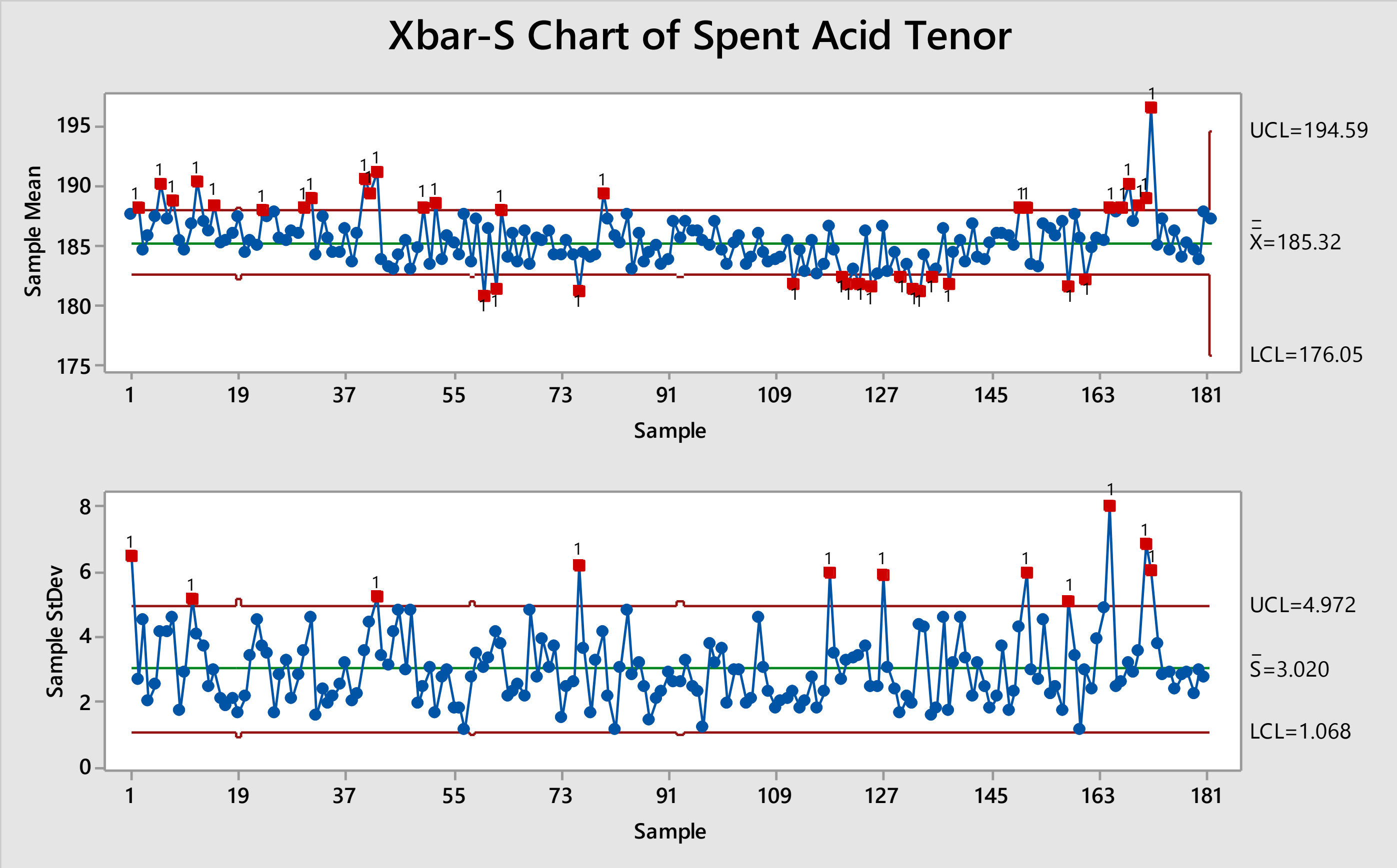
The control charts for current efficiency factors were also created in a similar manner. However, it should be noted that unlike for current efficiency the factors have subgroups. This means the appropriate control charts would be the Xbar-R and Xbar-S control charts depending on the number of subgroups as explained in section 4.3.1 above.

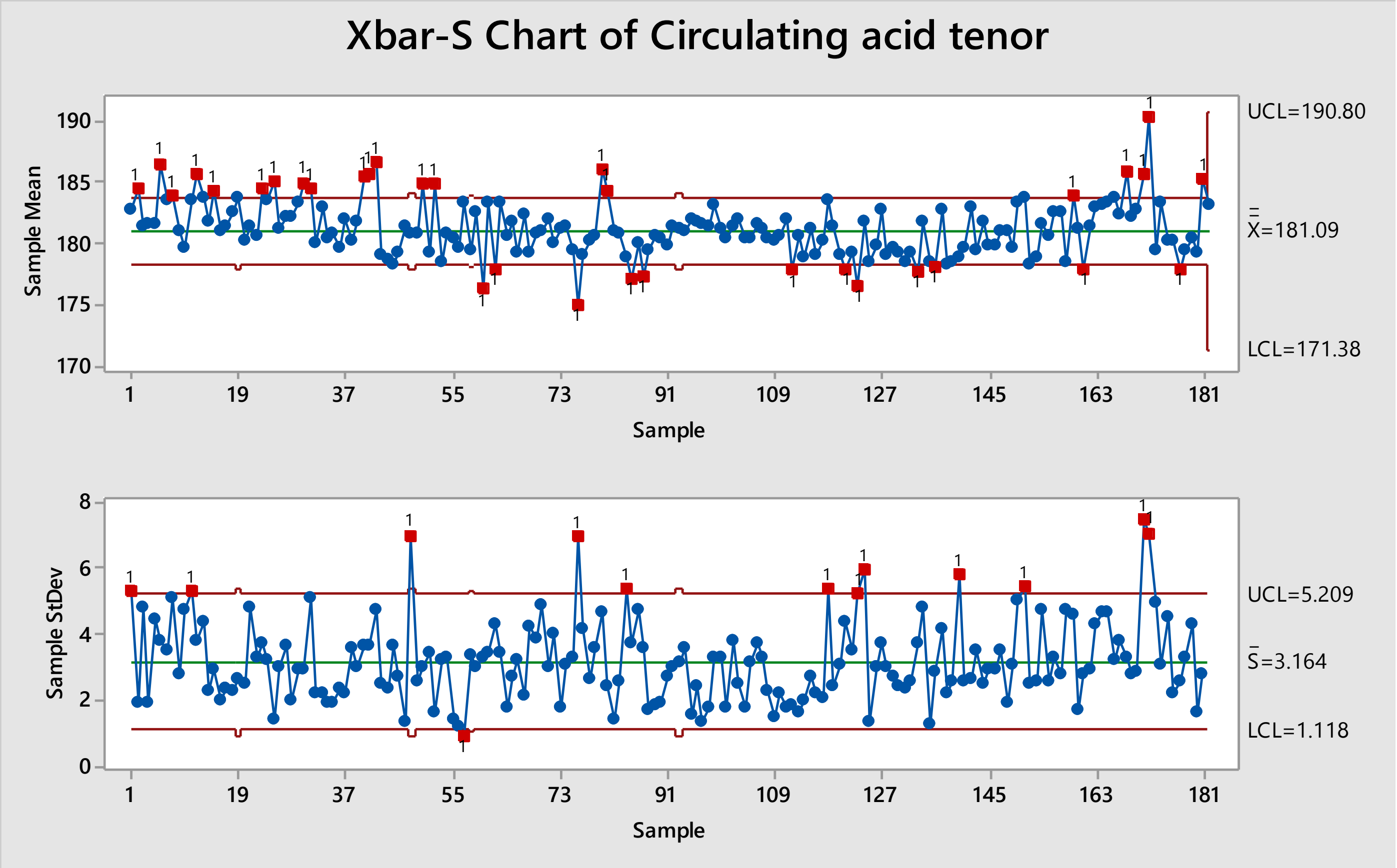

Xbar-S Chart of Advance Copper Tenor
Sample Mean
55.0
52.5
50.0
47.5
45.0
UCL=53.43
$\bar{\bar{X}}$=48.6
LCL=43.77
1
19
37
55
73
91
109
127
145
163
181
Sample
Sample StDev
4.8
3.6
2.4
1.2
0.0
UCL=2.593
$\bar{S}$=1.575
LCL=0.557
Sample

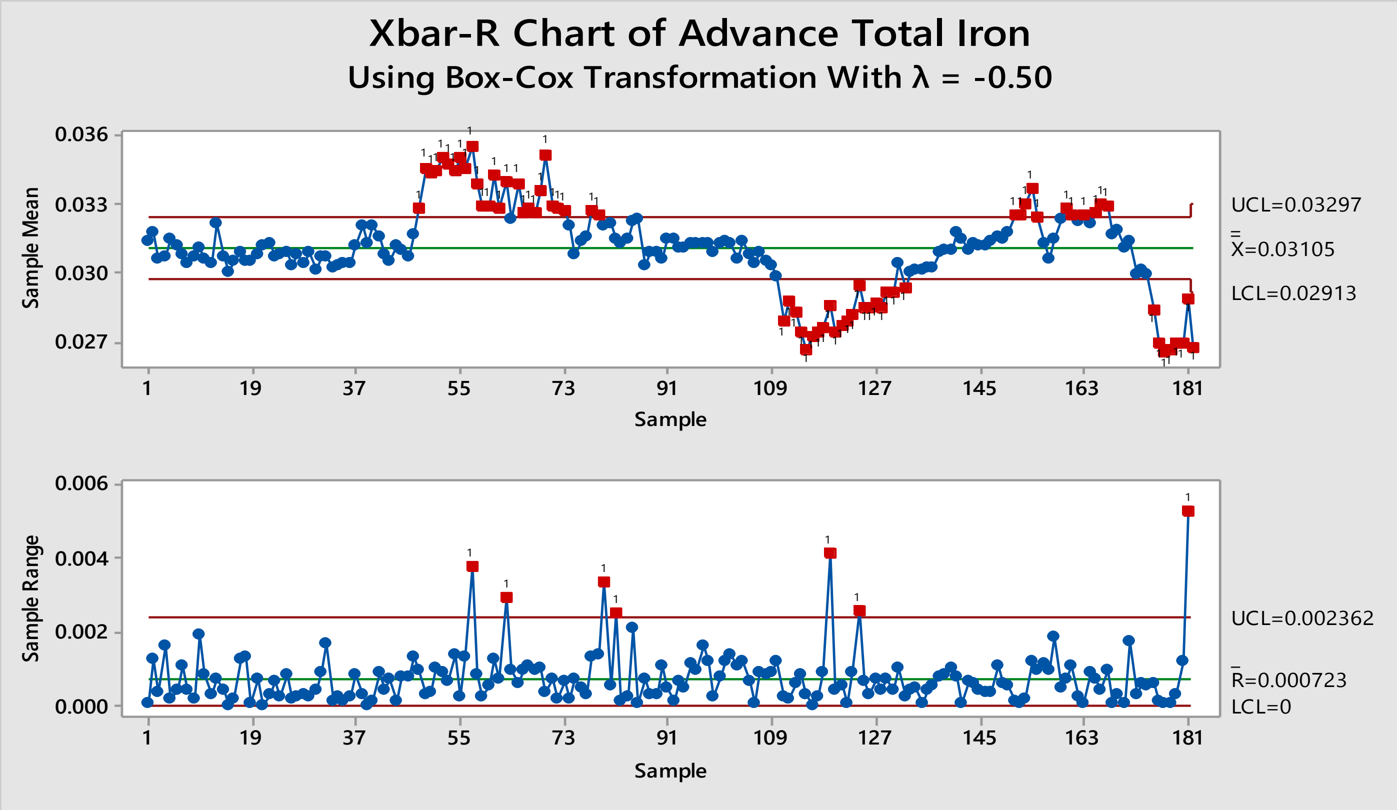

Xbar-S Chart of Spent Copper Tenor
Sample Mean
42
40
38
36
34
UCL=39.050
$\bar{\bar{X}}$=37.99
LCL=36.930
1
19
37
55
73
91
109
127
145
163
181
Sample
Sample StDev
4
3
2
1
0
UCL=1.970
$\bar{S}$=1.196
LCL=0.423
Sample

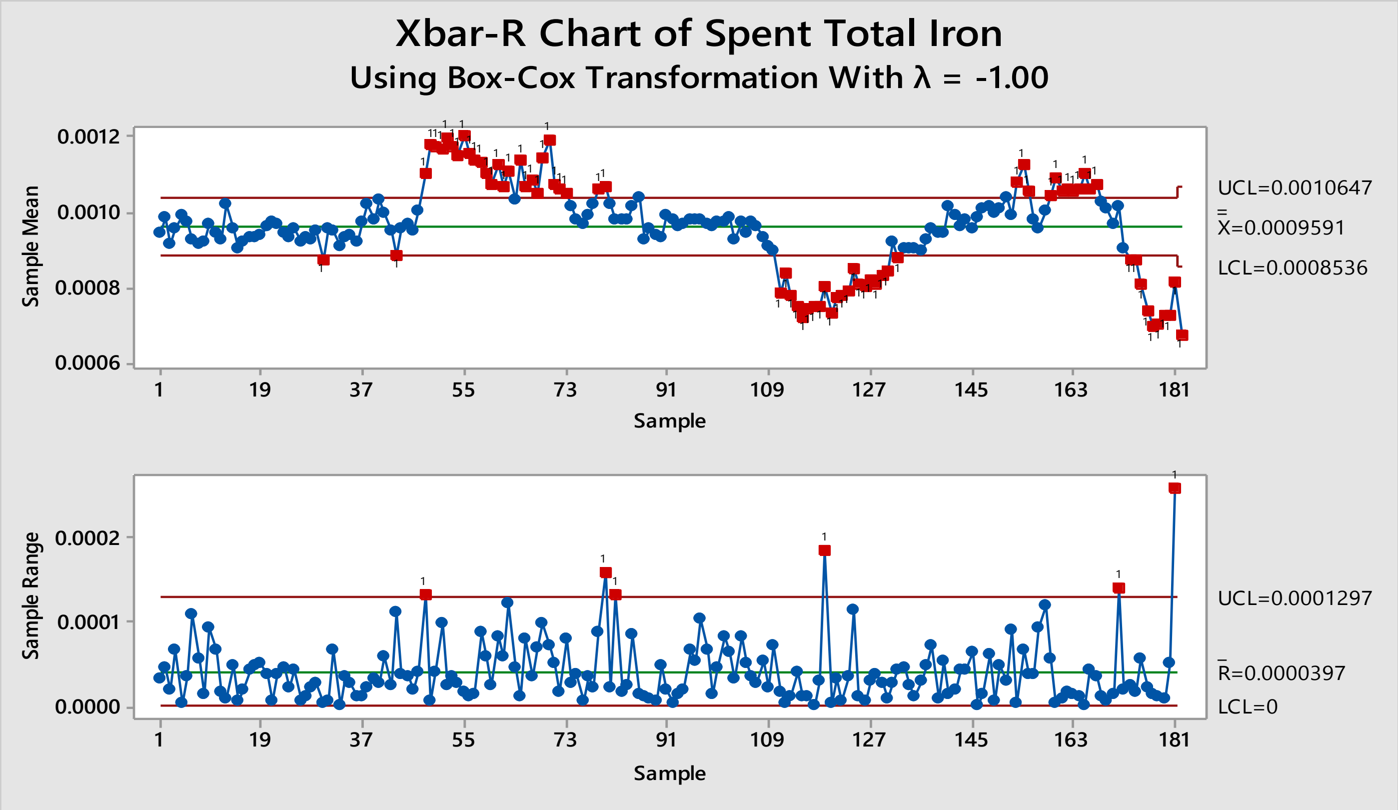

Xbar-S Chart of Circulating Copper Tenor
Sample Mean
45.0
42.5
40.0
37.5
35.0
UCL=44.02
$\bar{\bar{X}}$=40.19
LCL=36.36
1
19
37
55
73
91
109
127
145
163
181
Sample
Sample StDev
4
3
2
1
0
UCL=2.056
$\bar{S}$=1.249
LCL=0.441
Sample

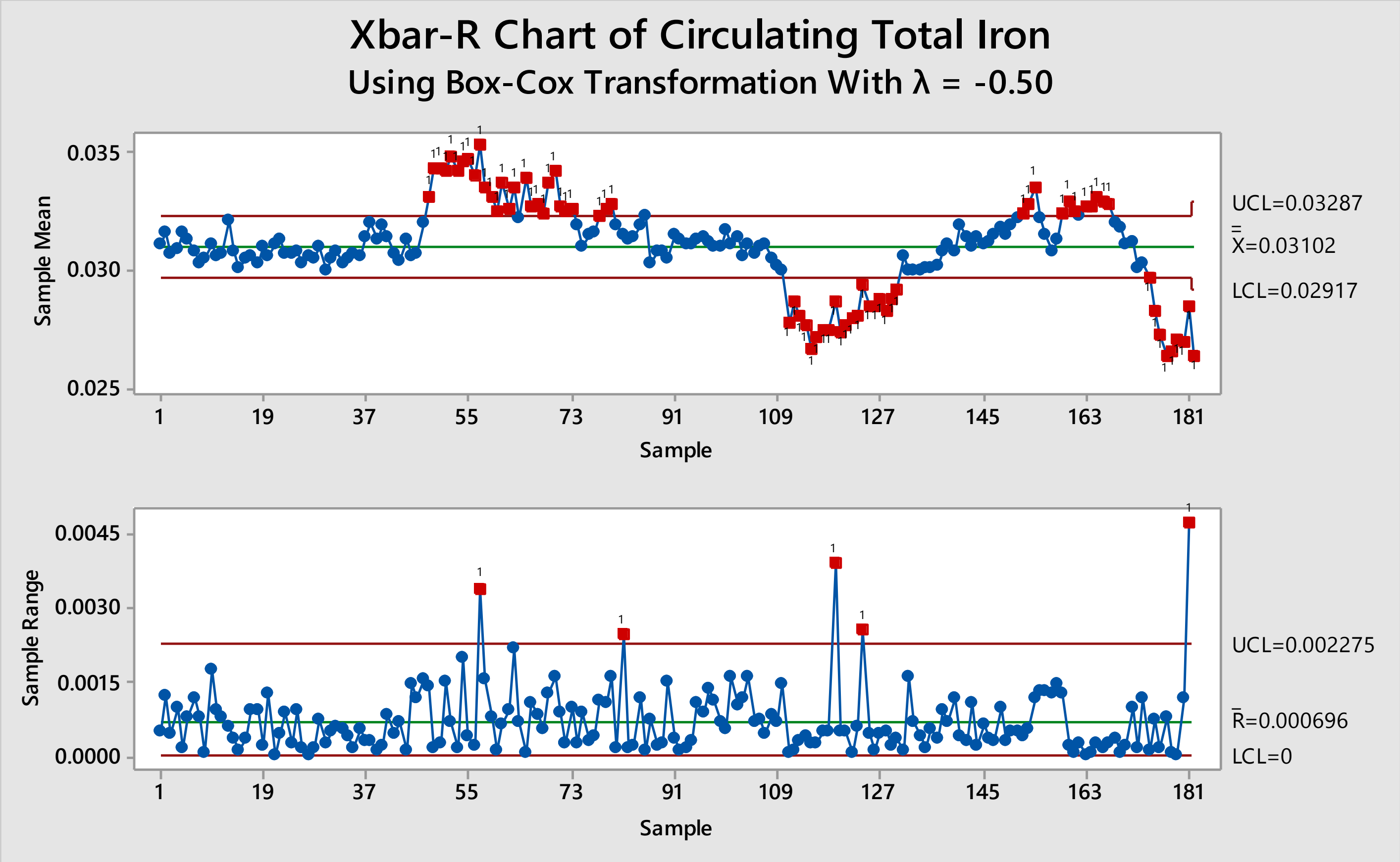

Xbar-S Chart of Advance Acid Tenor
Sample Mean
180
175
170
165
160
UCL=178.06
$\bar{\bar{X}}$=167.96
LCL=157.85
1
19
37
55
73
91
109
127
145
163
181
Sample
Sample StDev
10.0
7.5
5.0
2.5
0.0
UCL=5.42
$\bar{S}$=3.29
LCL=1.16
Sample

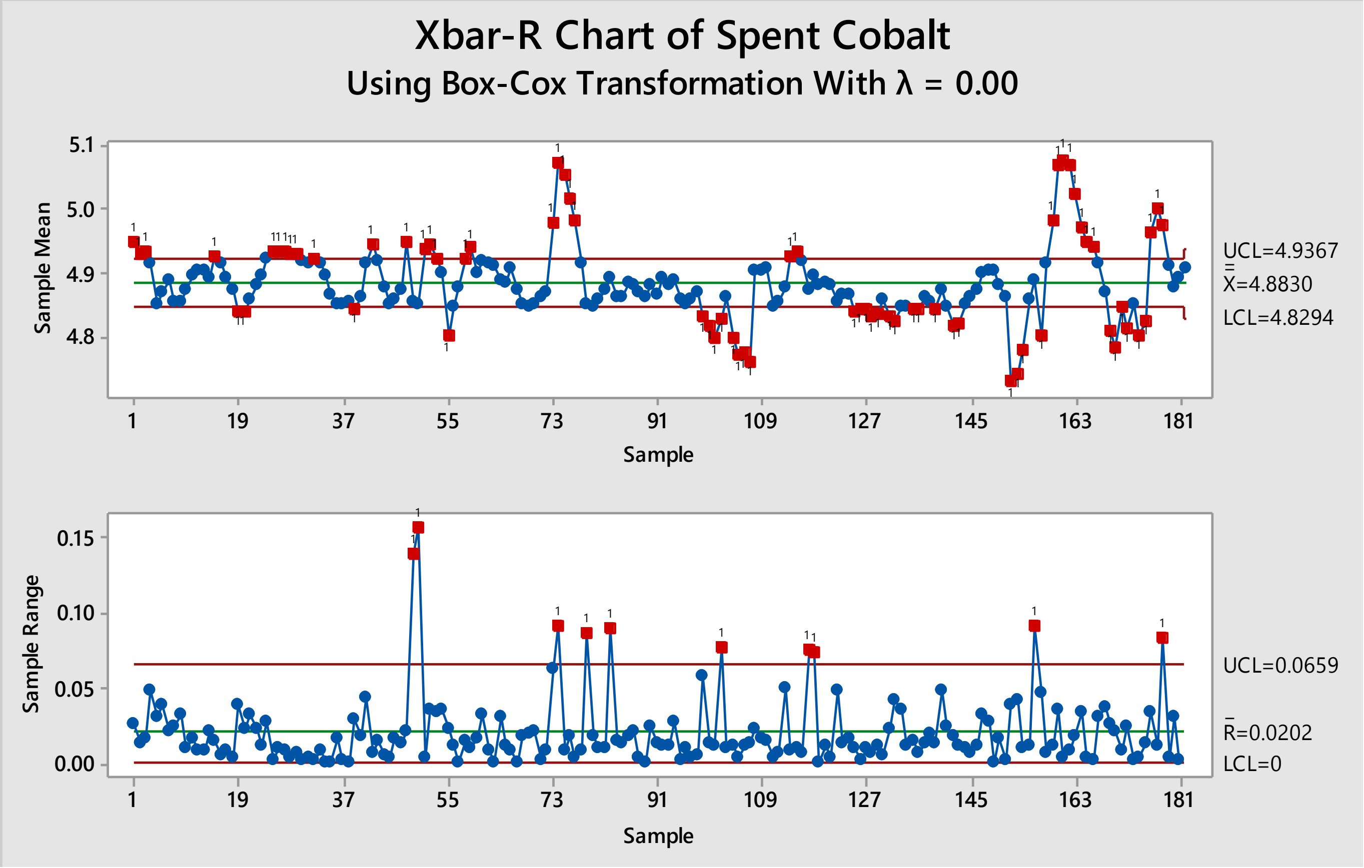

Xbar-S Chart of Spent Acid Tenor

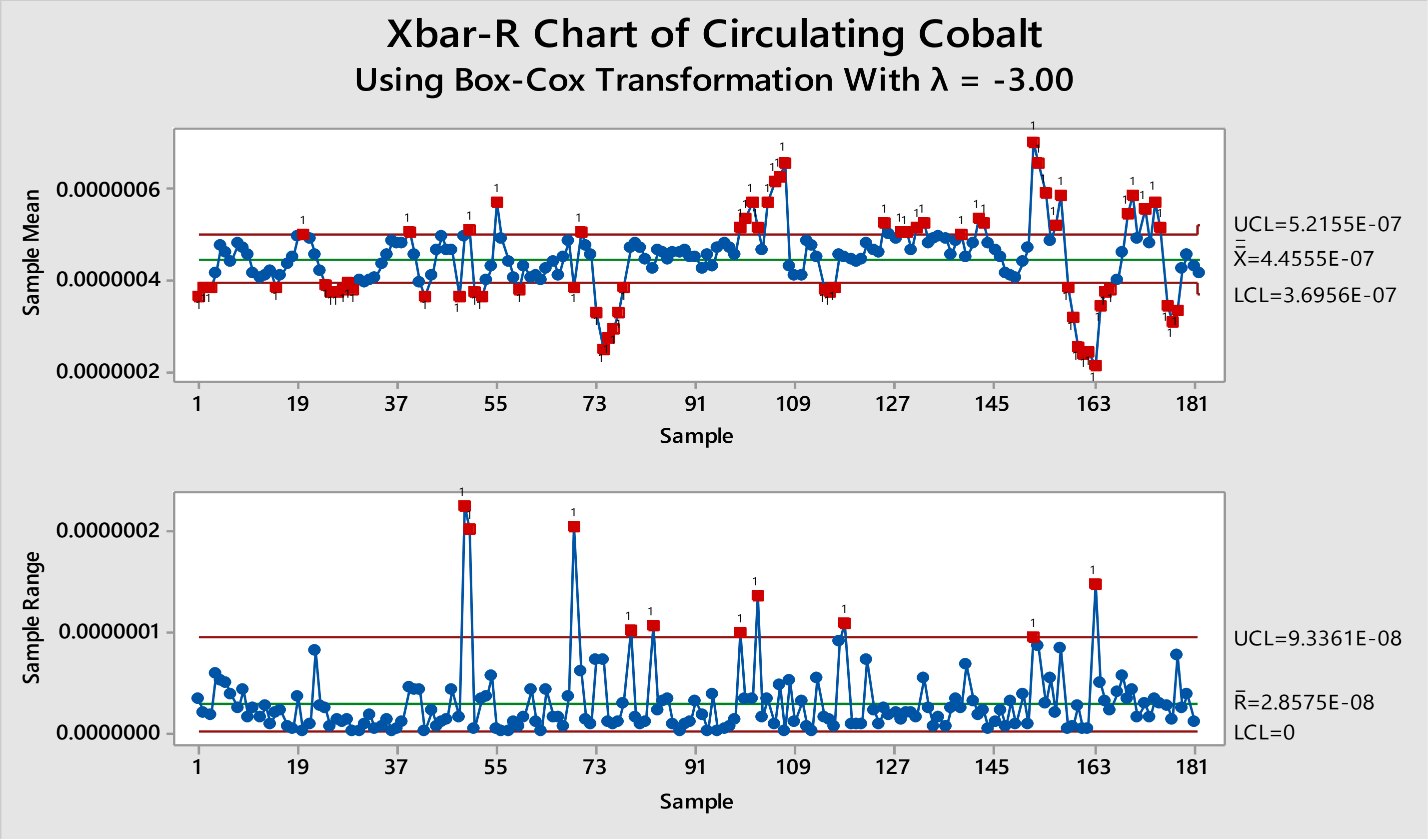

Xbar-S Chart of Circulating acid tenor

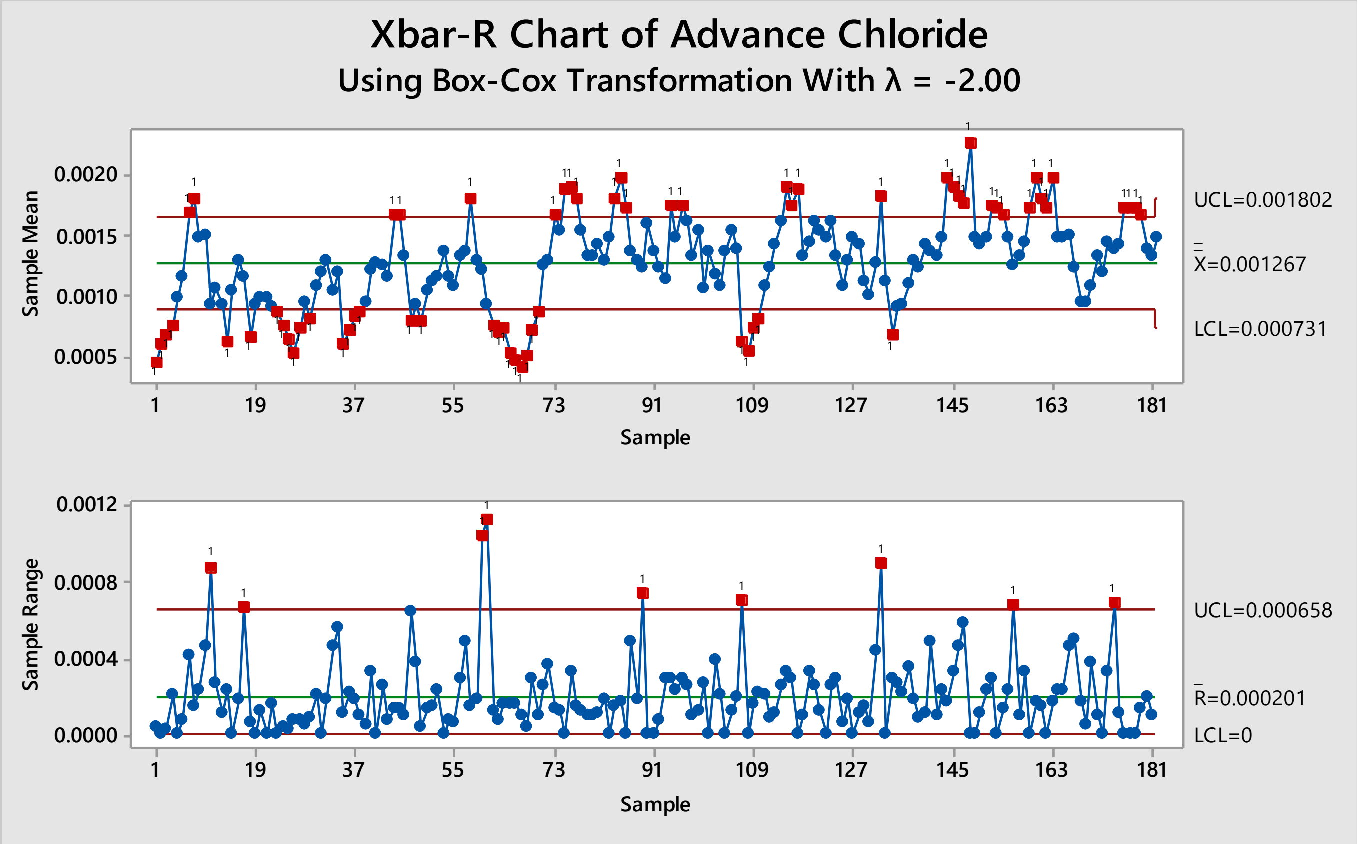

Xbar-R Chart of Advance Total Iron
Using Box-Cox Transformation With λ = -0.50

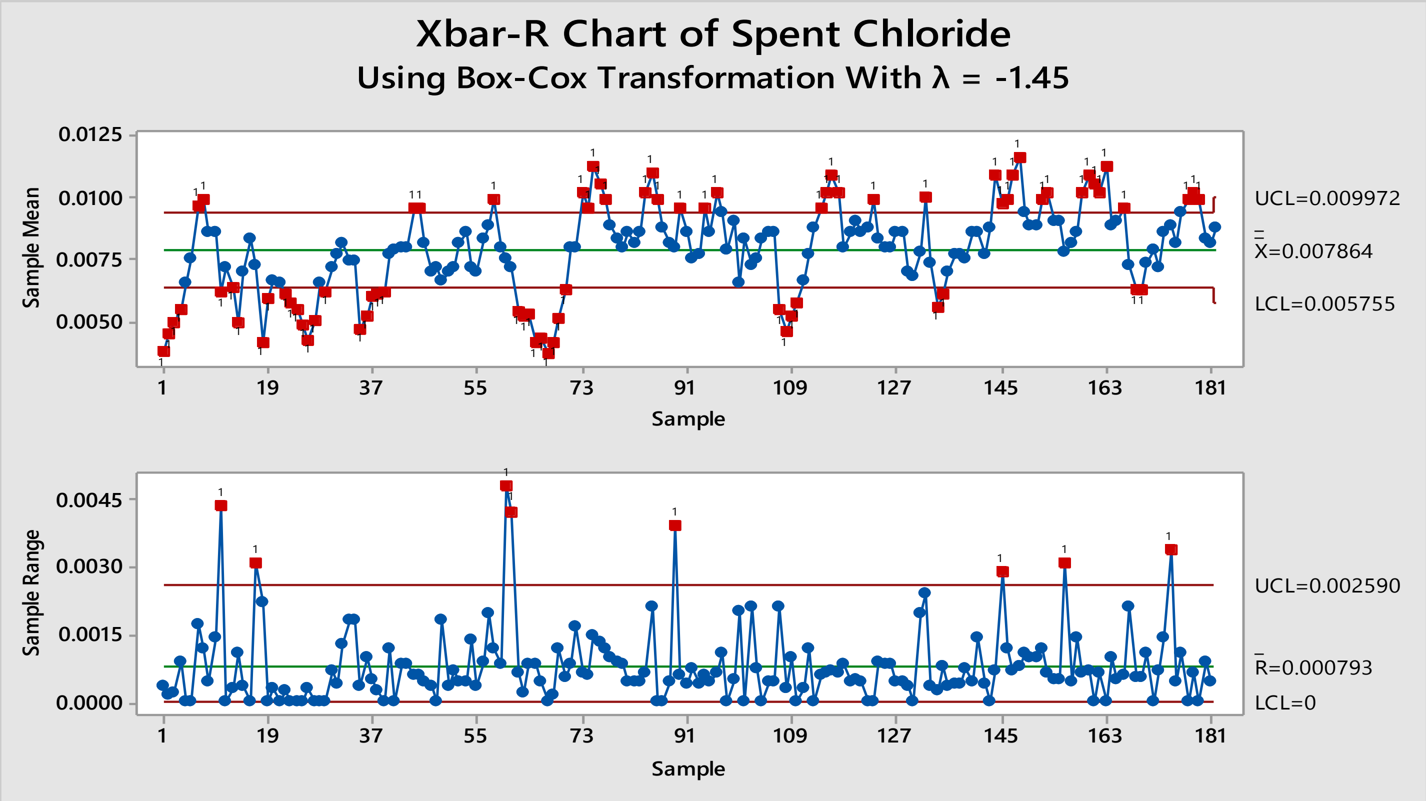

Xbar-R Chart of Spent Total Iron
Using Box-Cox Transformation With λ = -1.00

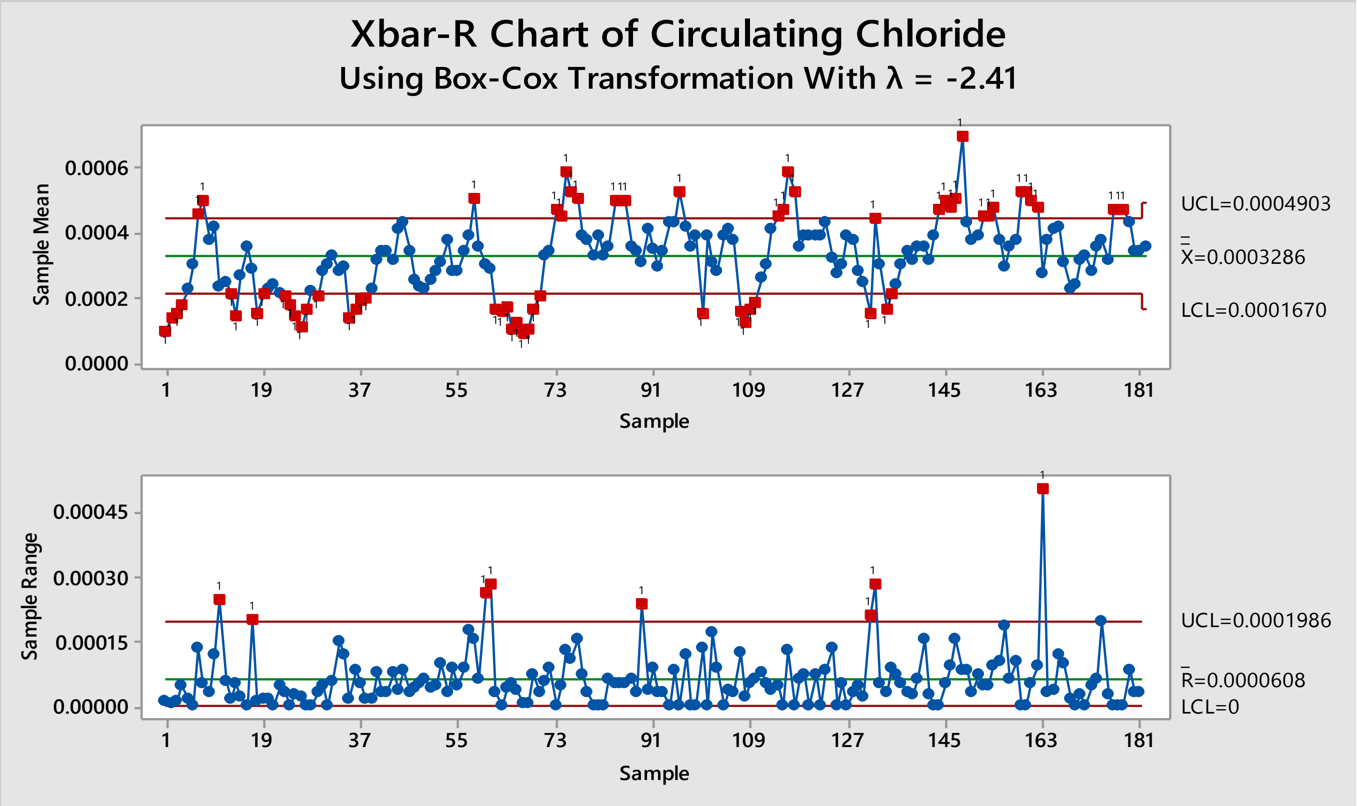

Xbar-R Chart of Circulating Total Iron
Using Box-Cox Transformation With λ = -0.50
Sample Mean
0.035
0.030
0.025
UCL=0.03287
X̿=0.03102
LCL=0.02917
Sample Range
0.0045
0.0030
0.0015
0.0000
UCL=0.002275
R̄=0.000696
LCL=0
1 19 37 55 73 91 109 127 145 163 181
Sample

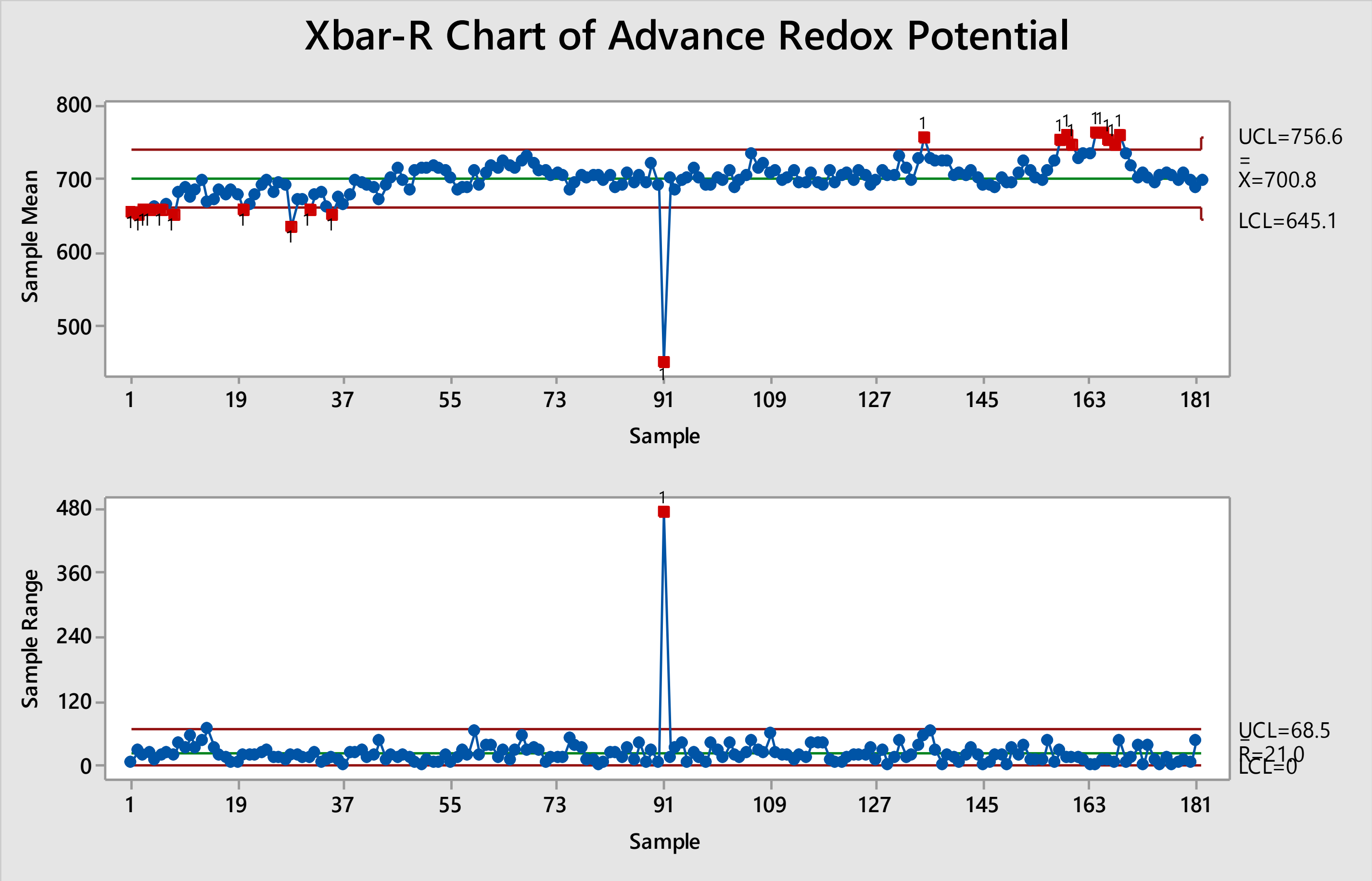

Xbar-R Chart of Spent Cobalt
Using Box-Cox Transformation With λ = 0.00
Sample Mean
5.1
5.0
4.9
4.8
UCL=4.9367
X̿=4.8830
LCL=4.8294
Sample Range
0.15
0.10
0.05
0.00
UCL=0.0659
R̄=0.0202
LCL=0
1 19 37 55 73 91 109 127 145 163 181
Sample

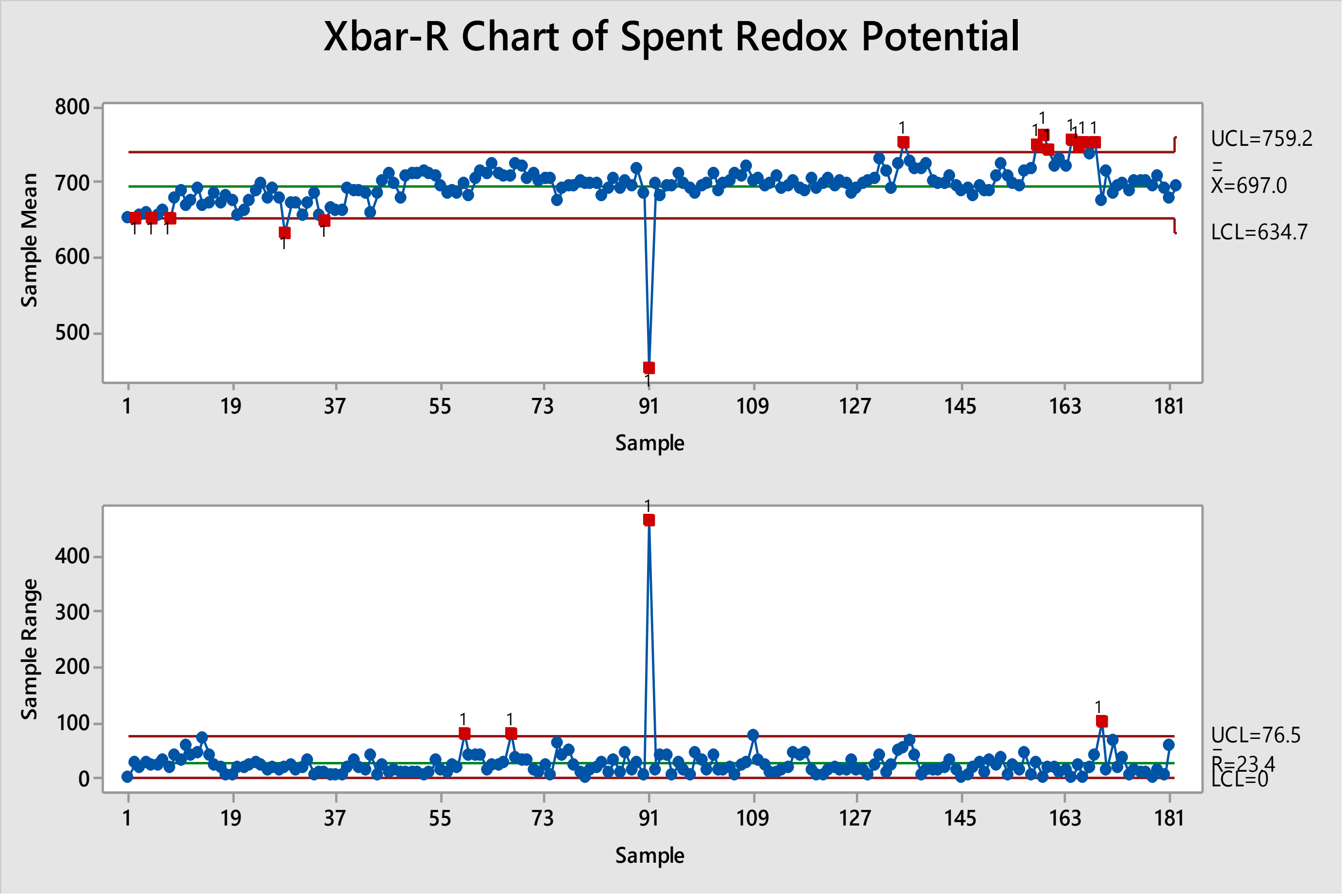

Xbar-R Chart of Circulating Cobalt
Using Box-Cox Transformation With λ = -3.00
Sample Mean
0.0000006
0.0000004
0.0000002
UCL=5.2155E-07
X̿=4.4555E-07
LCL=3.6956E-07
Sample Range
0.0000002
0.0000001
0.0000000
UCL=9.3361E-08
R̄=2.8575E-08
LCL=0
1 19 37 55 73 91 109 127 145 163 181
Sample

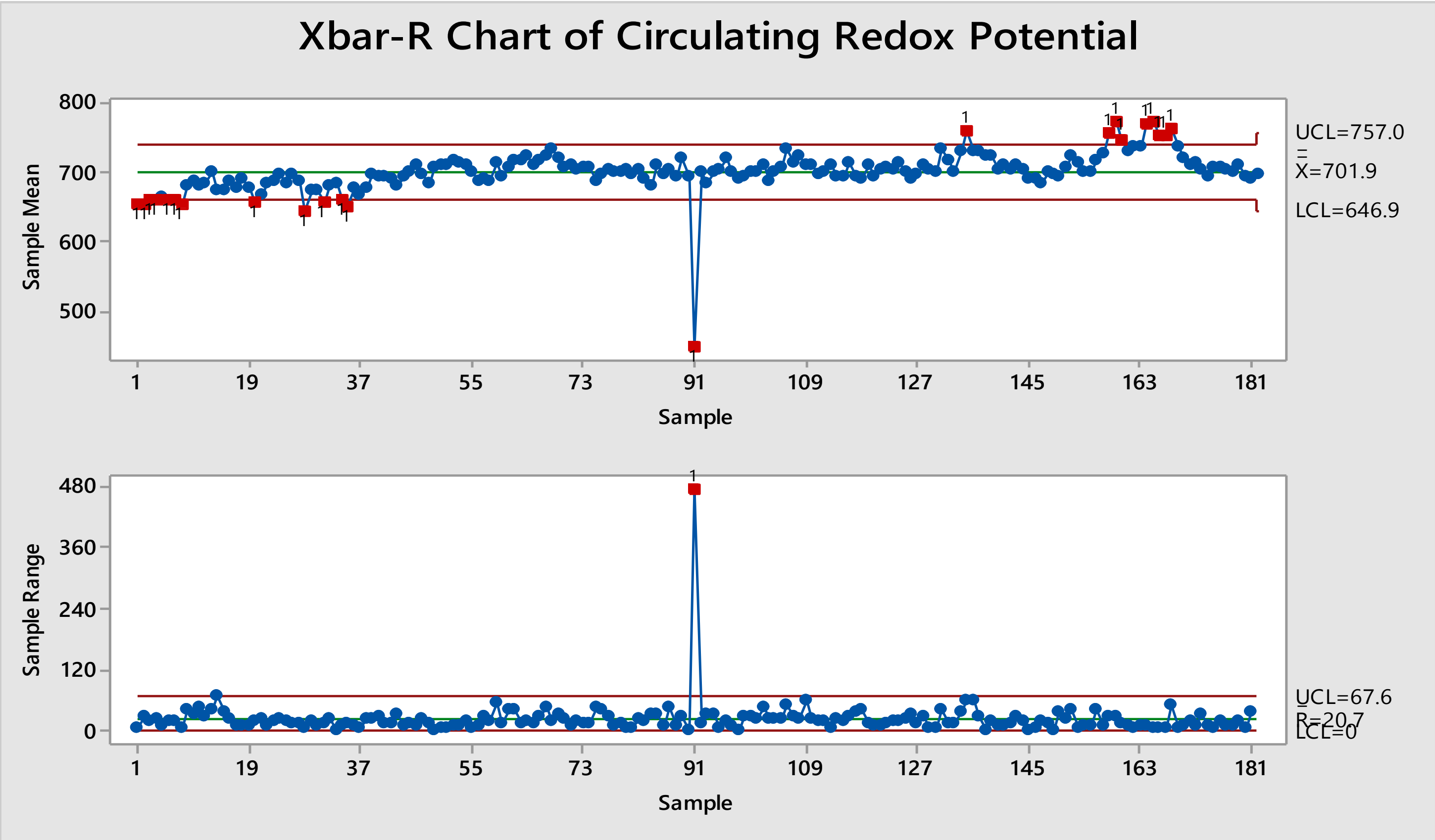

Xbar-R Chart of Advance Chloride
Using Box-Cox Transformation With λ = -2.00
Sample Mean
0.0020
0.0015
0.0010
0.0005
UCL=0.001802
X̿=0.001267
LCL=0.000731
Sample Range
0.0012
0.0008
0.0004
0.0000
UCL=0.000658
R̄=0.000201
LCL=0
1 19 37 55 73 91 109 127 145 163 181
Sample


Xbar-R Chart of Spent Chloride
Using Box-Cox Transformation With λ = -1.45
Sample Mean
0.0125
0.0100
0.0075
0.0050
UCL=0.009972
X̿=0.007864
LCL=0.005755
Sample Range
0.0045
0.0030
0.0015
0.0000
UCL=0.002590
R̄=0.000793
LCL=0
1
19
37
55
73
91
109
127
145
163
181
Sample

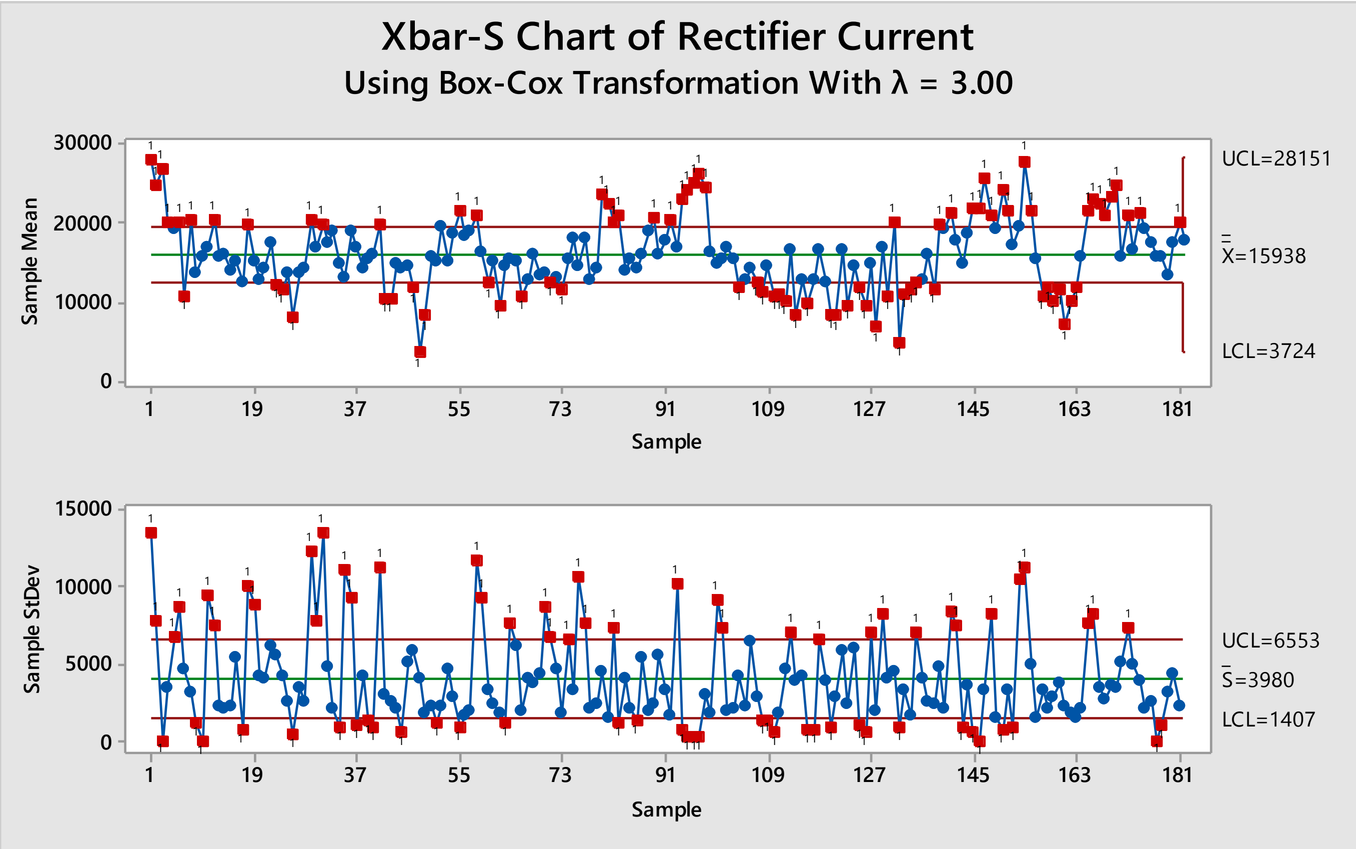

Xbar-R Chart of Circulating Chloride
Using Box-Cox Transformation With λ = -2.41
Sample Mean
0.0006
0.0004
0.0002
0.0000
UCL=0.0004903
X̿=0.0003286
LCL=0.0001670
Sample Range
0.00045
0.00030
0.00015
0.00000
UCL=0.0001986
R̄=0.0000608
LCL=0
1
19
37
55
73
91
109
127
145
163
181
Sample


Xbar-R Chart of Advance Redox Potential
Sample Mean
800
700
600
500
UCL=756.6
X̿=700.8
LCL=645.1
Sample Range
480
360
240
120
0
UCL=68.5
R̄=21.0
LCL=0
1
19
37
55
73
91
109
127
145
163
181
Sample


Xbar-R Chart of Spent Redox Potential
Sample Mean
800
700
600
500
UCL=759.2
X̿=697.0
LCL=634.7
Sample Range
400
300
200
100
0
UCL=76.5
R̄=23.4
LCL=0
1
19
37
55
73
91
109
127
145
163
181
Sample

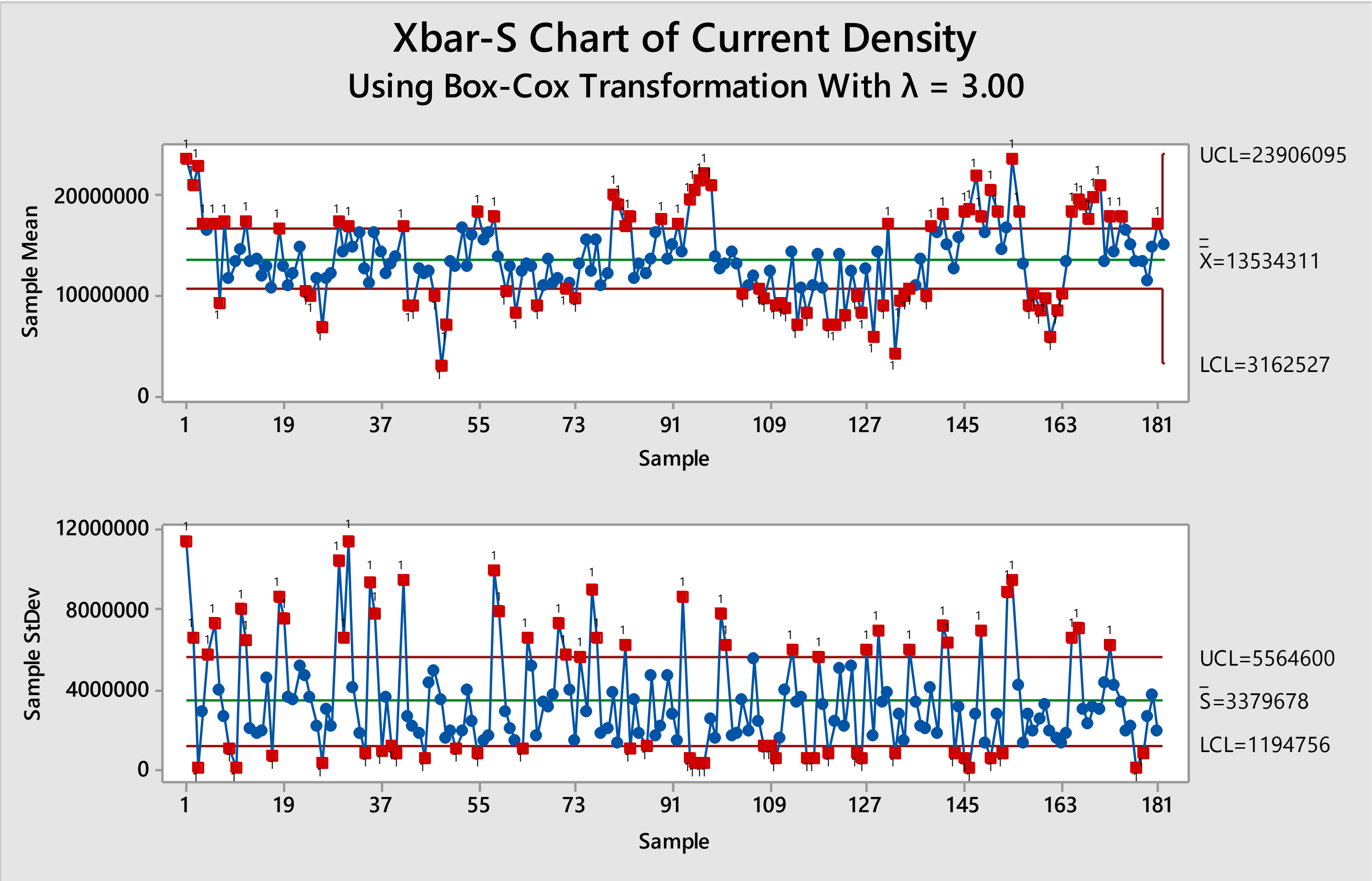


Xbar-R Chart of Circulating Redox Potential



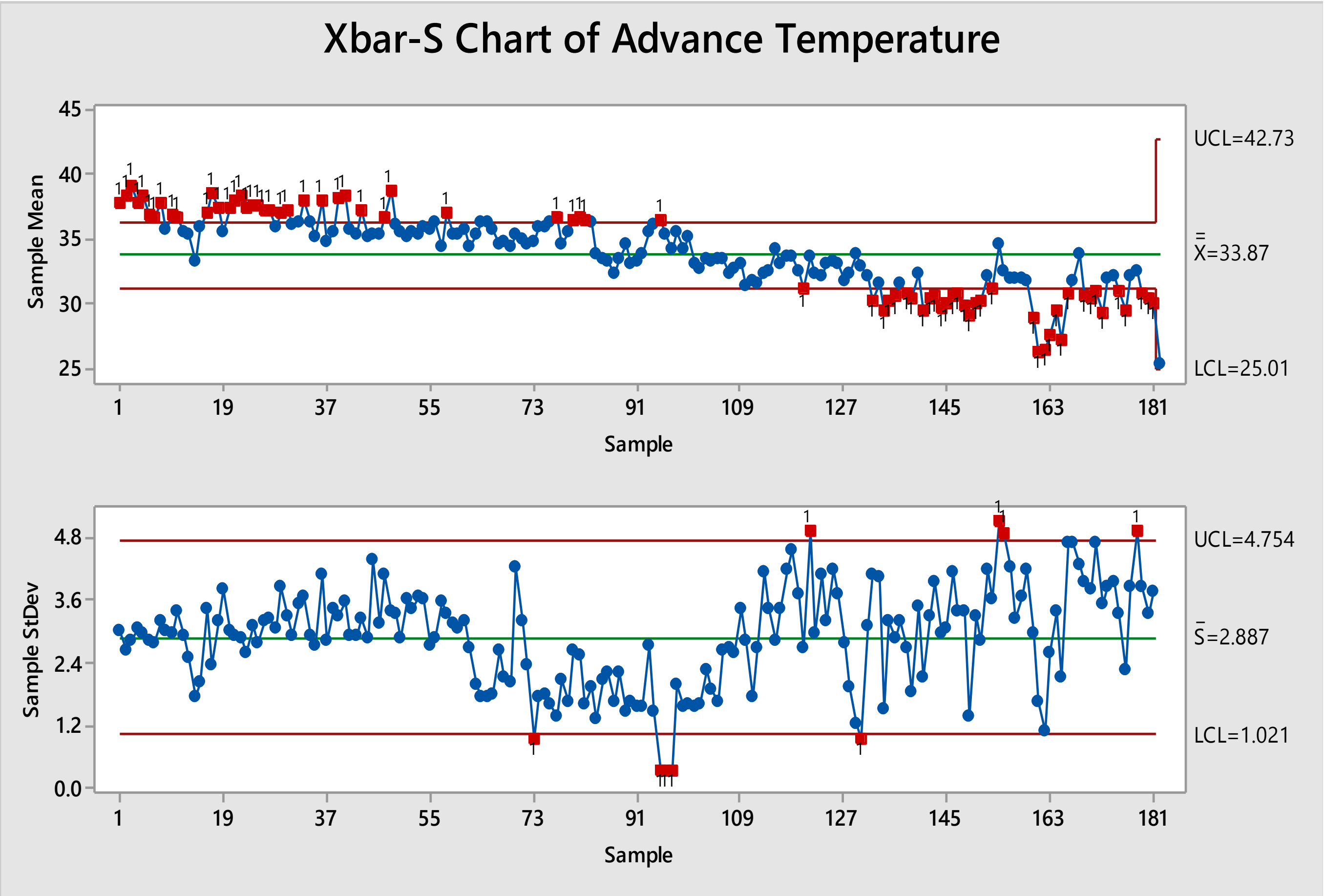
Xbar-S Chart of Rectifier Current

Using Box-Cox Transformation With λ = 3.00



Xbar-S Chart of Current Density

Using Box-Cox Transformation With λ = 3.00



Xbar-S Chart of Advance Temperature

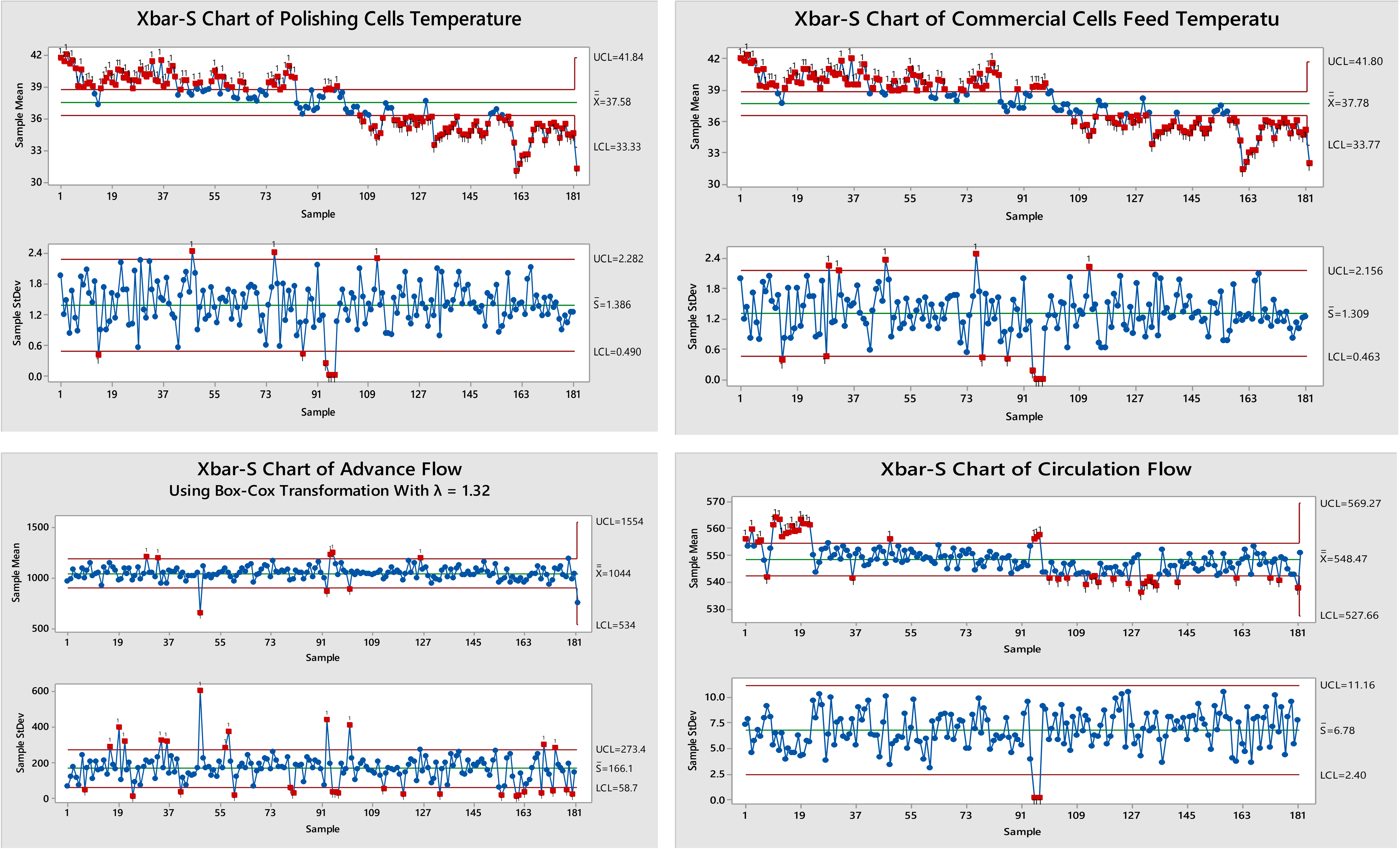


Figure 4.11: Xbar-R and Xbar-S charts for current efficiency factors (created by the author)

Table 4.6: Analysis of the control chart results (created by the author)

Parameter	Out of control points for a specific control chart						Percent of total	OOC points aligned to CE OOC points							
	I chart	MR Chart	Xbar chart	S chart	R chart	Total	OOC points (%)	I chart	MR Chart	Xbar chart	S chart	R chart	Total	Aligned (%)	Misaligned (%)
Current efficiency	3	5	0	0	0	8	0.43	3	5	0	0	0	8	100.00	-
1. PCF_Cu concentration (g/l)	0	0	62	8	0	70	3.72	0	0	3	0	0	3	37.50	95.71
2. SEX_Cu concentration (g/l)	0	0	72	28	0	100	5.32	0	0	3	0	0	3	37.50	97.00
3. CCF_Cu concentration (g/l)	0	0	67	25	0	92	4.89	0	0	2	0	0	2	25.00	97.83
4. PCF_H2SO4 concentration (g/l)	0	0	46	11	0	57	3.03	0	0	0	1	0	1	12.50	98.25
5. SEX_H2SO4 concentration (g/l)	0	0	38	11	0	49	2.61	0	0	1	1	0	2	25.00	95.92
6. CCF_H2SO4 concentration (g/l)	0	0	33	13	0	46	2.45	0	0	1	1	0	2	25.00	95.65
7. PCF_Total Fe concentration (ppm)	0	0	67	0	7	74	3.94	0	0	0	0	0	0	-	100.00
8. SEX_Total Fe concentration (ppm)	0	0	72	0	6	78	4.15	0	0	0	0	0	0	-	100.00
9. CCF_Total Fe concentration (ppm)	0	0	68	0	5	73	3.88	0	0	0	0	0	0	-	100.00
10. SEX_Co concentration (ppm)	0	0	69	0	10	79	4.20	0	0	3	0	0	3	37.50	96.20
11. CCF_Co concentration (ppm)	0	0	68	0	10	78	4.15	0	0	3	0	0	3	37.50	96.15
12. PCF_Cl concentration (ppm)	0	0	67	0	9	76	4.04	0	0	3	0	1	4	50.00	94.74
13. SEX_Cl concentration (ppm)	0	0	76	0	8	84	4.47	0	0	3	0	0	3	37.50	96.43
14. CCF_Cl concentration (ppm)	0	0	67	0	8	75	3.99	0	0	3	0	1	4	50.00	94.67
15. PCF_Eh (mV)	0	0	20	0	1	21	1.12	0	0	2	0	0	2	25.00	90.48
16. SEX_Eh (mV)	0	0	14	0	4	18	0.96	0	0	1	0	0	1	12.50	94.44

17. CCF_Eh (mV)	0	0	22	0	1	23	1.22	0	0	2	0	0	2	25.00	91.30
18. Rectifier Current (kA)	0	0	85	74	0	159	8.46	0	0	4	3	0	7	87.50	95.60
19. Current density (A/m2)	0	0	85	74	0	159	8.46	0	0	4	3	0	7	87.50	95.60
20. Advance temperature (°C)	0	0	71	9	0	80	4.26	0	0	3	0	0	3	37.50	96.25
21. Polishing cells temperature (°C)	0	0	134	9	0	143	7.61	0	0	3	0	0	3	37.50	97.90
22. Commercial cells temperature (°C)	0	0	139	13	0	152	8.09	0	0	4	1	0	5	62.50	96.71
23. Circulation flowrate (m3/h)	0	0	43	3	0	46	2.45	0	0	1	0	0	1	12.50	97.83
24. Advance flowrate (m3/h)	0	0	8	32	0	40	2.13	0	0	1	0	0	1	12.50	97.50
					Total	**1880**	**100.00**					**Total**	**70**		-

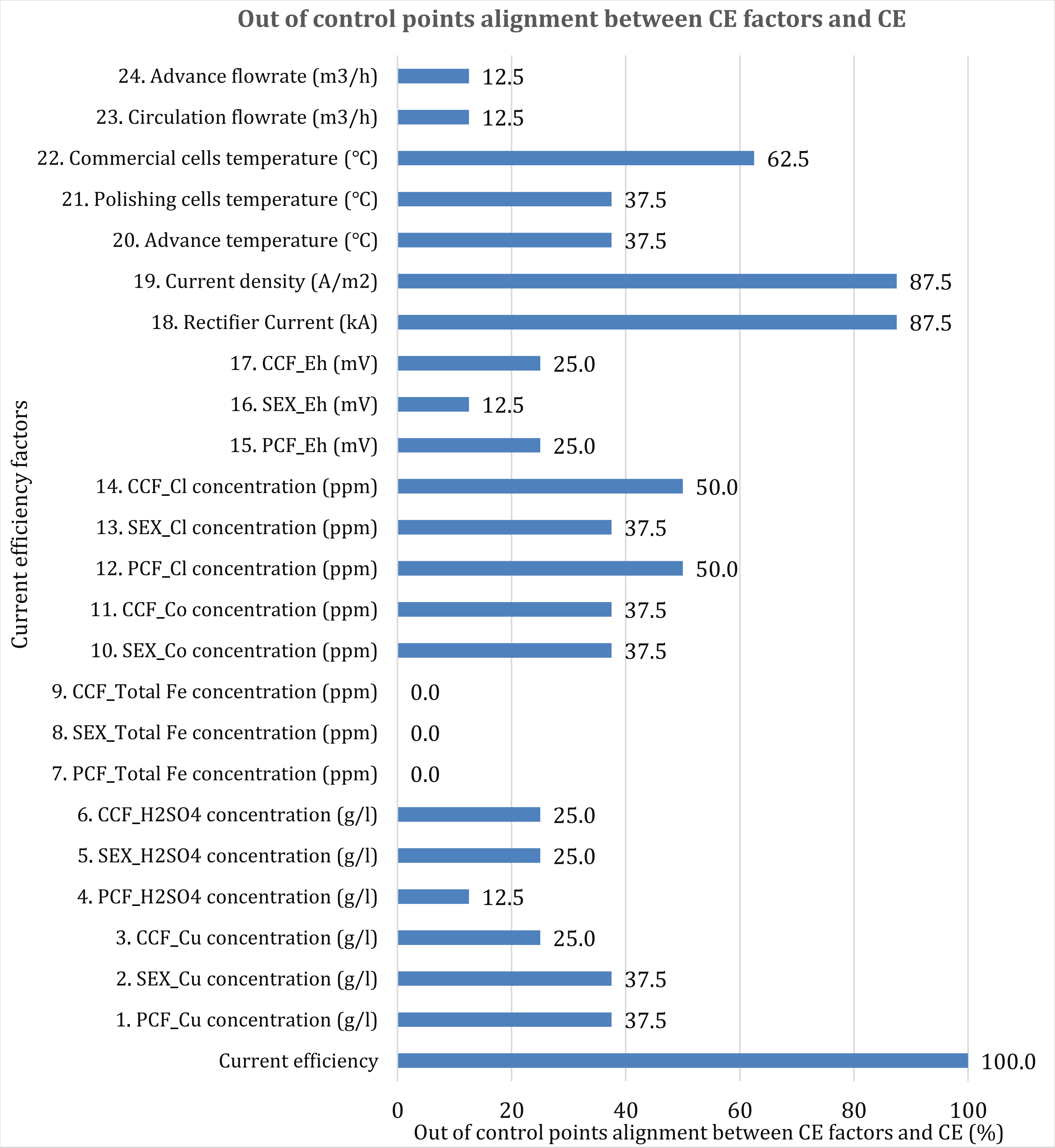


Figure 4.12: Bar chart for comparing the alignment between the out of control points (created by the author)

4.3.3.1 Discussing current efficiency factor control charts

All the current efficiency factors were not under statistical control. This is because they all failed the first test (first Shewhart rule). Current efficiency was also out of control. Due to the complexity of the electrowinning process, it is difficult to justify that all these special causes contributed to CE being out of control.

<u>The following has been deduced from the above control charts:</u>

1. An instantaneous change in the current efficiency factor may be regarded as an out of control point due to a special cause. However, the current efficiency factor might still be magnitude low to have a significant effect on CE. This is why it is important to understand which factors have a significant effect on current efficiency. The impact or magnitude of their contribution differs. Nonetheless, a trend should be observed between the factor and current efficiency.

2. Some current efficiency factors such as temperature have seasonal changes. This can clearly be seen on the control chart. The high temperature was reported during summer and low temperatures during winter as expected. As a result, there is a notable decreasing trend in temperature. These upper and lower extremes in temperature are reported as out of control points. The heat exchanger is unable to maintain the temperature within a specific range due to changes in the weather condition.

3. The electrolyte iron concentration was found to be very unstable. Because it is showing sharp uptrends and downtrends. These high and low extremes are regarded as out of control points. The upward trend normally occurs due to an impurity excursion event or any other reason as shown in Figure 4.14 below. While the downtrend is normally the reaction aimed at reducing the electrolyte iron as an action to rectify impurity excursion. This can be done by applying the methods depicted in Figure 4.15 below.

4. Current efficiency factors such as the electrolyte chloride and cobalt concentration show repeated uptrends and downtrends. This is basically due to poor process control because these reagents are dosed manually and there is no online controller for them. However, sometimes they are purposefully increased as a response to process changes especially cobalt which is increased whenever manganese excursion is experienced.

5. Amongst all the factors investigated only the spent electrolyte sulphuric acid concentration has been properly controlled. This is mainly because there is an inline mixer instrument that controls sulphuric acid concentration. This makes controlling easy and it reduces the chances of out of control points.

6. It is difficult to conclude on the impact of any of the CE factors on CE by using the control charts only. This can be addressed further by doing a correlation analysis between current efficiency and the factors.

4.3.3.2 Analyzing the out of control points for CE and CE factors

The control charts have been further analyzed as shown in Table 4.6 and Figure 4.12 above. In this case, the out of control point's alignment was evaluated. The data shows the following:

1. The factors whose out of control points are mostly aligned with the current efficiency out of control points can be arranged as follow: Rectifier current, current density, commercial cells temperature, chloride concentration, polishing cells temperature, advance temperature, copper concentration, cobalt concentration, advance flowrate and circulating flowrate and iron concentration.

2. Current and current density have 159 out of control points each. This is the highest out of control points amongst all other factors. These represent 8.46 % of all the total out of control points. These two factors have 87.5 % alignment and 95.60 % misalignment to CE out of control points respectively. These factors were expected to have a lot of out of control points because they are due to a known special cause. The

special cause is decreased rectifier current when short-circuiting during non-stripping days. This is done for 2 consecutive days after every 4 stripping days. If the rectifier current and current density had a significant effect on current efficiency there will be a lot of out of control points corresponding to the decrease in rectifier current.

3. Interestingly, the electrolyte iron concentration does not have any out of control points aligned with the current efficiency out of control points. This does not mean it does not have an effect on current efficiency. Theoretically, high iron concentration has a significant effect on current efficiency, but its concentration plays a big role. However, for this electrowinning process iron concentration is low.

4. The out of control point's alignment analysis will only work if the factor has a very significant effect on current efficiency. This is because a variable might not have a significant effect, but it has many out of control points that might be aligned with current efficiency. This can easily result in a wrong conclusion deduced. It is, therefore best to do a correlation analysis in order to have an in-depth understanding of the effect of the factors on current efficiency.

4.3.4 Correlation analysis between CE and CE factors

The correlation between current efficiency and its factors is presented in Figure 4.13 below. The p-value less than the significance level of 0.05 indicates that the correlation coefficient is significant. If the p-value is greater than 0.05 it means there is inconclusive evidence about the significance of the association between CE and its factors. On the other hand, the Pearson correlation coefficient ranges from -1 to +1. The larger the absolute value of the coefficient the stronger the relationship between current efficiency and its factors. An absolute Pearson correlation value of 1 indicates a perfect linear relationship. While a correlation coefficient near 0 indicates no linear relationship between CE and its factors.

Table 4.7: Correlation analysis between CE and CE factors (compiled by the author)

Factor	P-value	Pearson correlation coefficient
1. PCF_Cu concentration (g/l)	0.310	0.093
2. SEX_Cu concentration (g/l)	0.807	0.023
3. CCF_Cu concentration (g/l)	0.276	-0.100
4. PCF_H_2SO_4 concentration (g/l)	0.187	0.121
5. SEX_H_2SO_4 concentration (g/l)	0.423	0.074
6. CCF_H_2SO_4 concentration (g/l)	0.416	0.075
7. PCF_Total Fe concentration (ppm)	0.068	-0.167
8. SEX_Total Fe concentration (ppm)	0.054	-0.177
9. CCF_Total Fe concentration (ppm)	0.066	-0.169
10. SEX_Co concentration (ppm)	0.351	-0.086
11. CCF_Co concentration (ppm)	0.333	-0.089
12. PCF_Cl concentration (ppm)	0.375	0.082
13. SEX_Cl concentration (ppm)	0.344	0.087
14. CCF_Cl concentration (ppm)	0.238	0.108
15. PCF_Eh (mV)	0.125	-0.141
16. SEX_Eh (mV)	0.136	-0.137
17. CCF_Eh (mV)	0.120	-0.143
18. Rectifier Current (kA)	0.567	-0.053
19. Current density (A/m^2)	0.050	0.179
20. Advance temperature (°C)*	0.000	0.321
21. Polishing cells temperature (°C)*	0.001	0.301
22. Commercial cells temperature (°C)*	0.001	0.295
23. Circulation flowrate (m^3/h)	0.069	0.167
24. Advance flowrate (m^3/h)	0.839	0.019

In which the asterisk (*) indicates factors with a p-value less than 0.05 and they have the highest Pearson correlation coefficient.

Discussing Pearson correlation analysis results

The results of the correlation analysis show that only factors whose p-value is less than 0.05 are statistically correlated to current efficiency. The Pearson correlation coefficient is indicating the strength and direction of the correlation. The correlation analysis was done by testing for the correlation between current efficiency and one of the factors at a time. This will only reflect the correlation between current efficiency and that specific factor.

However, sometimes there are interactions between the factors and the effect on current efficiency will become more complicated. In addition to that, a low Pearson correlation coefficient does not mean that no relationship exists between the variable and current efficiency. The variable may have a nonlinear relationship. To check for nonlinear relationships graphically, a scatterplot or simple regression should be created. Nonetheless, the results in Table 4.7 above are presented in Figure 4.13 below. The asterisk (*) indicates factors with a p-value less than 0.05 and they have the highest Pearson correlation coefficient.

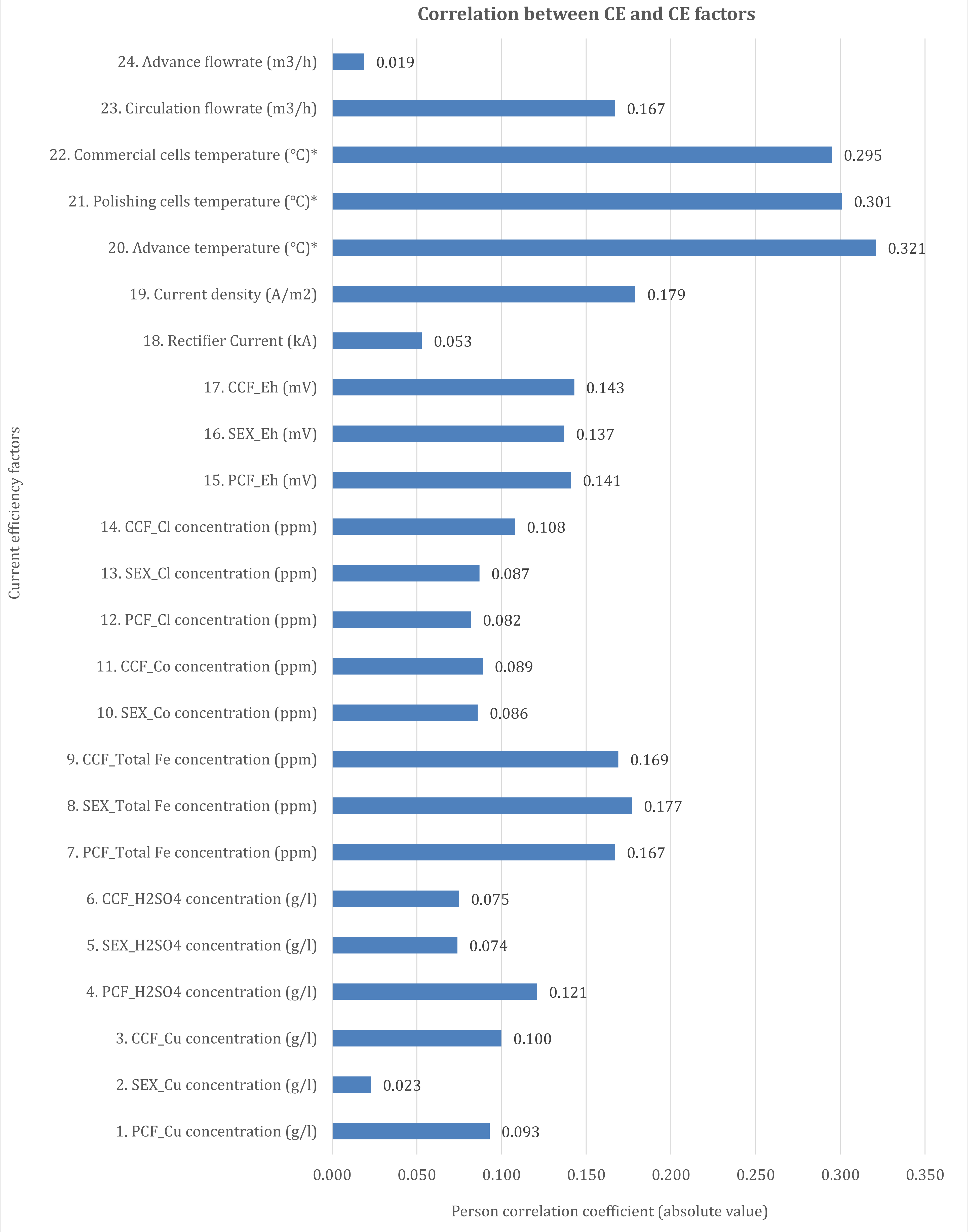


Figure 4.13: A bar chart depicting Pearson correlation coefficient between CE and CE factor (created by the author)

Further discussion of the correlation results

As shown in Figure 4.13 above the factor that depicts a very strong correlation to current efficiency is the electrolyte temperature, followed by current density, electrolyte iron concentration, circulating electrolyte flowrate, electrolyte reduction-oxidation potential, electrolyte chloride concentration, electrolyte copper concentration, electrolyte cobalt concentration, rectifier current and then the advance flow rate. The correlation analysis clearly shows whether there is a directly proportional or inversely proportional relationship between the factor and current efficiency. The negative correlation coefficient shows the inverse proportional direction and vice-versa.

Ishikawa diagram presenting the root cause analysis (RCA) of high electrolyte iron tenor

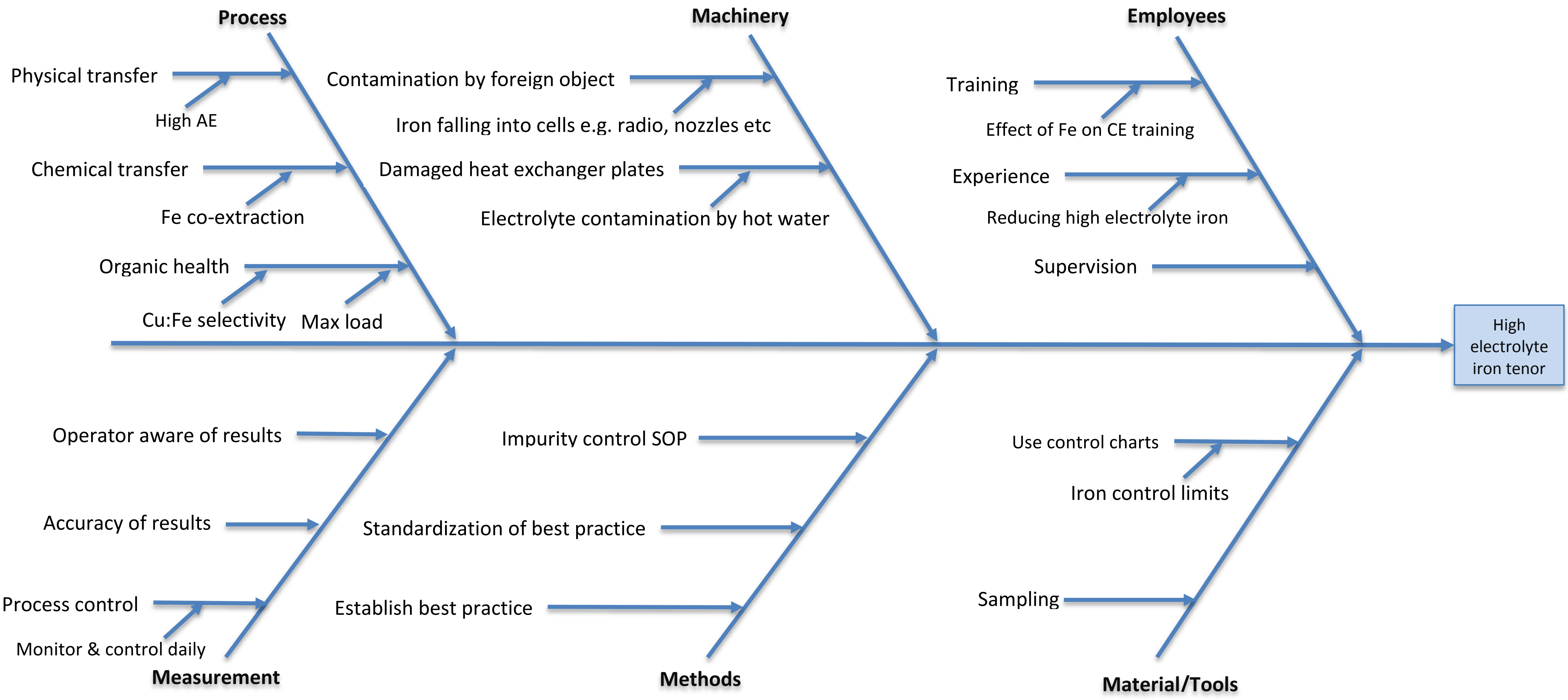


Figure 4.14: The Ishikawa diagram for high electrolyte iron tenor (designed by the author)

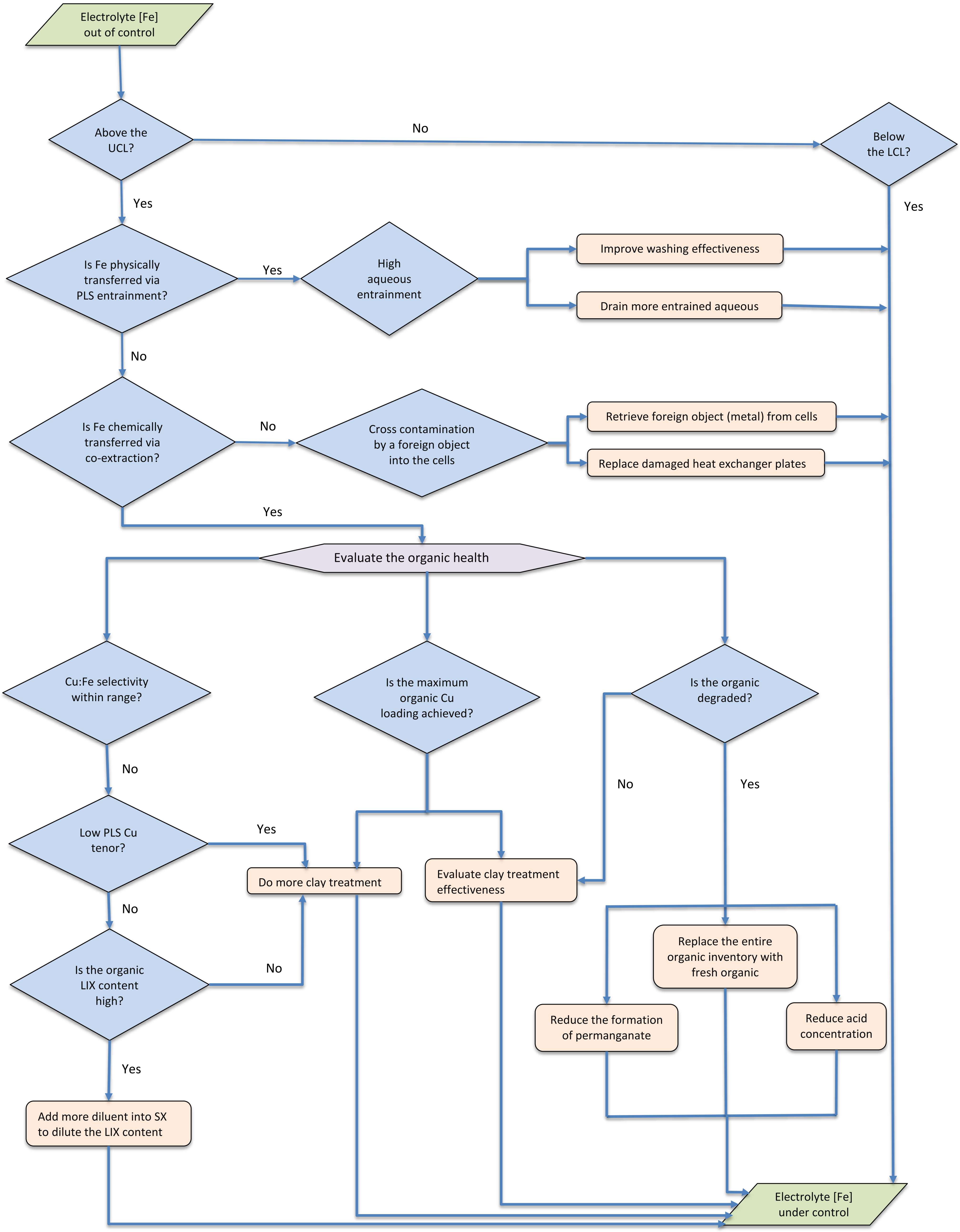


Figure 4.15: An out of control action plan for electrolyte Fe tenor (designed by the author)

4.3.5 Discussing the Ishikawa diagram for electrolyte iron tenor

An RCA presented in Figure 4.14 above shows that there are a lot of potential root causes of high electrolyte iron concentration. The root causes were identified from the process, machinery, employees, measurement, methods and the material/tools.

The possible special causes of variation due to the process are issues such as the physical transfer example due to high aqueous entrainment, chemical transfer via co-extraction and the organic health issues such as Cu:Fe selectivity and maximum copper loading onto the extractant.

The machinery at the electrowinning plant can also cause increased electrolyte iron concentration. This can occur if a foreign object/metal fall into the electrolyte. The damaged plates of heat exchangers can also result in cross-contamination of the electrolyte with high iron-contained hot water.

The employees can have an effect on the electrolyte iron concentration depending on their level of training and/or understanding of current efficiency. The experience of the operators, supervisor and technical team plays a big role. This is because the electrolyte iron concentration needs to be controlled within a specific range and if the employees do not know how to do it, the electrolyte iron tenor can get out of control.

Measurement can cause increased iron concentration especially if the analytical equipment is not giving accurate results. Early awareness of the operator regarding the changes in the measured/analyzed results can help with the fast response so that the iron tenor is kept under control. Having an appropriate process control system in place also assists with monitoring and controlling the process and hence the iron concentration.

The methods of controlling high electrolyte iron such as having procedures for reducing electrolyte iron, having the best practice established and standardized. These all facilitate in getting iron under control. The material or the tools in place such as the usage of control charts for monitoring iron tenor and also how the samples are taken can also be the special causes of high iron concentration.

4.3.6 Discussing electrolyte iron tenor out of control action plan

The out of control action plan (OCAP) for electrolyte iron tenor is depicted in Figure 4.15 above. The electrolyte iron concentration will be deemed out of control if it has points above the upper control limit (UCL) or below the lower control limit (LCL). It should be noted that this parameter is not usually controlled within a specific range. Because the lower it is the better. This means if it is below the lower control limit its actually good. However, it should not be allowed to exceed the upper control limit. Therefore, if the electrolyte iron concentration is below the lower control limit may be considered to be under control. If it is above the upper control limit it is not under control and an out of control action plan should be initiated immediately.

Iron can get transferred from solvent extraction (SX) to electrowinning (EW) either by physical transfer or by chemical transfer. Physical transfer occurs mainly due to high aqueous (PLS) entrainment. This can be mitigated by improving organic washing effectiveness and also by draining out all the entrained aqueous. On the other hand, the chemical transfer of iron includes the co-extraction of iron by the extractant. The third potential source of iron is if a foreign object or metal fall into the electrolytic cells. This iron-based metal will dissolve hence contaminating the electrolyte with iron. The iron-based object needs to be retrieved from the cells immediately. It is also possible that the heat exchanger plates might be damaged. Hence causing cross-contamination of the electrolyte and hot water which has high iron concentration. This is normally detected due to the decrease in hot water pH. The pH decreases because of the presence of the increased hydrogen ions. The hot water pH is normally controlled at around 9.00 if it decreases, it is due to high acid from the electrolyte. This only happens if the plates are damaged. They should be replaced. Regular inspection of the heat exchanger plates is crucial.

If iron is chemically transferred via co-extraction, it is crucial to evaluate the organic health. This should be done by looking at Cu:Fe selectivity, maximum organic copper loading, and organic degradation. Low Cu:Fe selectivity usually occurs if the PLS Cu tenor is low and/or the LIX content is too high. This can be improved by doing clay treatment which removes the contaminants from the organic. High LIX content should be diluted by adding more diluent (shellsol/masimosol) into the SX plant.

Low maximum copper loading can also be resolved by doing clay treatment and also by evaluating the effectiveness of clay treatment. If maximum loading is not achieved it gives iron a high chance for it to become extracted. Degraded organic affects the performance of the extractant. The organic parameters such as Cu:Fe selectivity and maximum copper loading are also affected. This can indirectly affect electrolyte iron concentration. Organic degradation can be improved by reducing the formation of permanganate at electrowinning, exposing barren organic to excessive sunlight and increased sulphuric acid concentration in the spent electrolyte. The entire organic inventory can be replaced with fresh organic depending on the extent of the degradation.

4.4 Analysis of current efficiency attribute factors

All the factors analyzed above are mainly chemical or instrument measured factors. They are easily quantifiable since samples are collected every day and online instruments are measuring them. However, other current efficiency factors not easily quantifiable. The historical data for these factors is not available also. These factors include the formation of metallurgical short-circuits (hotspots), the degree by how much the electrode contacts are covered by organic stains (especially on the intermediate bus bars and electrodes) and the degree of electrode alignment (rat patrol). Most of these factors are impossible to quantify accurately. It is for this reason only the metallurgical short-circuits (hotspots) will be presented. These attribute factors were investigated and improved during a current efficiency improvement campaign for almost 2 months (September to October 2019). The images below shows activities during this improvement campaign.

4.4.1 Metallurgical short-circuits (hotspots)

During the current efficiency improvement campaign, it was observed that there were a lot of hotspots in the cells. The hotspots were detected by making use of an infrared (IR) camera. The temperature of the electrode contacts is normally controlled at $\leq 55℃$. However, high electrode contact temperatures were observed as shown in Figure 4.28 below. It was observed that the formation of hotspots was mainly due to plated copper protrusions called nodules, missing side insulators and bend anodes. In this case, the cathodes are manually removed from the cells and the nodules are knocked off as shown in Figure 4.22 below.

However, this is a reactive approach. The proactive approach is ensuring no nodule formation by monitoring and controlling the flocculant plant. The bend anodes are replaced with new anodes this resulted in increased electrode replacement. From theory, it is known that the short-circuits will result in high resistance. Instead of current being used for electroplating copper it is heating the electrode contacts or short-circuit. Hence reducing current efficiency. It is almost impossible to accurately quantify the extent by which current efficiency is effected by metallurgical short-circuits (hotspots).

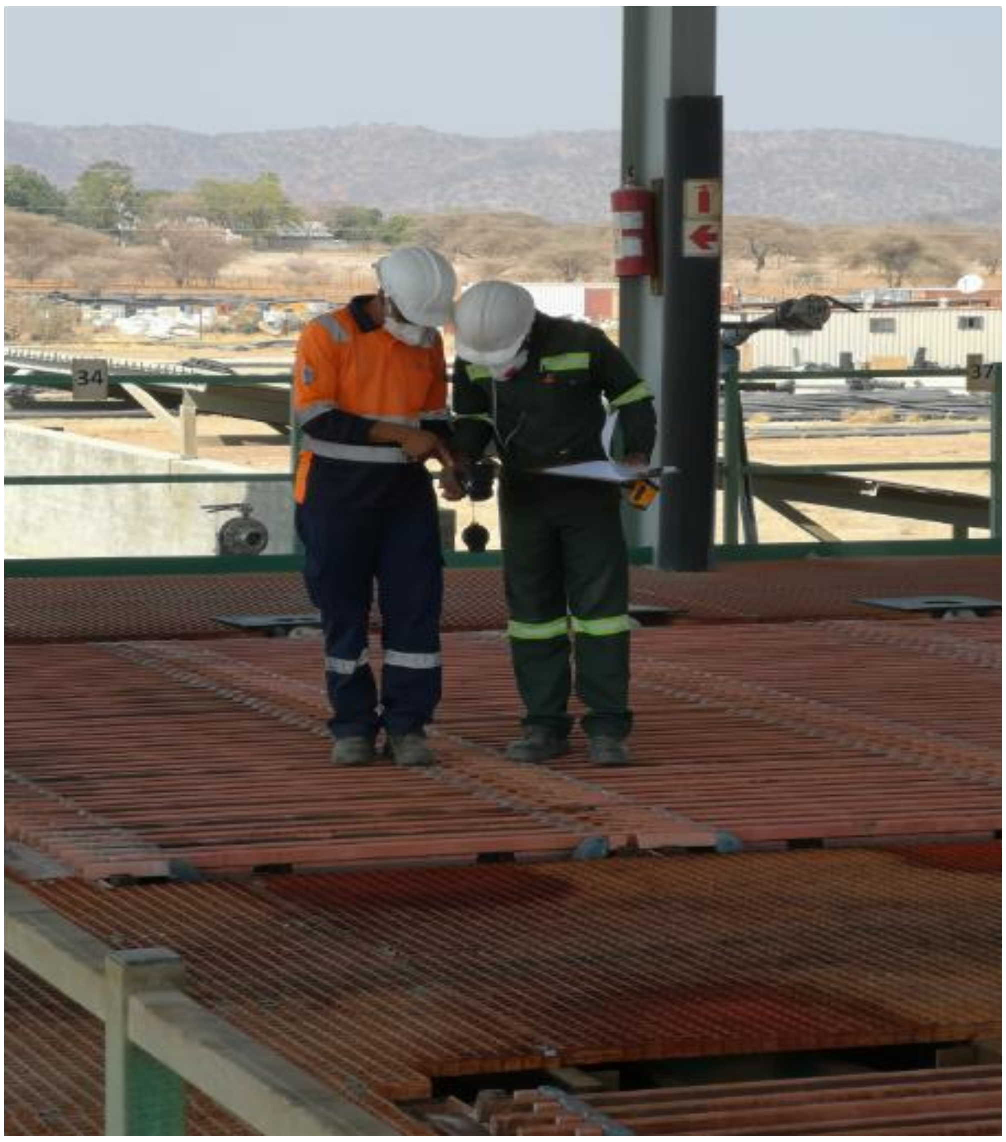


Figure 4.16: Using an IR camera for hotspots detection (picture taken by the author)

Figure 4.17: Removing a suspected cathode for inspection (picture taken by the author)

Figure 4.18: Removing a suspected anode for inspection (picture taken by the author)

Figure 4.19: A burned anode with a missing side insulator (picture taken by the author)

Figure 4.20: A burned anode which was contacting a cathode (picture taken by the author)

Figure 4.21: Short-circuit due to nodules on a cathode (picture taken by the author)

Figure 4.22: Knocking off nodules on a cathode sheet (picture taken by the author)

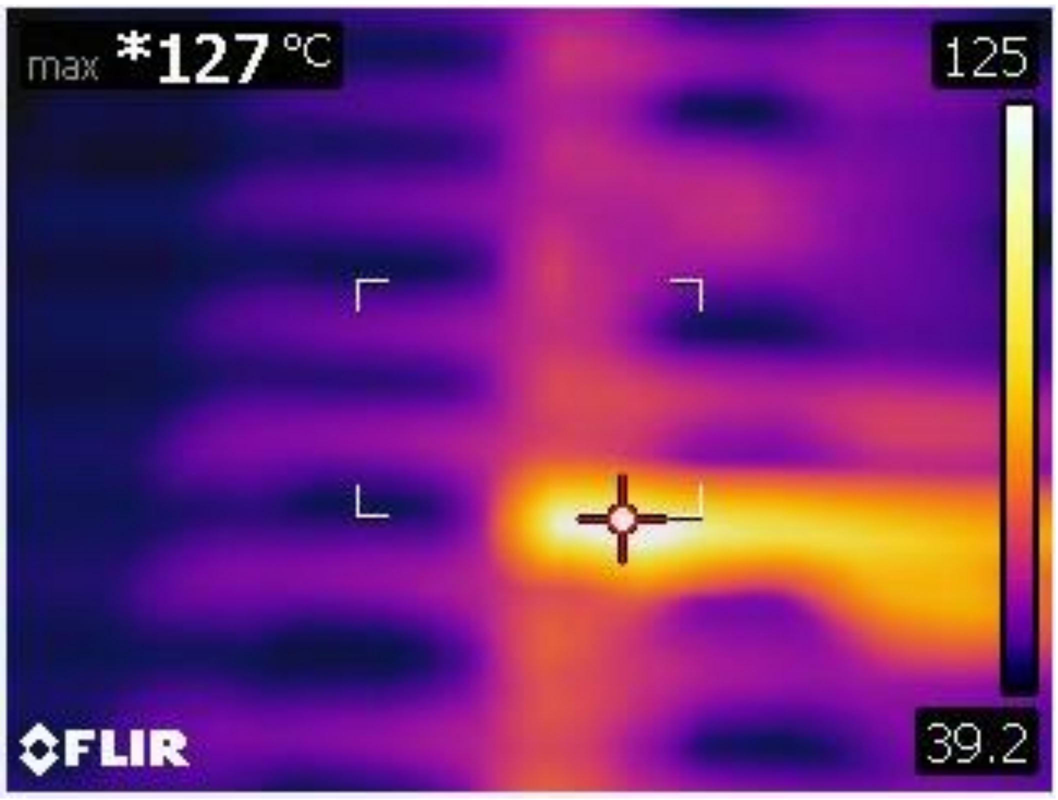
Figure 4.23: Straightening a bend anode with a wood (picture taken by the author)

Figure 4.24: Replacing a burnt anode with a brand new anode (picture taken by the author)

Figure 4.25: Cleaning cathode contacts using acetone (picture taken by the author)

Figure 4.26: Cleaning anode contacts using steel brushes (picture taken by the author)

Figure 4.27: Aligning electrodes by doing rat patrol (picture taken by the author)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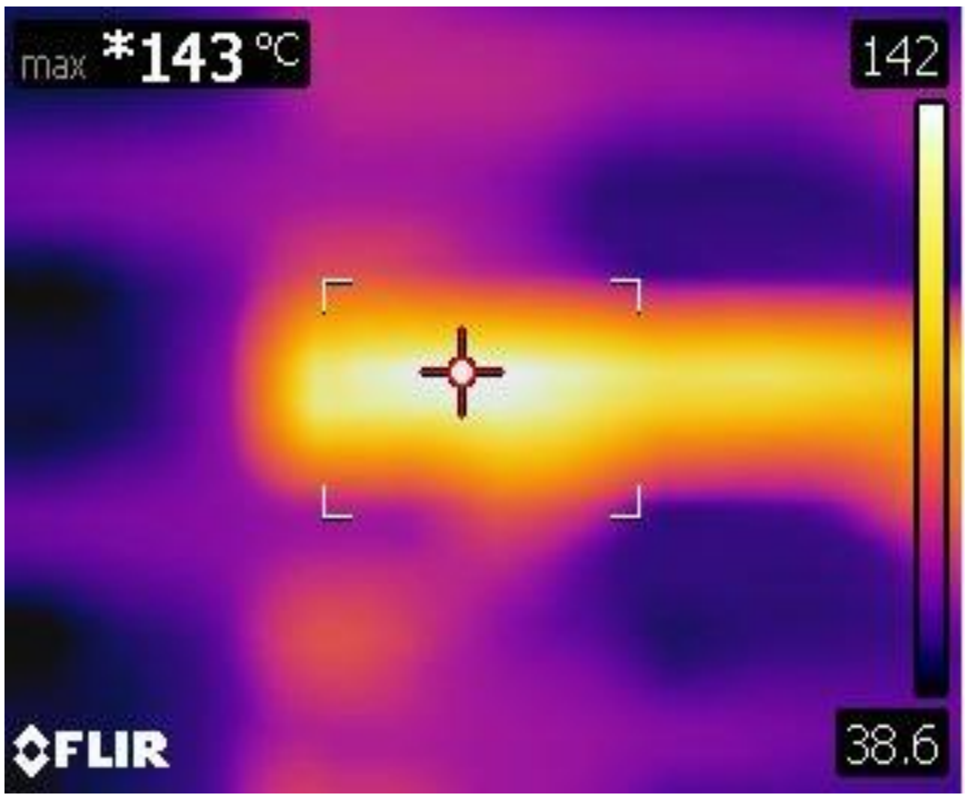
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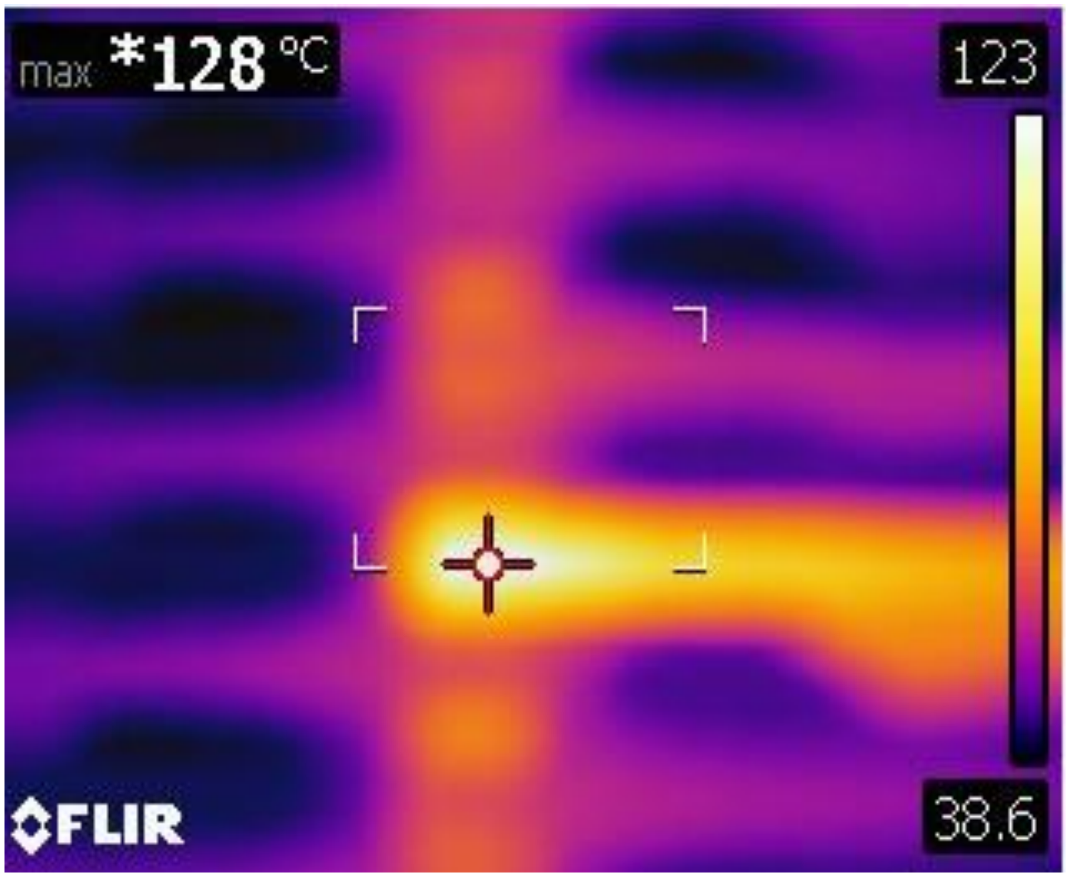
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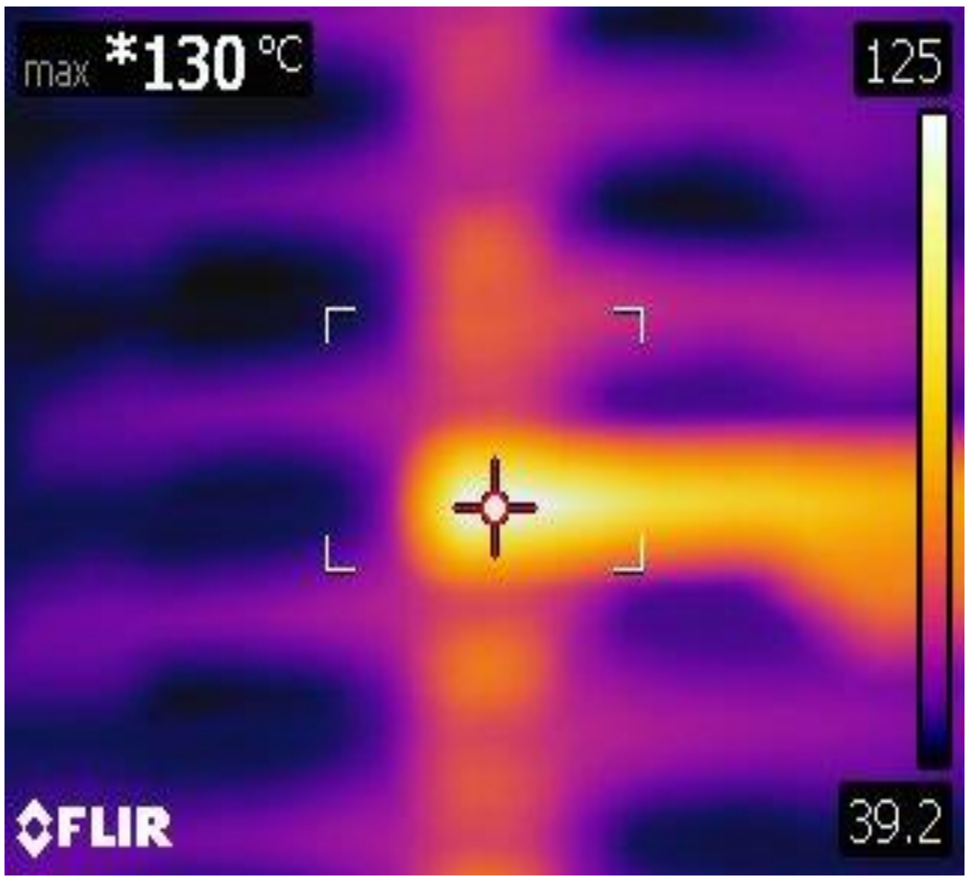
38.6
FLIR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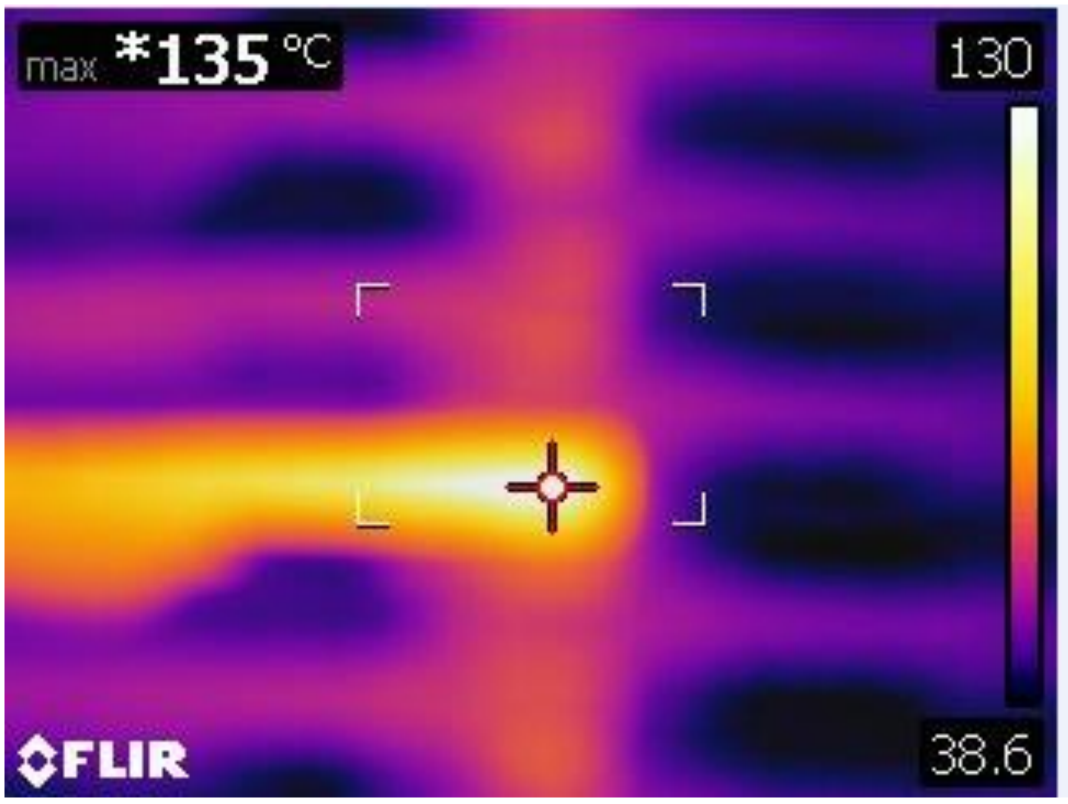
39.2
FLIR


max *135 °C
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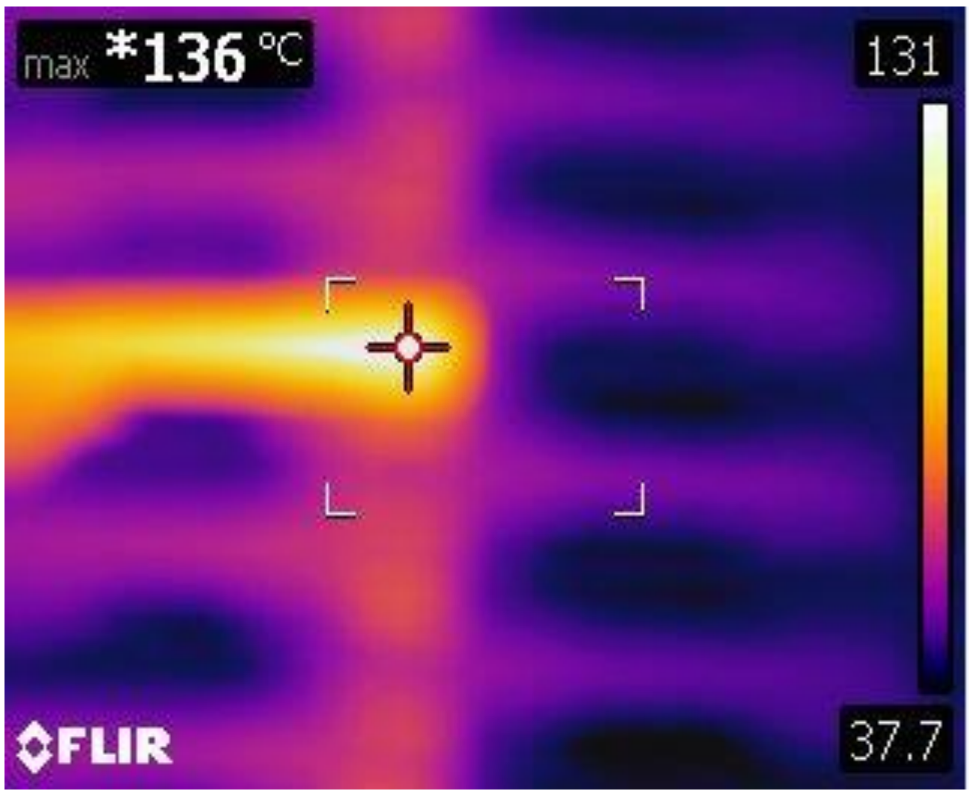
38.6
FLIR


max *136 °C
131
37.7
FLIR

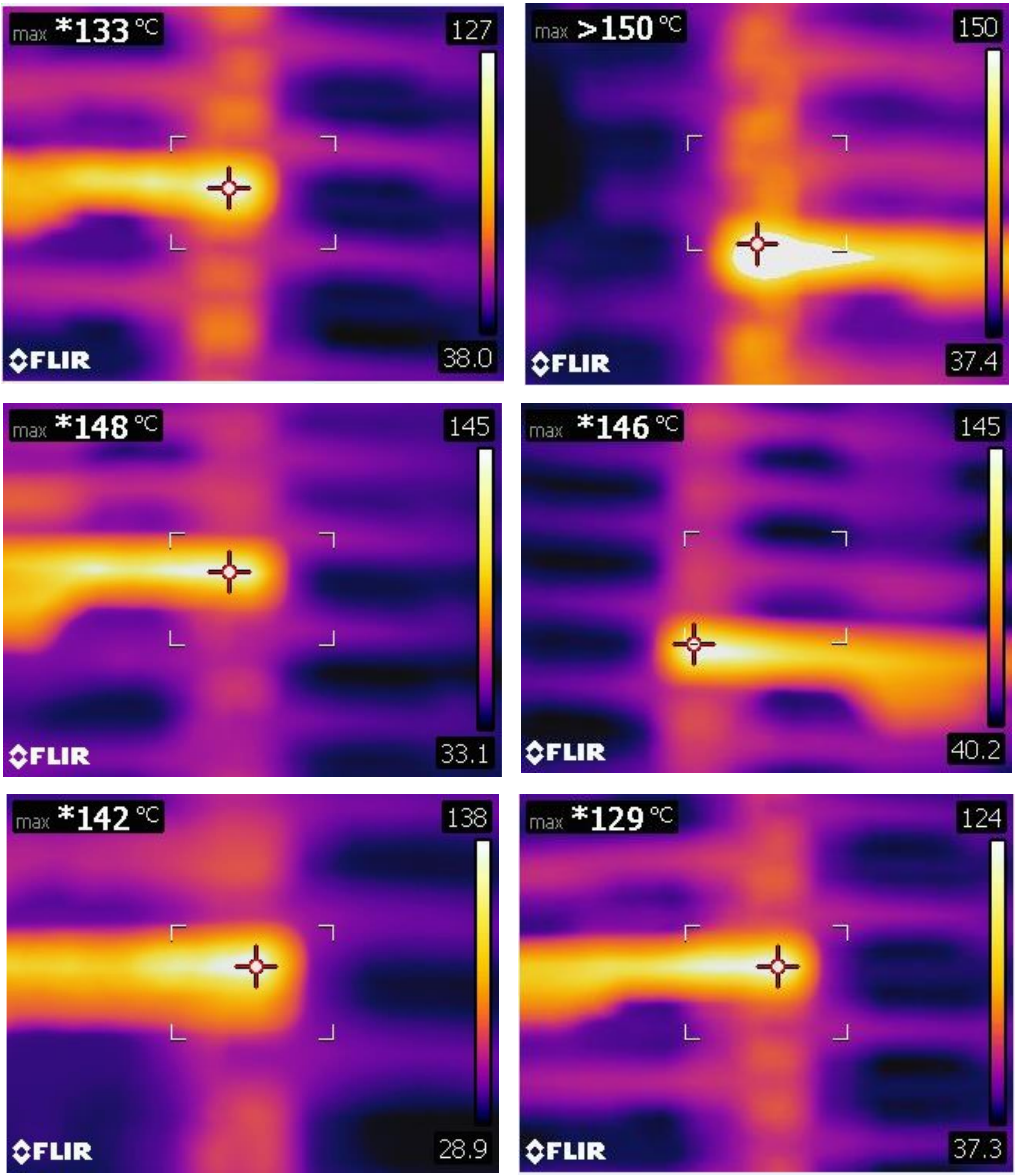


Figure 4.28: Infrared (IR) camera pictures for detected metallurgical short-circuits (hotspots) (Infrared pictures taken by the author)

4.4.2 Explaining the improvement in current efficiency

Current efficiency was improved during the current efficiency improvement campaign period. The improvement in current efficiency was mainly attributable to the reduction in the number of metallurgical short-circuits (hotspots). The improvement in current efficiency is presented as daily current efficiency, running average current efficiency and average current efficiency per stripping cycle presented in Figure 4.29, Figure 4.30 and Figure 4.31 respectively as shown below.

From the graphs, it can clearly be seen that current efficiency has improved. The daily current efficiency trend in Figure 4.29 shows an improvement in current efficiency from a minimum value of 89.64 % to a maximum value of 95.04 %. This represents an improvement of 5.40 %. A daily current efficiency linear trend has an R^2 value of 0.7741. Meaning the linear trend could only represent 77.41 % of the data. This is because the data points seem more scattered at the beginning of the improvement campaign than at the end.

It is worth noting that, the improvement in current efficiency by 5.40 % translated into 74 metric tons of 99.999 % purity grade A copper cathode production. This is after taking into account 1378 metric tons of copper cathodes produced in September 2019. Considering a copper price of US$ 6000 per metric ton and the currency conversion rate from US$ to N$ of N$15/US$, the monetary electrical energy savings or value created due to the improvement in current efficiency may be estimated, and it will clearly indicate the significance of this research.

The running average current efficiency graph in Figure 4.30 shows an increase in current efficiency during the campaign. This is in line with the daily current efficiency graph. The running average line increased from 90.47 % to as high as 92.58 % running average current efficiency. The running average current efficiency shows an improvement of 2.11 %. A linear trend line also has a positive gradient indicating an increase in current efficiency and it has a coefficient of determination (R^2 value) of 95.71 %. This is a very good linear model.

On the other hand, the average current efficiency per stripping cycle in Figure 4.31 also shows that current efficiency has improved. On the bar graph, the average current efficiency has increased from 90.79 % to 95.04 % (an increase by 4.25 %). The linear trend line has a positive gradient confirming the increase in current efficiency and it represents 93.78 %.

Therefore, the framework that will be designed has a potential to improve current efficiency by at least 5.40 %. This can be achieved by focusing on metallurgical short-circuits (hotspots) monitoring, and rectification, cleaning dirty contacts by using steel brushes and/or acetone, regular electrode maintenance by replacing bend/damaged electrodes, cleaning anodes regularly, replacing missing side insulators, cathode smoothing agent monitoring and control, removing formed cathode nodules and doing cell cleaning regularly.

Nonetheless, the main contributing factor is monitoring and rectifying metallurgical short-circuits (hotspots). These findings may be used in general (as a rule of thumb) for improving electrowinning current efficiency. This is because metallurgical short-circuits (hot-spots) result in a significant conversion of electrical energy into heat which then contributes substantially to the decrease in current efficiency. Therefore, the findings may be generalized to other electrowinning operations.

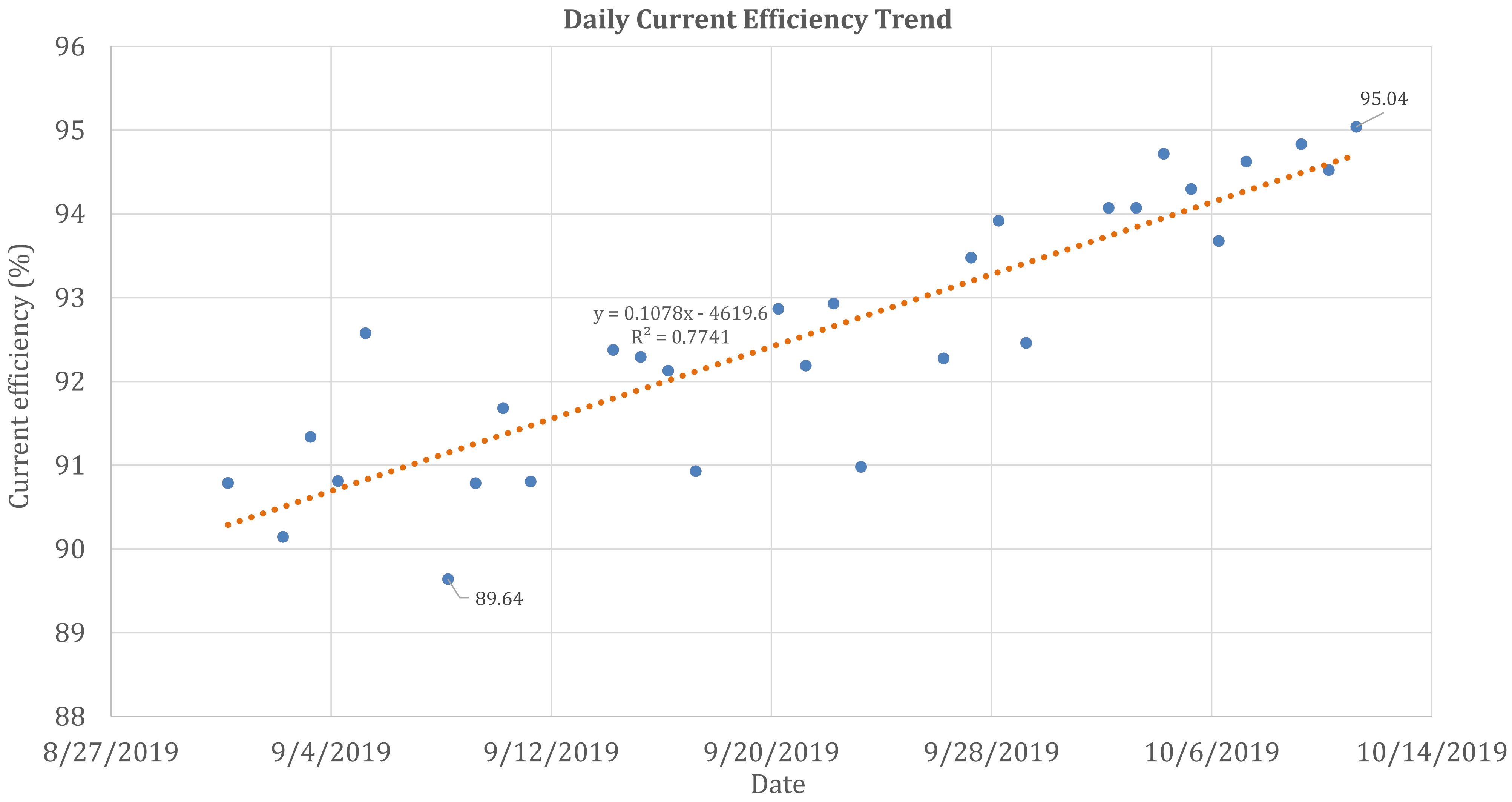


Figure 4.29: Daily current efficiency trend during the current efficiency improvement campaign (constructed by the author)

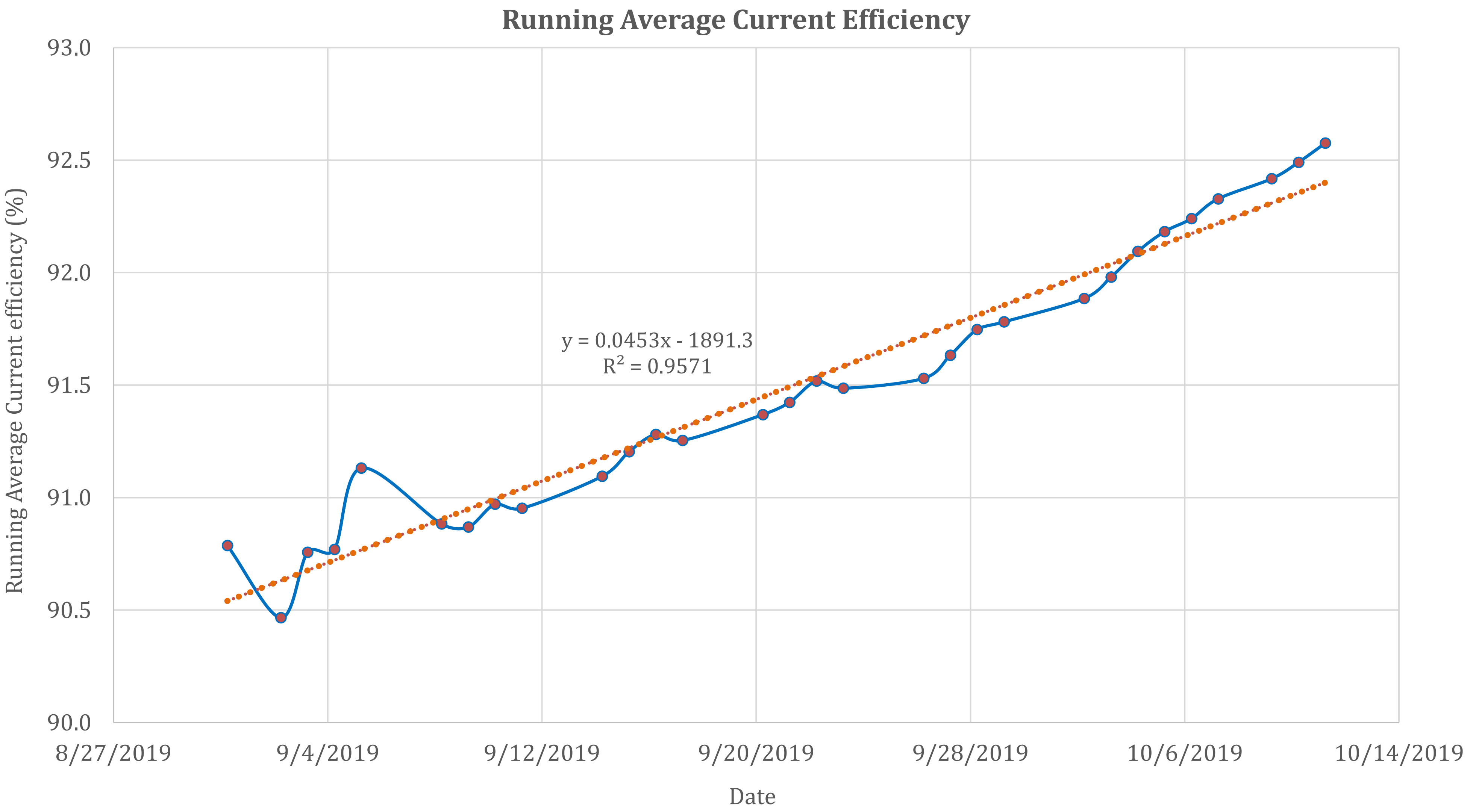


Figure 4.30: Running average CE during CE improvement campaign (constructed by the author)

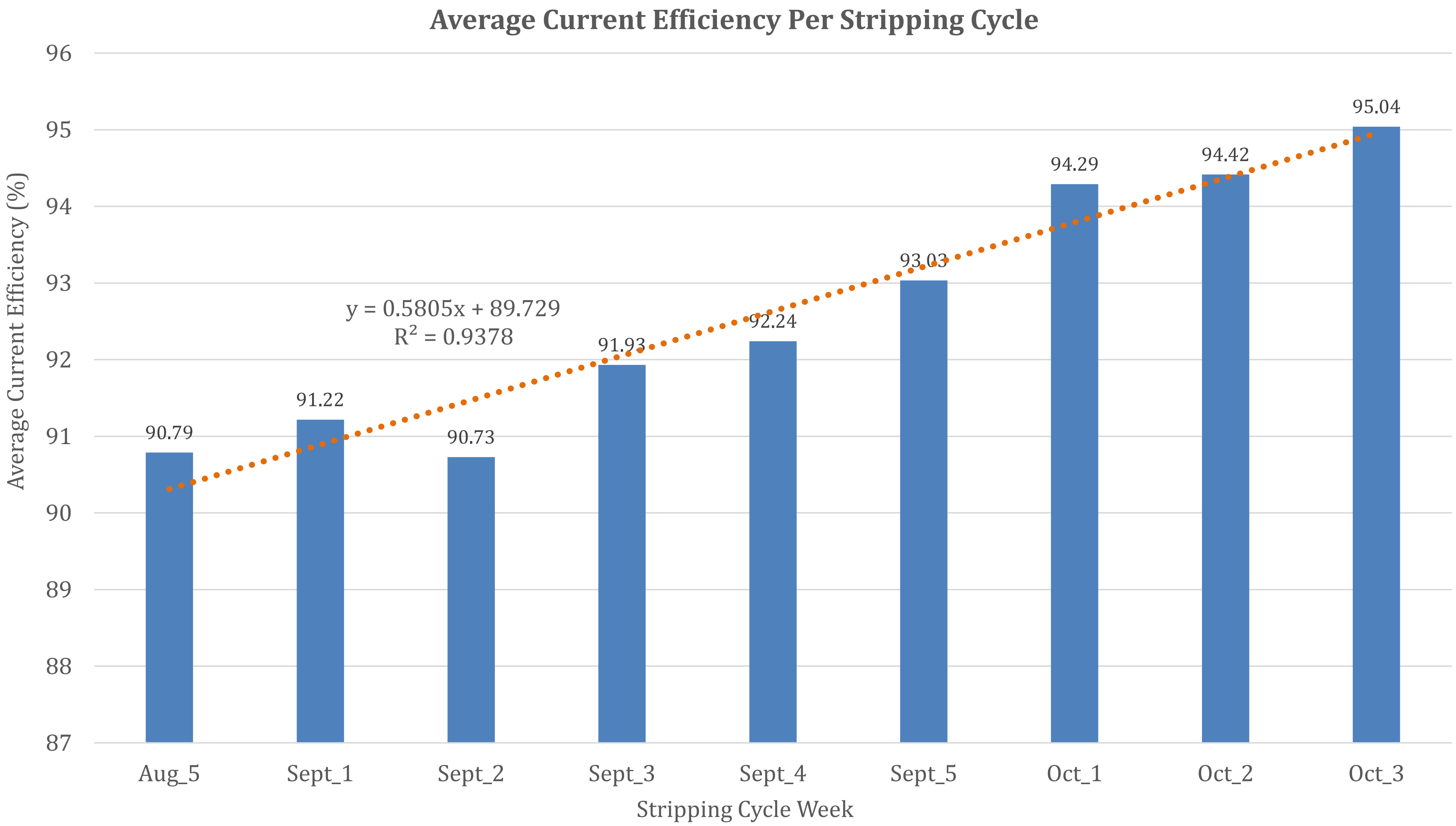


Figure 4.31: Average CE per stripping cycle during CE improvement campaign (constructed by the author)

4.5 Current efficiency attribute factors normal distribution test

Similar to the analysis done for current efficiency factors with continuous data, the attribute factors will also be tested for normality first. This will be followed by developing a control chart. In this case, these will only be done for current efficiency and the metallurgical short-circuits (hotspots).

4.5.1 Normality test results for current efficiency and attribute factors

A normality test was done for data collected during the study. The data was collected for current efficiency, the number of hotspots detected per cell and percent of cells with hotspots. A normality test was then completed for all these parameters. Minitab normality test output shows in Figure 4.32 and Figure 4.33 that both current efficiency and percent of cells with hotspots data follow a normal distribution. This is because the p-values are more than 0.05. The p-value for the number of hotspots per cell is less than 0.05 (see Figure 4.34). Which means the data does not follow a normal distribution. The data was then transformed so that it follows a normal distribution by using Johnson transformation as shown in Figure 4.35 below. Thereafter, the transformed data were tested for normality and it now follows a normal distribution (see Figure 4.36 below).

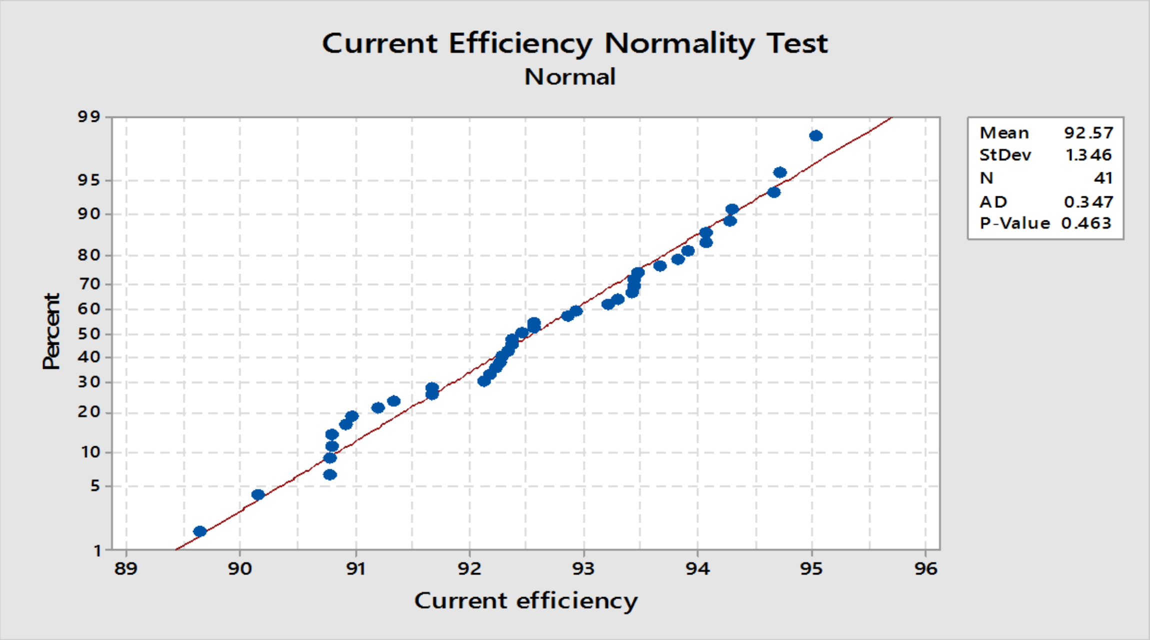


Figure 4.32: Minitab normality test output for current efficiency (created by the author)

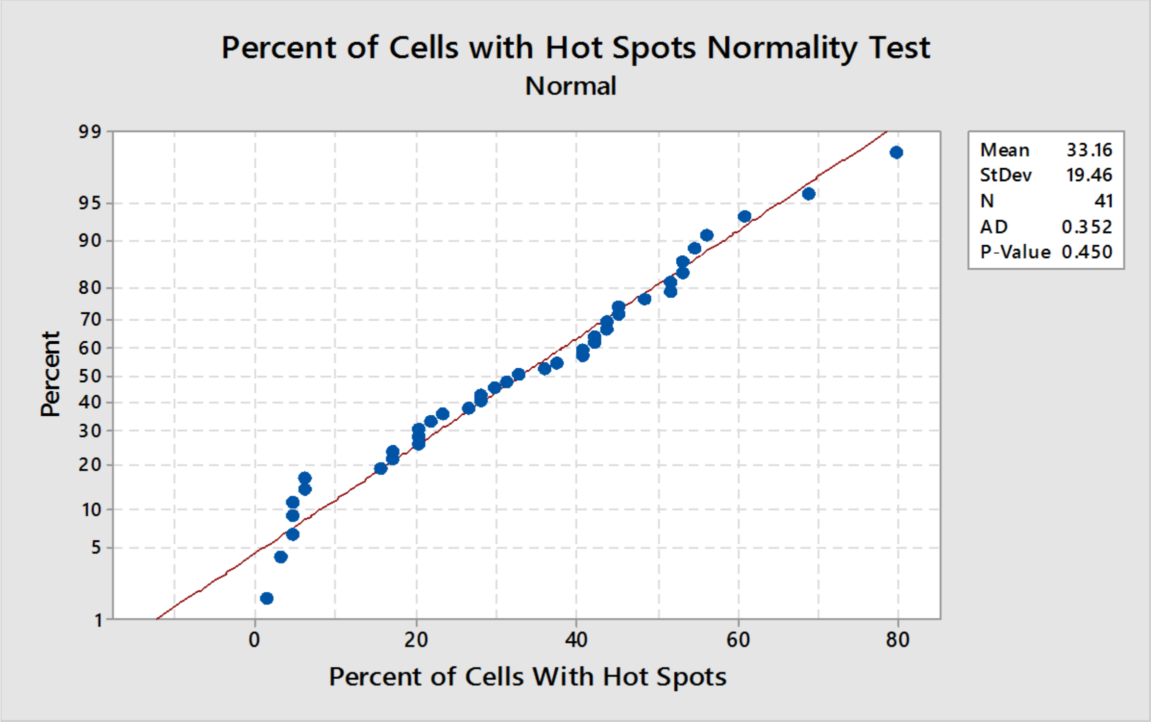


Figure 4.33: Minitab normality test output for percent of cells with hotspots (created by the author)

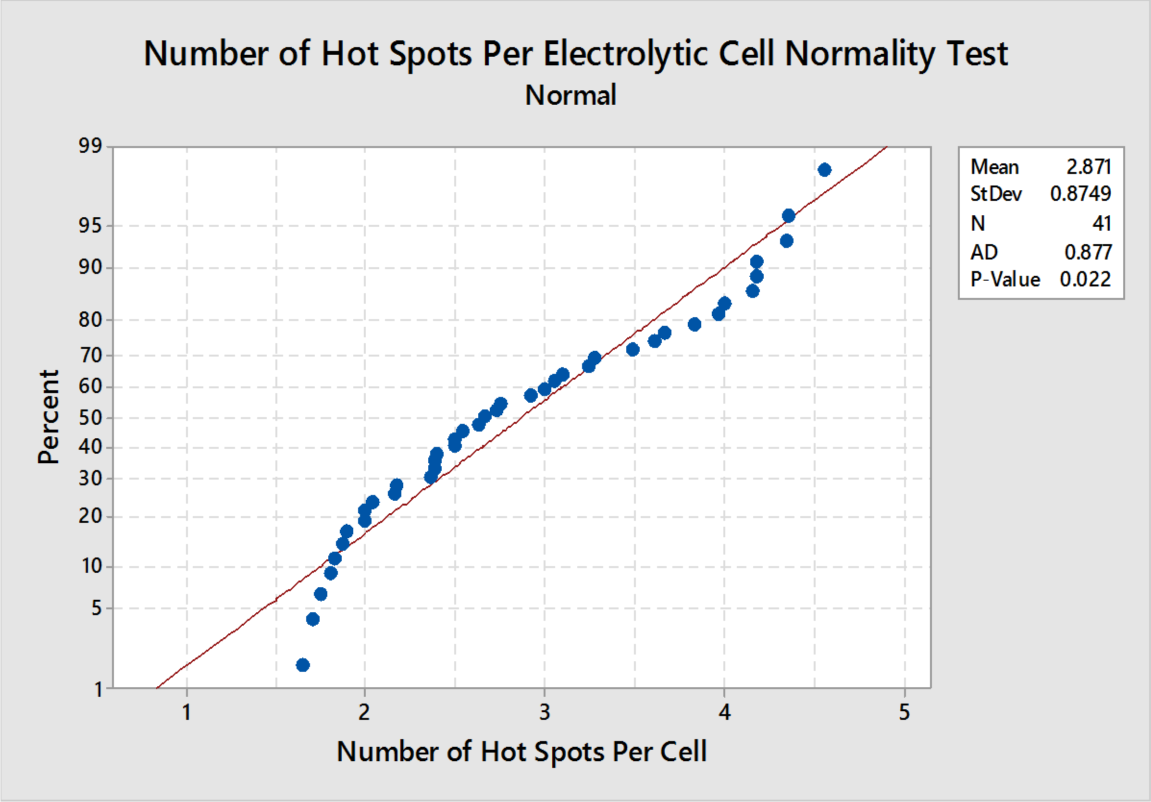


Figure 4.34: Minitab normality test output for number of hotspots per cell (created by the author)

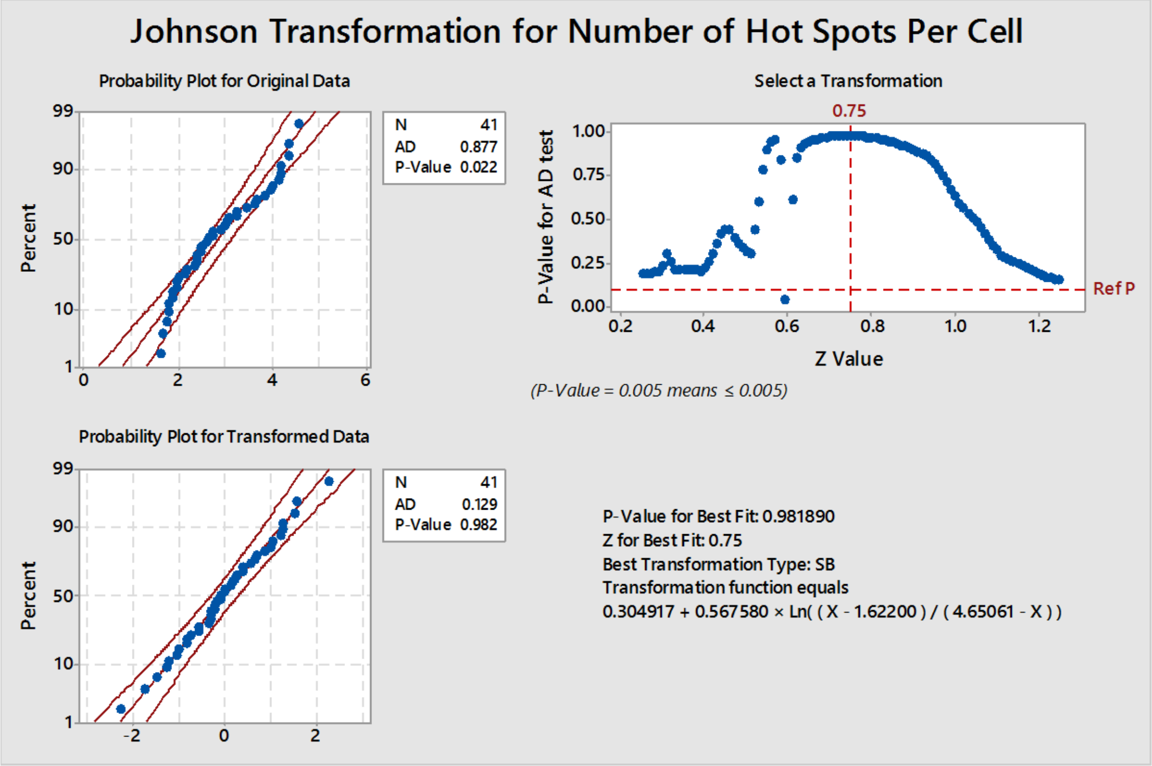


Figure 4.35: Using Johnson Transform to transform data for the number of hotspots per cell (Created by the author)

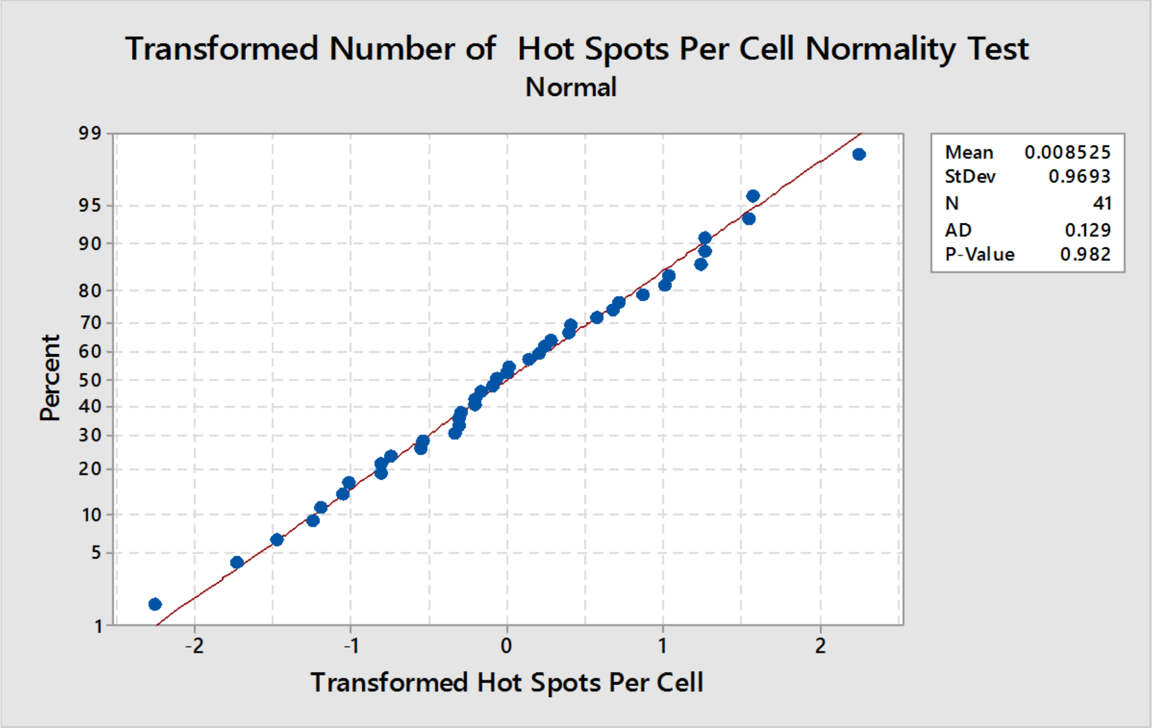


Figure 4.36: Minitab normality test output for transformed number of hotspots per cell data (Created by the author)

4.6 Applying statistical process control on attribute factors

4.6.1 Justification for the control charts to be applied

Now that all three factors follow a normal distribution the type of control charts to be created must be justified. Current efficiency will still be depicted on an I-MR chart because it is continuous data. However, the hotspots were manually counted which makes it fall under attribute data. The number of hotspots per cell is similar to defects per unit and a U chart is used as a control chart. On the other hand, the percentage of cells with hotspots can be regarded as a proportion of defective items that were presented using a P chart. The types of control charts chosen are shown in Figure 4.37 below.

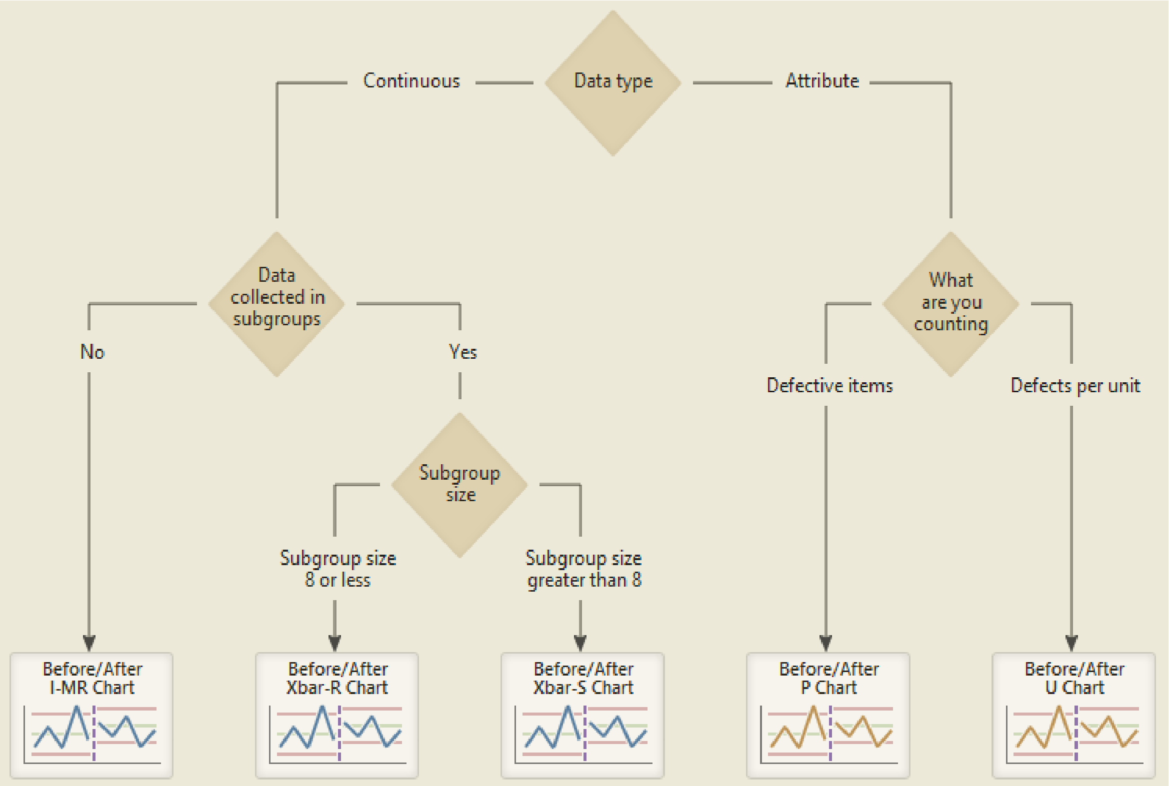


Figure 4.37: A decision tree for choosing the type of control chart (adopted from Mintab, 2019)

4.6.2 Control charts during current efficiency improvement campaign

4.6.2.1 I-MR control chart for current efficiency

An I-MR chart for current efficiency shown in Figure 4.38 below shows that current efficiency was out of control especially the first seventeen points. On the individual chart, it can be seen that the current efficiency was roughly ranging from 89 % to 91 %. After starting with metallurgical short-circuit (hotspot) monitoring and rectification, the current efficiency I-MR was under statistical control most of the time. This clearly shows that there was an improvement in current efficiency after the hotspot intervention. The moving range chart only shows two out of control points this is mainly because even when current efficiency was out of control on the individual chart the difference between them (or the range) was very small. This explains why there are few out of control points on the moving range chart.

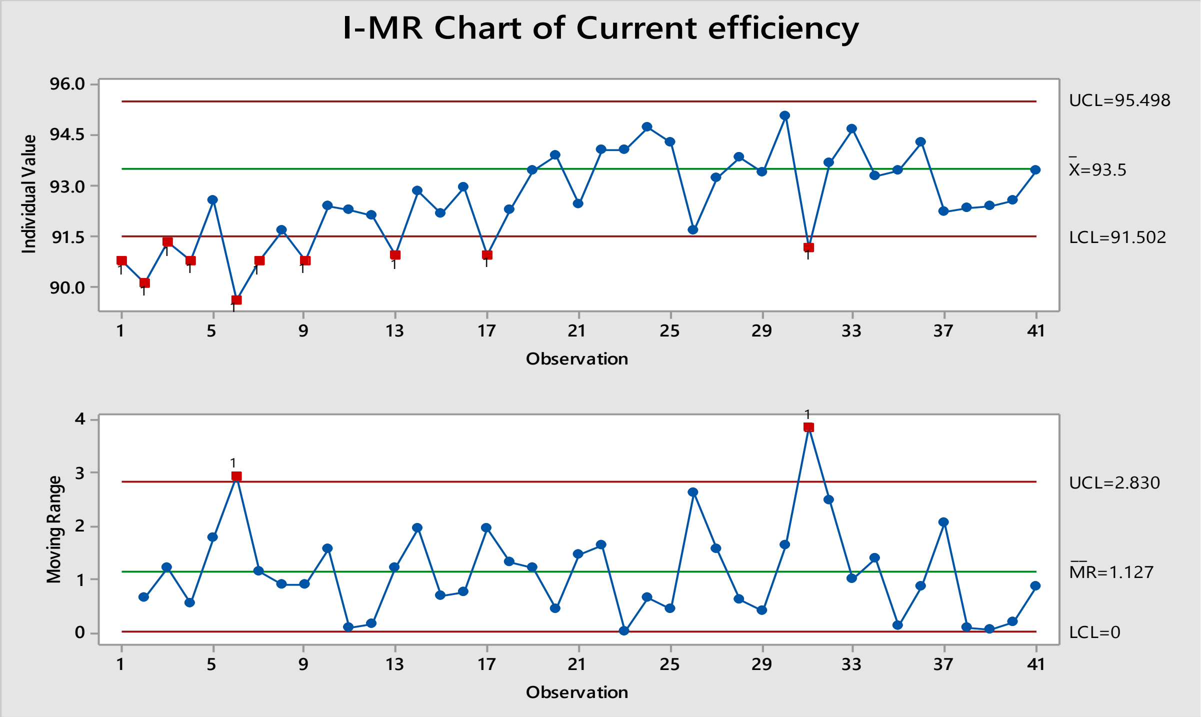


Figure 4.38: Current efficiency I-MR control chart during hotspot monitoring and rectification (created by the author)

4.6.2.2 P control chart for percent of cells with hotspots

The P chart below presented in Figure 4.39 below shows that there were 20 out of control points. It can also be seen that 10 out of control points are at the beginning of the chart and they are all above the upper control limit. This is correlating with the I-MR chart for CE because when there are a lot of cells with hotspots out of control points below the lower control limit for current efficiency were reported. This is corresponding to the literature reviewed.

The P chart also shows 10 out of control points which are below the lower control limit. This is a good sign because it means the effect of hotspots on current efficiency has been reduced significantly. This also corresponds to the increase in current efficiency as shown in the I-MR chart for CE above. Basically, the lower the percent of cells with hotspots the higher the current efficiency and vice-versa. There is an inversely proportional relationship between current efficiency and the percent of cells with hotspots. If correlation analysis is done, it should be able to reveal this. It will be done later.

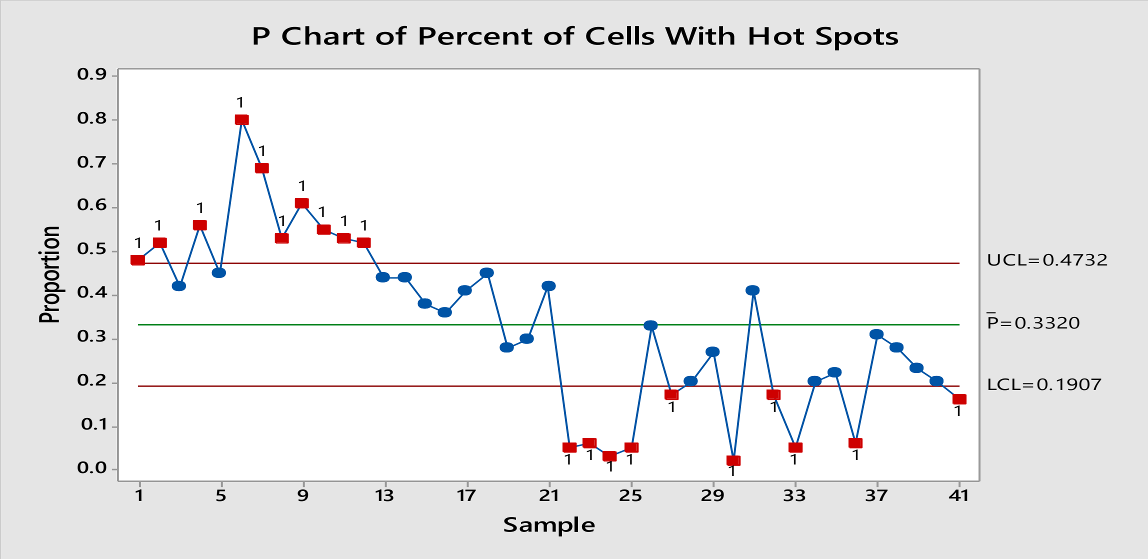


Figure 4.39: P control chart of percent of cells with hotspots (created by the author)

4.6.2.3 U control chart of the number of the hotspots per cell

The U chart below presented in Figure 4.40 below shows that there are 11 out of control points that are above the upper control limit. Most of these points are at the beginning of the U chart, which means they are corresponding to the out of control points that exceeded the upper control limit on the I-MR chart for current efficiency. In short, when current efficiency was out of control (below target) the number of hotspots per cell was high. Meaning hotspots are inversely proportional to current efficiency. Again, the correlation analysis should be able to reveal the relation between the two parameters. Interestingly, there are no out of control points that are below the lower control limit. This is expected because it is almost impossible to eliminate hotspots.

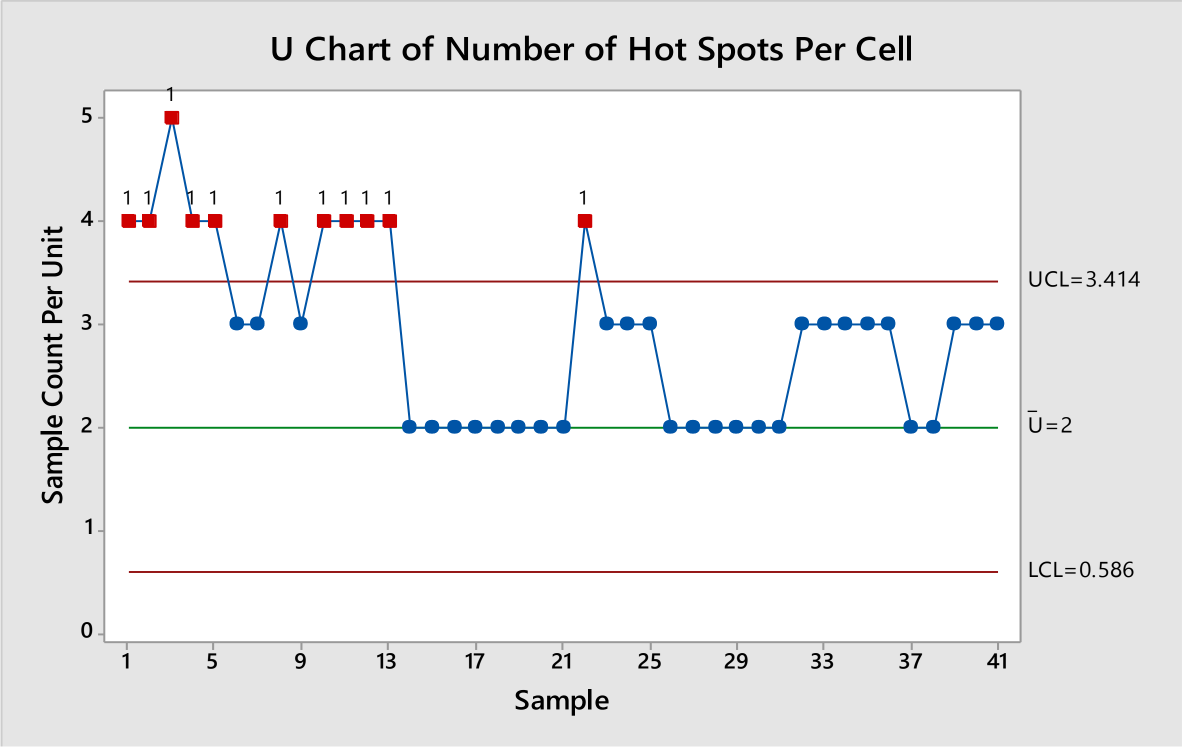


Figure 4.40: U control chart of the number of hotspots per cell (created by the author)

4.6.3 Analysis of out of control points

The results of the above control charts are presented in Table 4.8 below. The data shows that both the numbers of hotspots per cell and the percentage of cells with hotspots have 45.45 % out of control points which are aligned with the out of control points for current efficiency. The highest out of control alignment percent previously found was 87.50 % for both rectifier current and current density. Interestingly, 87.50 % alignment is high but the percent of OOC points that are misaligned was 95.60 % for both variables. However, the percent of OOC points that are misaligned for the number of hotspots per cell and the percentage of cells with hotspots is 54.55 % and 50.00 % respectively. This is an indication that hotspots might have a significant effect on current efficiency than all the other variables which were previously studied. This may explain also why the reduction in hotspots has resulted in increased current efficiency.

Table 4.8: Analysing the alignment of out of control points for the control charts (compiled by the author)

Parameter	OOC points aligned to CE OOC points		
	OOC points aligned	Percent aligned (%)	Percent misaligned (%)
Current efficiency	11.00	100.00	0.00
Number of hotspots per cell	5.00	45.45	54.55
Percent of cells with hotspots	5.00	45.45	50.00

4.6.4 Correlation analysis of hotspots and current efficiency

The Pearson correlation analysis results shown in Table 4.9 shows that hotspots have a negative effect on current efficiency. Which means the more hotspots the lower the current efficiency. This is because the electrical power is used for heating instead of electroplating copper onto the cathodes. The Pearson correlation for both number of hotspots per cell and percent of cells with hotspots was found to be -0.361 and -0.878 respectively. These correlation coefficients are the highest comparing to the correlation coefficients for the continuous data that was discussed earlier. Again, this proves that hotspots have the most significant effect on current efficiency for this copper electrowinning process.

Table 4.9: Pearson correlation analysis results for hotspots and current efficiency (compiled by the author)

Parameter	P-value	Pearson correlation coefficient
Number of hotspots per cell	0.020	-0.361
Percent of cells with hotspots	0.000	-0.878

4.6.5 Implications of hotspots rectification

During the current efficiency improvement campaign, a lot of electrodes were which were either bend or damaged or having missing insulators were replaced with brand new electrodes. This led to an increase in the consumption of new anodes and cathodes as shown in Figure 4.41 below.

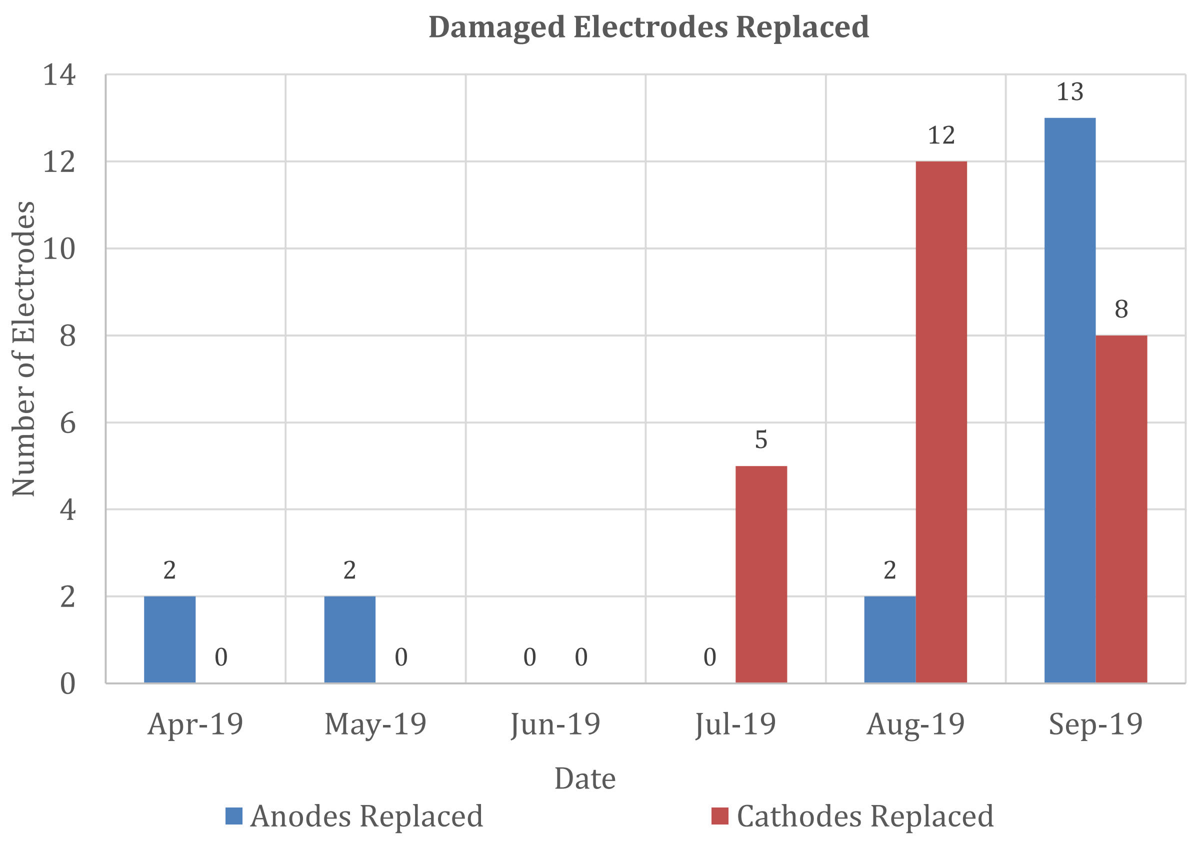


Figure 4.41: Damaged electrodes replacement during CE improvement campaign (created by the autho

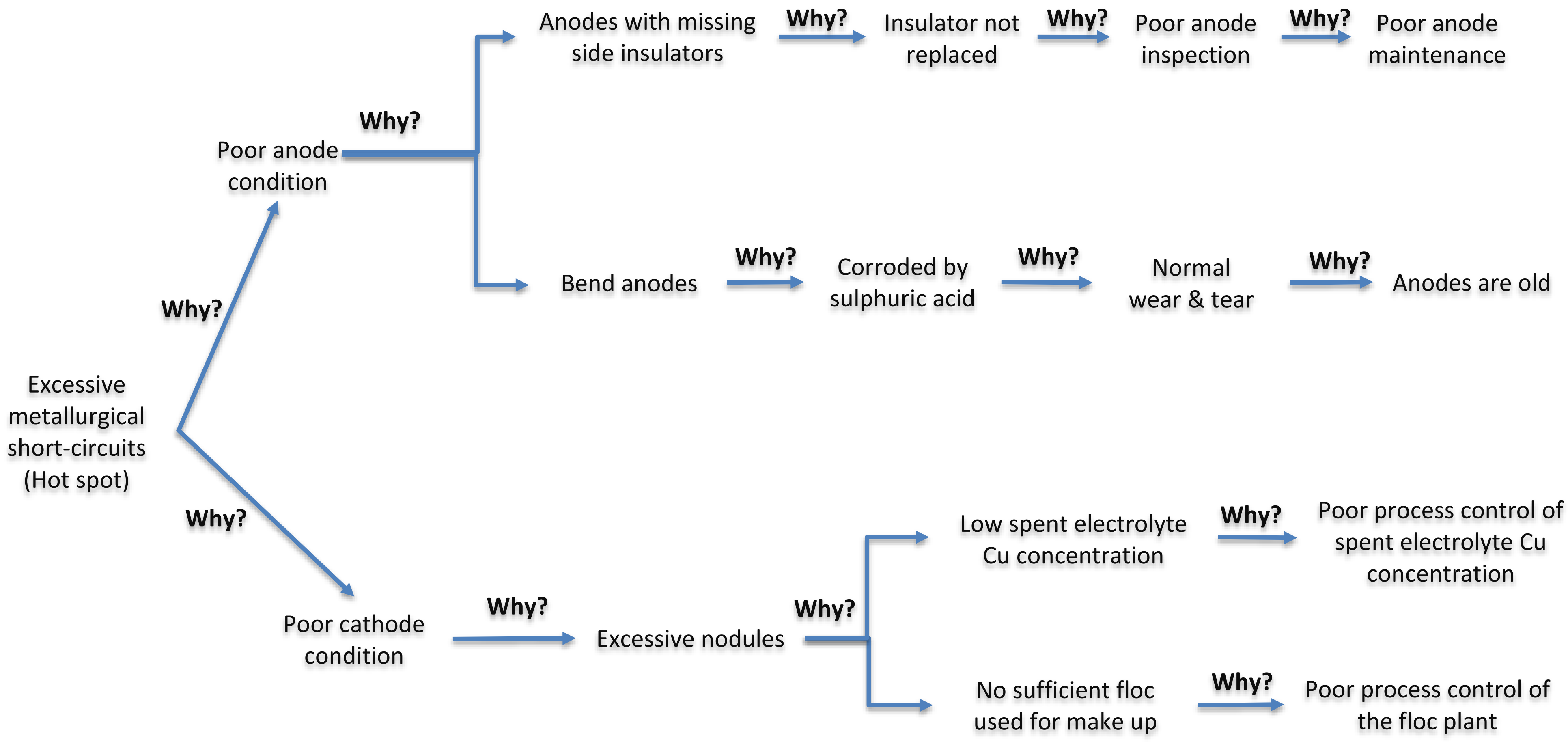


Figure 4.42: A five why root cause analysis for excessive hotspots (developed by the author)

4.7 Standardizing current efficiency improvement best practice

Having improved current efficiency as shown in Figure 4.29, Figure 4.30, and Figure 4.31 the strategic actions executed need to be embedded in daily operational activities. Thereby ensuring that current efficiency will always remain maximized by standardizing the best practice. This can only be achieved by developing a safe operating procedure (SOP) for improving current efficiency. The procedure will ensure continuous quality improvement.

4.7.1 Procedure for improving current efficiency

The procedure for improving current efficiency should be applied as part of the routine duties for the electrowinning operations team (both the EW operator and the entire stripping crew). If current efficiency improvement requires special attention the Process Engineer will request for at least two extra contract workers. The procedure is aimed at standardizing the best practice and for maintaining the maximum possible current efficiency.

Table 4.10: Procedure for improving current efficiency (created by the author)

Step	Action	Comments/ Controls
Monitoring and rectifying hotspots		
1.	Detecting hotspots using an infrared camera (IR camera)	• To be safe first, make sure that there is no crane movement on the row that will be scanned using an infrared camera (IR camera). • Detect hotspots by scanning along the contact points of the electrodes and the intermediate busbar using an infrared camera. • The infrared camera is an expensive device and there is only one onsite. Therefore, only the Process Engineer is allowed to use it.

		 *Figure 4.43: Detecting hotspots using an IR camera (picture taken by the author)* • For all the hotspots (>55°C) take a picture and record the temperature in the hotspot monitoring log sheet. • The operating rectifier current should also be recorded in the hotspot monitoring log sheet. • The IR camera picture for a hotspot has the hotspot temperature written on it (see Figure 4.44). • The maximum temperature that the IR camera can detect is 150°C. Any temperature higher that will be labelled as >150 °C as shown in Figure 4.44 below.

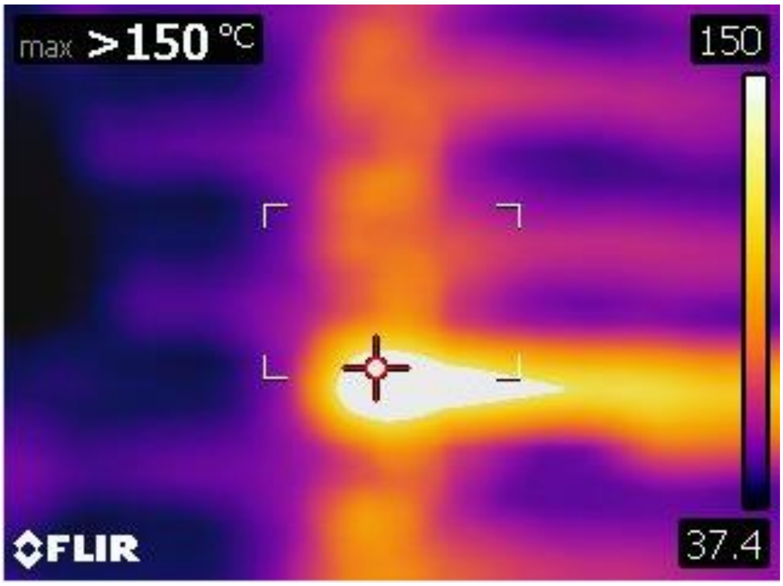


Figure 4.44: IR camera picture of a hotspot with >150℃ (infrared image taken by the author)

- The temperature gun can also detect hotspots when used well. However, it is not very sensitive like the IR camera. Figure 4.45 below shows the IR camera on the left and a temperature gun on the right.

Figure 4.45: Comparing the IR camera to the temperature gun (picture taken by the author)

		• It should be noted that spraying water over the cell does not remove the hotspot. It only cools the electrode for a few minutes and then it heats up again because the hotspot is still there. Therefore, the hotspot must be investigated further. Spraying with water is a temporary solution. The permanent solution is to identify the root cause of the hotspot and then eliminate it.  *Figure 4.46: Spraying water over a hotspot (picture taken by the author)*
2	Removing electrodes suspected to have a hotspot	• After scanning with an IR camera, the hotspot monitoring log sheet will have recorded temperatures for all the detected hotspots for all 64 cells. • This log sheet is then handed over to the stripping operators who are authorized to operate the crane so they can investigate the root cause. • If only a few hotspots were detected in a specific cell. The stripping operators can use a sling to remove and inspect those specific electrodes one by one. Figure 4.47 and Figure 4.48 below show how anodes and cathodes are were removed from a cell.

		 *Figure 4.47: Removing an anode from a cell using a sling (picture taken by the author)*

		 *Figure 4.48: Removing a cathode from a cell using a sling (picture taken by the author)* • If a specific cell has a lot of hotspots detected just remove and inspected all the cathodes one position at a time until they are all inspected in that cell as shown in Figure 4.49 below.

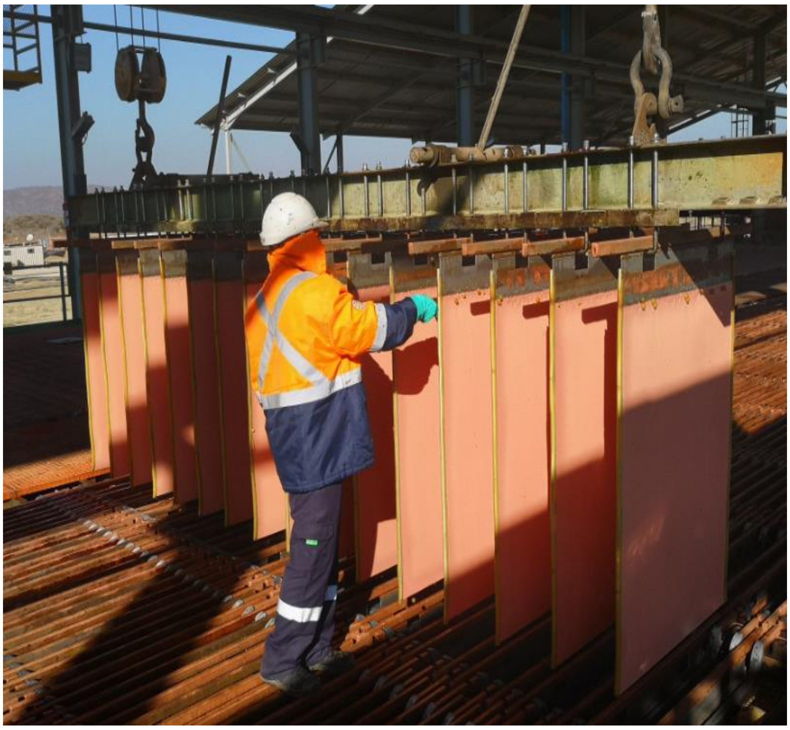
		 *Figure 4.49: Inspecting cathodes from a cell with excessive hotspots (picture taken by the author)* NB: Removing of all three sets of cathodes can only be done when the short-circuiting frame is correctly installed forming a parallel path for the plating current.
3	Inspecting the suspected electrodes	• After lifting up the electrodes. They must be visually inspected in order to find the root cause of hotspots. • Look out for nodules, bend electrodes, missing anode insulators and any other anomalies. • Anything that can cause the anode and cathode to contact can result in a short-circuit (hotspot).

		 *Figure 4.50: An anode with a missing side insulator (picture taken by the author)*

		 *Figure 4.51: A burnt anode which is also bend (picture taken by the author)*
4	Rectifying the detected hotspots	• Rectifying the hotspots depends on the root cause and the severity of the damage. • If it is caused by nodules, they can be knocked off. In this case, there might be no excessive nodules spread on cathodes all over the cells but only a few nodules.

		 *Figure 4.52: Knocking off nodules that caused a hotspot (picture taken by the author)* . • In case there are excessive nodules that have spread over a lot of cells. An investigation must be done to ensure that the flocculant plant is working as required. • This can be done by checking flocculant measurement with metallurgical lab operators, the EW operator can ensure smooth flocculant plant operation and the instrumentation artisan can ensure the flocculant make-up settings have not been tampered with. • It should be noted that the flocculant plant was supposed to be interlocked with the rectifier current. In such a way that the make-up flocculant concentration increases

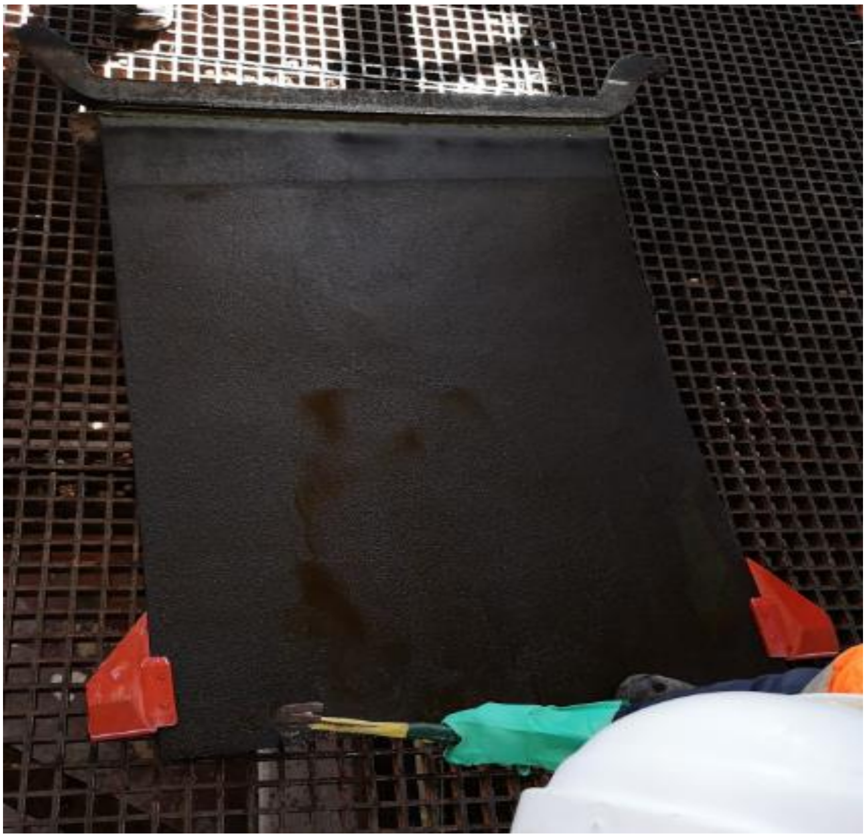
		automatically when operating at a high rectifier current and vice-versa. Nonetheless, this can be done manually. • If an insulator is missing it should be replaced. If it cannot be replaced, the anode should be replaced with a new anode dressed with new insulators. Before any replacement is done approval must be done by the process engineer and/or supervisor.  Figure 4.53: *Replacing anode insulators (picture taken by the author)*

		 *Figure 4.54: Hoisting up a new anode (picture taken by the author)* • A bend electrode can be straightened by safely pressing it while it is well-positioned. See Figure 4.55 and Figure 4.56 below.

		 *Figure 4.55: Straightening a bend anode (picture taken by the author)*

		 *Figure 4.56: Stepping on an anode to straighten it (picture taken by the author)*
5	Cleaning electrode contacts with acetone and/or using steel brushes	• The cathode contacts should be cleaned with acetone and/or steel brushes on the discharge conveyor. This is normally done on a stripping day. It requires two contract workers to be arranged either from the heap or those that do gardening. Figure 4.57 below shows two contract workers cleaning cathode contacts.

<table>
<tr><td></td><td></td><td>


Figure 4.57: Cleaning cathode contacts on the discharge conveyor (picture taken by the author)

- The anode contacts should always be cleaned with acetone and/or steel brushes by the stripping operators when doing anode cleaning. This is normally done when anodes are hung on the racks behind EW as shown in Figure 4.58 below.


</td></tr>
</table>

		Figure 4.58: Cleaning anode contacts at the back of EW (picture taken by the author) • The intermediate bus bar should also be cleaned using steel brushes when short-circuiting and doing cell cleaning as shown in Figure 4.59 below. The cell short-circuiting frame installation and cell cleaning should still be done according to the procedure.  *Figure 4.59: Cleaning the intermediate bus bar while walking on electrodes (picture taken by the author)* • Do not use acetone to clean the intermediate bus bar. There is a risk of contaminating the electrolyte if acetone falls into the cells.
6	Monitoring and controlling flocculant plant	• The flocculant plant should be operated according to the procedure. This will prevent the formation of nodules proactively.

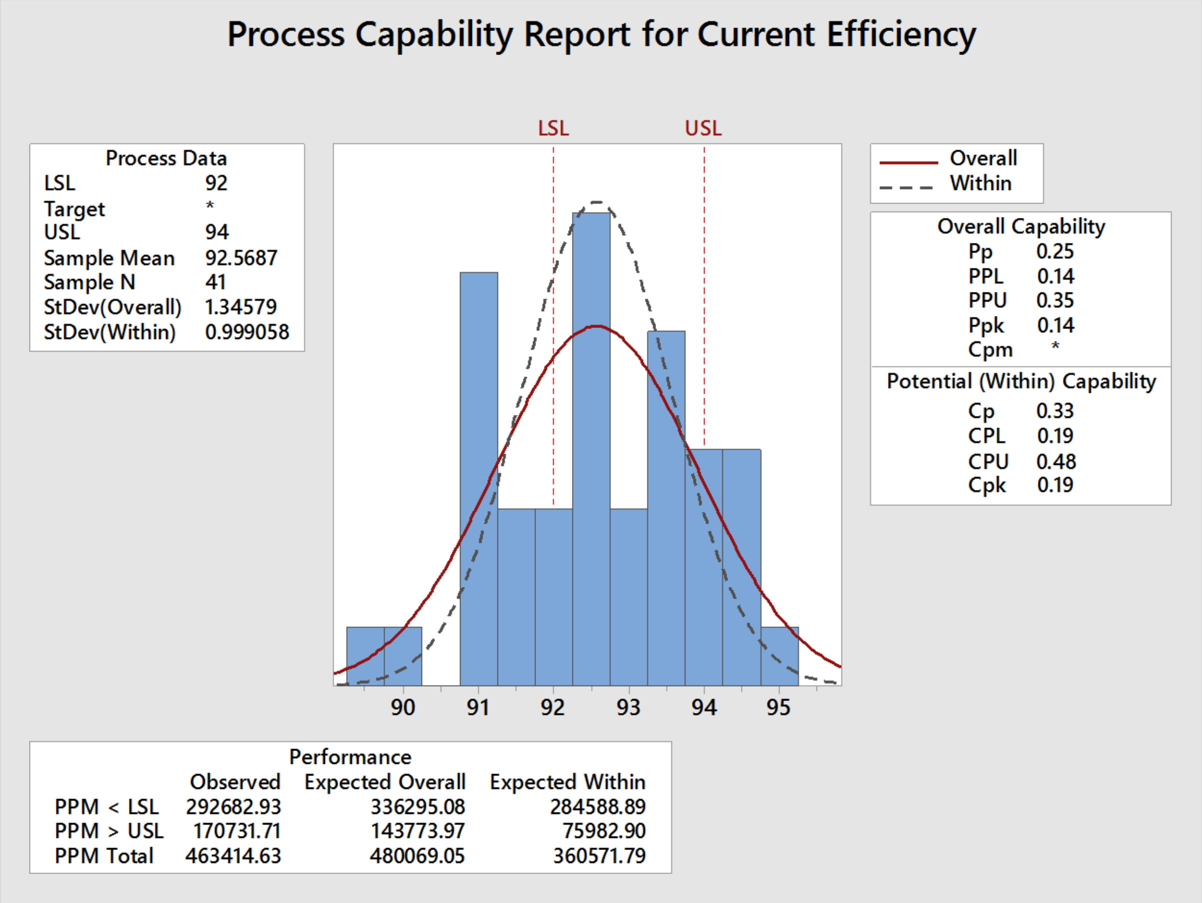
7	Electrode alignment (Rat patrol)	• Rat patrol ensures equal current density distribution to all cathodes. This reduces the chances of electrode contact by maintaining equal cathode weight. • Rat patrol must be done after putting electrodes back in the cells. This is done either after stripping, after cell cleaning, after rectifying hotspot or any other activity that removes the electrodes from the cells. Figure 4.60 shows an operator doing rat patrol.  *Figure 4.60: An operator doing rat patrol (picture taken by the author)*

4.8 Process capability analysis for CE and its factors

After determining that the factor has the biggest effect on current efficiency, it is worth determining if the process is actually capable of maintaining it under control. This can be accomplished by doing a process capability analysis using Minitab. This was done first by considering whether the data is following a normal distribution or not. If the data does not follow a normal distribution an individual distribution identification was done using Minitab, and it was used during process capability analysis. The distribution with the highest p-value which is greater than 0.05 fits the data best. For both normal and non-normal data, upper and lower specification limits were assigned. All the capability analysis reports for the factors were summarized and discussed.

4.8.1 Process capability analysis for current efficiency

Current efficiency data obtained during the current efficiency improvement campaign is following a normal distribution as shown in Figure 4.32 above. There is no need to compare p-values for identifying the best fitting distribution. The current efficiency process capability report in Figure 4.61 below for current efficiency shows that process capability index Cpk and Ppk are less than 1.33 which means the process is not capable of meeting the requirements. Therefore, an action should be taken in order to make the process capable of meeting the specified requirements. Cp and Cpk are not approximately equal. Which means the process is not cantered between the specification limits.



Process Data	
LSL	92
Target	*
USL	94
Sample Mean	92.5687
Sample N	41
StDev(Overall)	1.34579
StDev(Within)	0.999058

Overall Capability	
Pp	0.25
PPL	0.14
PPU	0.35
Ppk	0.14
Cpm	*

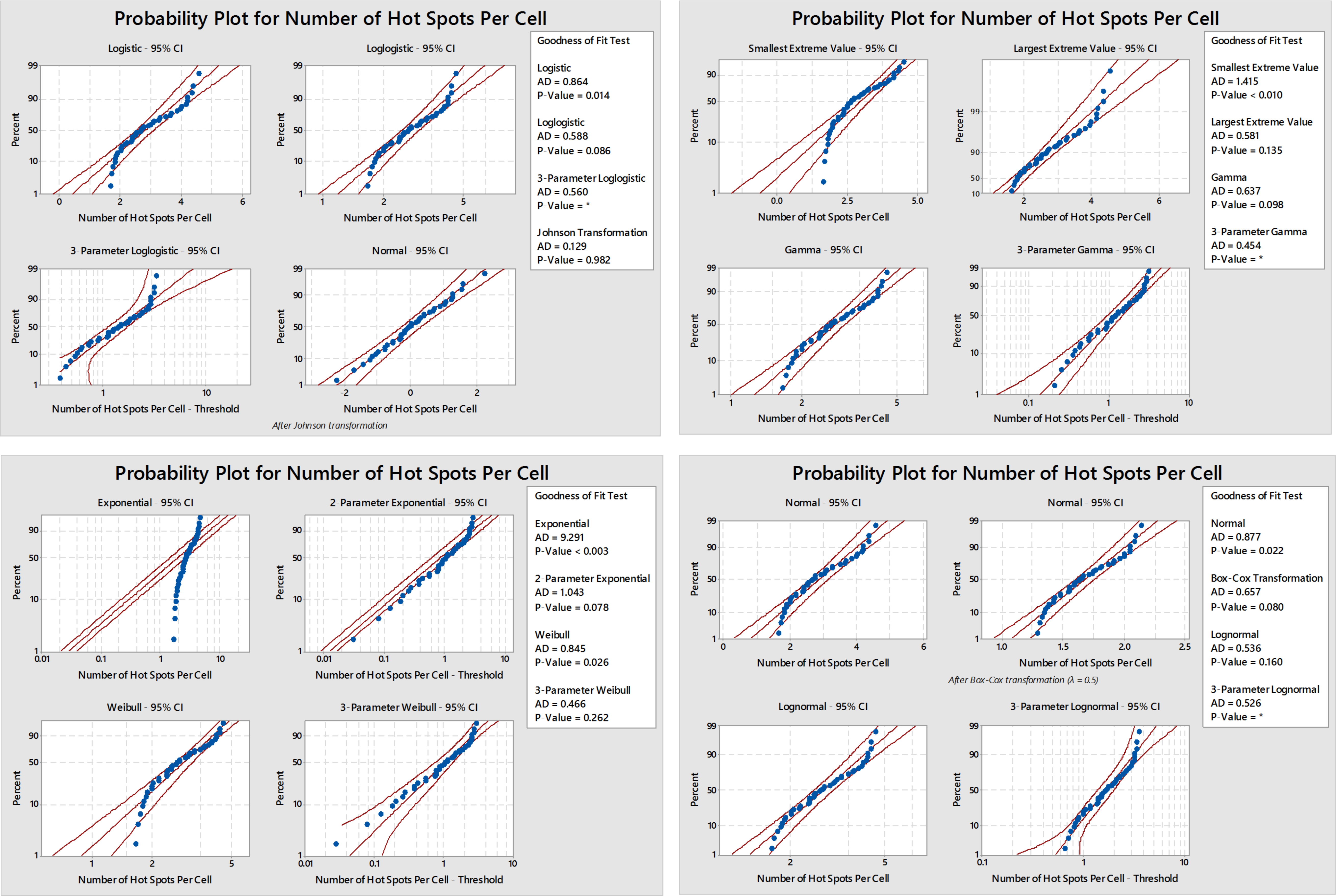
Potential (Within) Capability	
Cp	0.33
CPL	0.19
CPU	0.48
Cpk	0.19

Performance	Observed	Expected Overall	Expected Within
PPM < LSL	292682.93	336295.08	284588.89
PPM > USL	170731.71	143773.97	75982.90
PPM Total	463414.63	480069.05	360571.79

Figure 4.61: Process capability report for current efficiency (created by the author)

4.8.2 Process capability analysis for the number of hotspots per cell

The data for the number of hotspots per electrolytic cell does not follow a normal distribution. Therefore, individual distribution identification was applied to find the best fitting distribution. The individual distribution identification output from Minitab is shown in Figure 4.62 below. The report shows that the data fit the 3-Parameter Weibull distribution much better than any other distribution. This is because it has the largest P-value of 0.262 which is more than 0.05.



Goodness of Fit Test

Logistic
AD = 0.864
P-Value = 0.014

Loglogistic
AD = 0.588
P-Value = 0.086

3-Parameter Loglogistic
AD = 0.560
P-Value = *

Johnson Transformation
AD = 0.129
P-Value = 0.982

Goodness of Fit Test

Smallest Extreme Value
AD = 1.415
P-Value < 0.010

Largest Extreme Value
AD = 0.581
P-Value = 0.135

Gamma
AD = 0.637
P-Value = 0.098

3-Parameter Gamma
AD = 0.454
P-Value = *

Goodness of Fit Test

Exponential
AD = 9.291
P-Value < 0.003

2-Parameter Exponential
AD = 1.043
P-Value = 0.078

Weibull
AD = 0.845
P-Value = 0.026

3-Parameter Weibull
AD = 0.466
P-Value = 0.262

Goodness of Fit Test

Normal
AD = 0.877
P-Value = 0.022

Box-Cox Transformation
AD = 0.657
P-Value = 0.080

Lognormal
AD = 0.536
P-Value = 0.160

3-Parameter Lognormal
AD = 0.526
P-Value = *

Figure 4.62: Individual distribution identification report for the number of hotspots per cell (created by the author)

After identifying the best fitting distribution, the process capability report was generated from Minitab software. This was done using the non-normal capability report and then, choosing the 3-Parameter Weibull distribution. The specification limits were 1 and 3 for both lower specification limit (LSL) and upper specification limit (USL) respectively. The Ppk index is less than 1.33 which means the number of hotspots per electrolytic cell needs to be improved or reduced so that it goes back within the specified ranges.

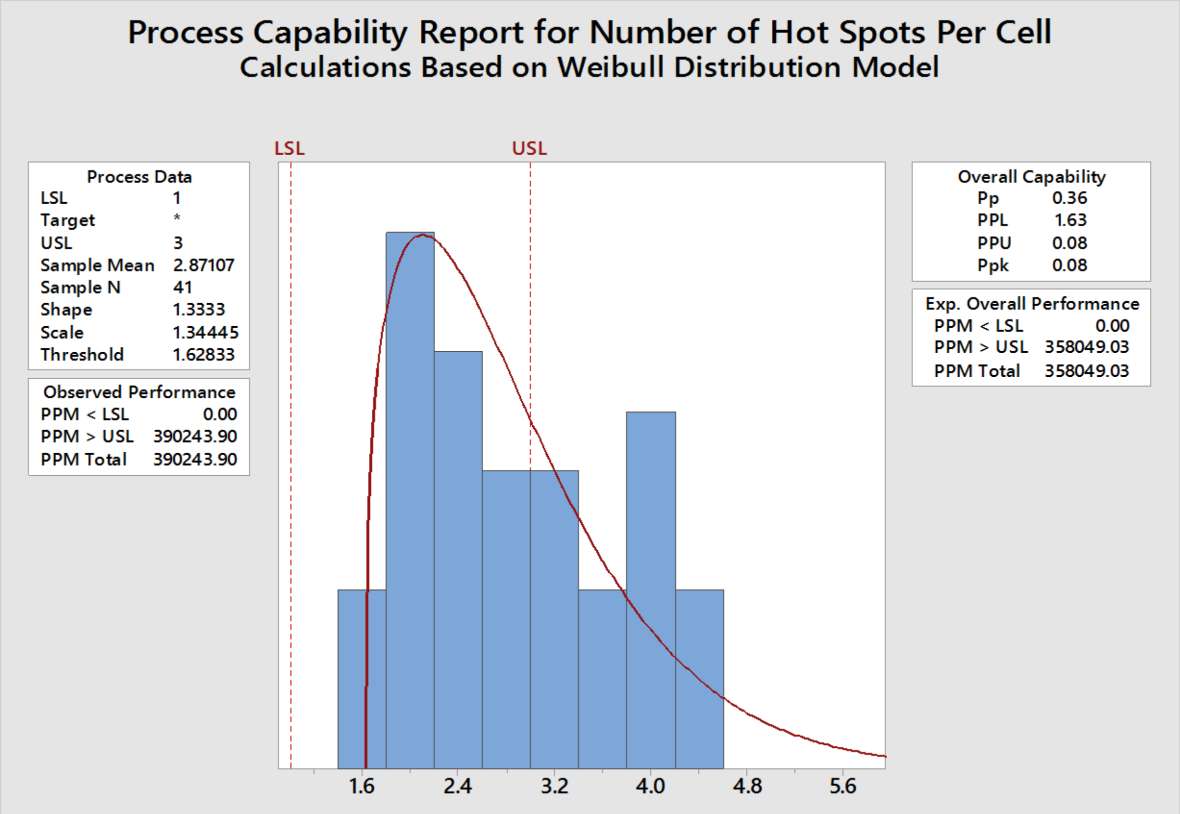
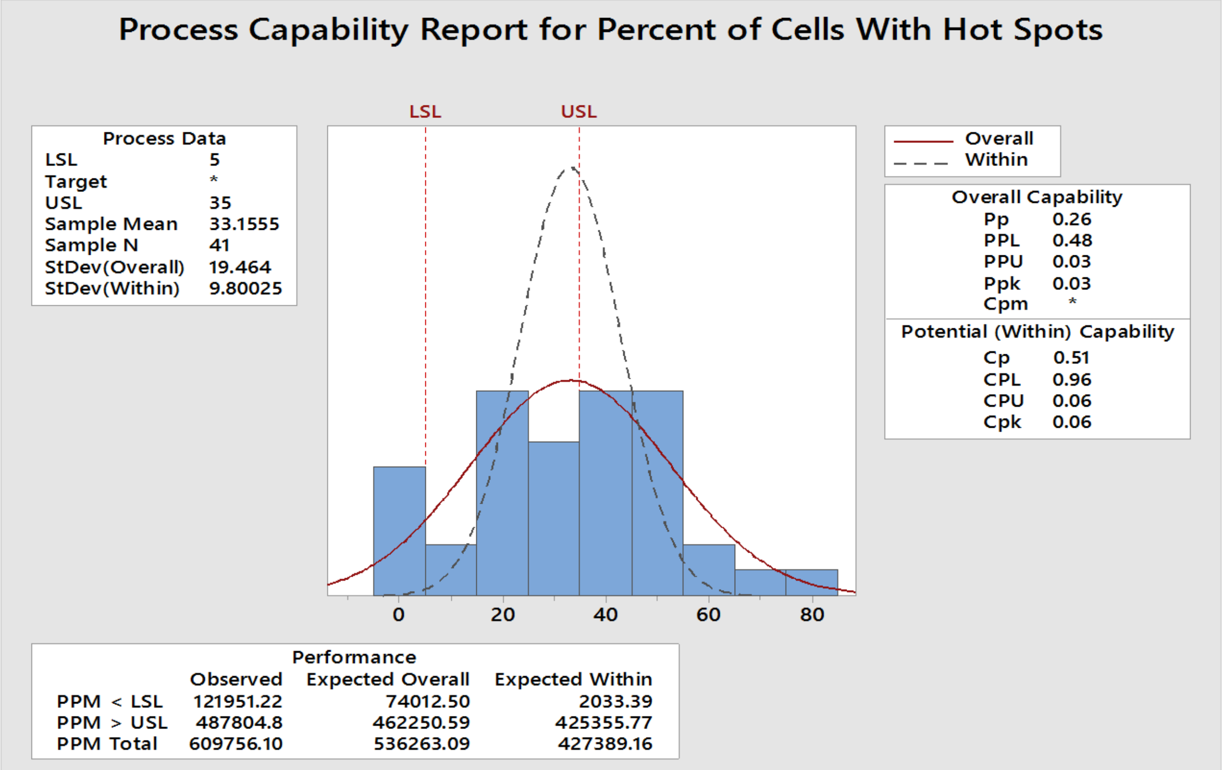


Figure 4.63: Process capability report for the number of hotspots per electrolytic cell (created by the author)

4.8.3 Process capability analysis for percent of cells with hotspots

The normality test results shown in Figure 4.33 above shows that the data for the percent of cells with hotspots follows a normal distribution. Therefore, there is no need to find the best fitting individual distribution. The Cpk index is less than 1.33 which means the percent of cells with hotspots need to be decreased. The process is currently not capable of maintaining within the specified ranges until an intervention is made.



Process Data	
LSL	5
Target	*
USL	35
Sample Mean	33.1555
Sample N	41
StDev(Overall)	19.464
StDev(Within)	9.80025

Overall Capability	
Pp	0.26
PPL	0.48
PPU	0.03
Ppk	0.03
Cpm	*

Potential (Within) Capability	
Cp	0.51
CPL	0.96
CPU	0.06
Cpk	0.06

Performance

	Observed	Expected Overall	Expected Within
PPM < LSL	121951.22	74012.50	2033.39
PPM > USL	487804.8	462250.59	425355.77
PPM Total	609756.10	536263.09	427389.16

Figure 4.64: Process capability report for the percent of cells with hotspot (created by the author)

5. Designing a continuous quality improvement framework for improving electrowinning current efficiency

5.1 Introduction

Designing a continuous quality improvement framework for improving current efficiency is the main aim of this research. The framework was developed the same way the improvement was achieved as mentioned above. This was completed by considering current efficiency factors, normality test, transforming non-normal data, classifying data type, selecting a suitable Shewhart control chart, Pearson correlation analysis, out of control point alignment, process capability analysis, and root cause analysis, out of control action plan, CE training and establishing a safe working procedure.

The continuous quality improvement framework was designed by diagrammatically representing all these steps in sequential order. Thereby displaying the arrangement and order for the steps that will result in improved current efficiency from a quality perspective. It includes a strategy for choosing suitable control charts as provided in Minitab-17. It is worth noting that the designed framework was tested already as discussed in the previous sections. Therefore, in this case, all essential components of the continuous quality improvement framework were only diagrammatically represented and sequentially arranged so that it is easy to follow.

5.2 Continuous quality improvement framework design considerations

5.2.1 Factors affecting current efficiency

The factors that influence current efficiency were considered in the continuous quality improvement framework. Any of the factors might contribute significantly to current efficiency. This depends on the specific operation and on the special causes of variation in current efficiency. Only a few of the factors will be put into the framework. All other factors were included under the title “other factors” since the factors are a lot. The data for all the factors influencing current efficiency need to be collected and analysed.

5.2.2 Normality test

It is essential to test if the data is following a normal distribution or not following it. Statistical process control charts are based on the assumption that the data is following a normal distribution. Minitab can be used to determine if the data follows a normal distribution.

5.2.3 Transforming non-normal data

If the data does not follow a normal distribution it must be transformed so that it can follow a normal distribution. Minitab has functionalities such as Johnson transformation and Box-Cox transformation for transforming data. After transforming the data, it should be tested for normality again. The specification limits can be calculated from the equation representing the transformed data.

5.2.4 Classifying data type

The data type should be classified whether it is continuous data or attribute data. For continuous data, the subgroup size should be identified. On the other hand, for attribute data, it should be indicated whether the data are for defective items or it is for defects per unit. Classifying the data type is crucial because it allows the right decision to be made on which control chart to construct for the specific data type.

5.2.5 Selecting a suitable control chart

After classifying data type, specific control charts can be applied depending on the type of data, the number of subgroup sizes and the type of defects. The out of control points on the control chart should then be investigated.

5.2.6 Pearson correlation analysis

The out of control factor should be analyzed first by doing a correlation analysis between that specific factor and current efficiency. Correlation analysis enables the impact or significance of the influence of the factor on current efficiency to be understood. Depending on the

Pearson correlation coefficient, further investigation into the cause of out of control points can be executed.

5.2.7 Out of control point alignment analysis

Based on the Minitab control chart report, the alignment of the out of control points for the factor and also for current efficiency should be carried out. The alignment of out of control points gives an indication that as the factor gets out of control current efficiency also corresponds by getting out of control either by tending towards the upper control limit or the lower control limit.

5.2.8 Process capability analysis

Before any action is taken, it is necessary to study if the process is actually capable of maintaining the parameter under statistical control. Process capability analysis can only be done for normally distributed data or else the type of distribution that the data follows must be identified. This is done by, making use of the individual distribution identification in Minitab.

5.2.9 Root cause analysis

The root cause of the factor to be out of control need to be identified. This can be done by doing a root cause analysis. Executing either a five why root cause analysis or the Fishbone (Ishikawa) diagram should be sufficient. The root cause of the special cause of variability will be addressed further by developing and implementing an out of control action plan (OCAP).

5.2.10 Developing and implementing an out of control action plan

An out of control action plan should be developed specifically to address the identified root cause of process variability. The action plan is aimed at eliminating and/or minimizing the impact of the root cause. Once the out of control action plan is implemented the type of data should be classified again and then a control chart should be created again. This is essential to test if the factor is indeed under statistical control after intervening. If there is no improvement in variability, the initial action plan can be revised and the process repeats over again until current efficiency has improved.

5.2.11 Current efficiency training

It is crucial to give current efficiency training to operators, shift supervisors, and other designed personnel. The training is important not only to have a competent team but also for people to assist with improving current efficiency.

5.2.12 Current efficiency improvement procedure

In order to maintain or sustain improved current efficiency for long, it is necessary to have a safe operating procedure. This procedure incorporates all operational aspects of improving current efficiency. This should be linked with the control charts which are monitored on a regular basis. The procedure should be embedded in the daily operational activities. This will result in maintaining the highest improved current efficiency. Hence the term continuous quality improvement. All these framework design considerations are diagrammatically and sequentially presented in Figure 5.5.1 and Figure 5.5.2 below.

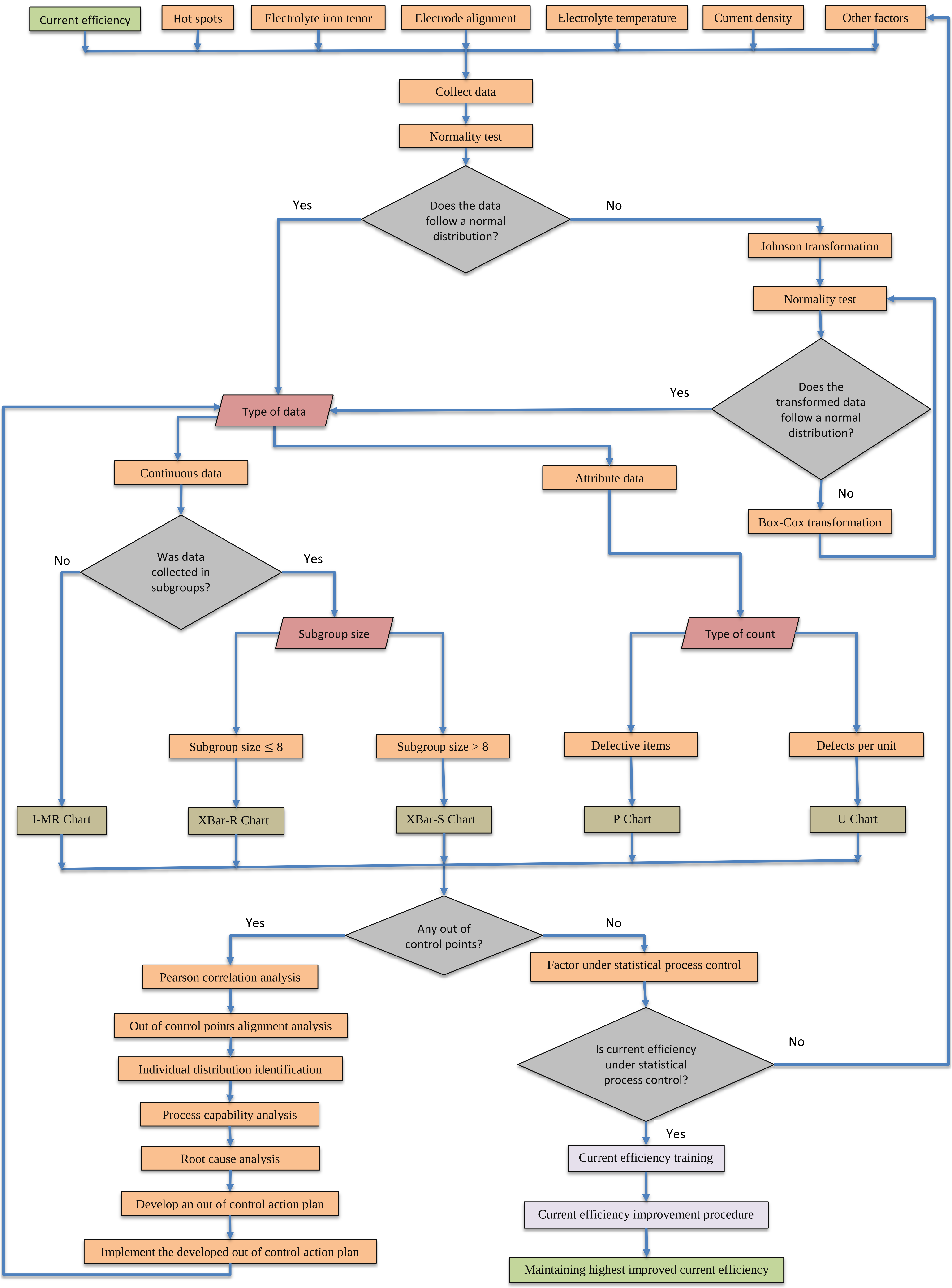


Figure 5.5.1: A detailed continuous quality improvement framework (designed by the author)

5.3 Simplified design of the continuous quality improvement framework

The detailed design of the continuous quality improvement framework in Figure 5.5.1 above has been simplified in Figure 5.5.2 below. The simplified version is easy to follow and understand the idea behind the continuous quality improvement framework for improving electrowinning current efficiency. The high-level framework below shows how statistical process control was applied to improve current efficiency. It is essential to illustrate how Shewhart control charts were integrated into the framework. As a result, this will clarify the strategy that resulted in current efficiency improvement from a quality perspective by applying statistical process control (Shewhart control charts).

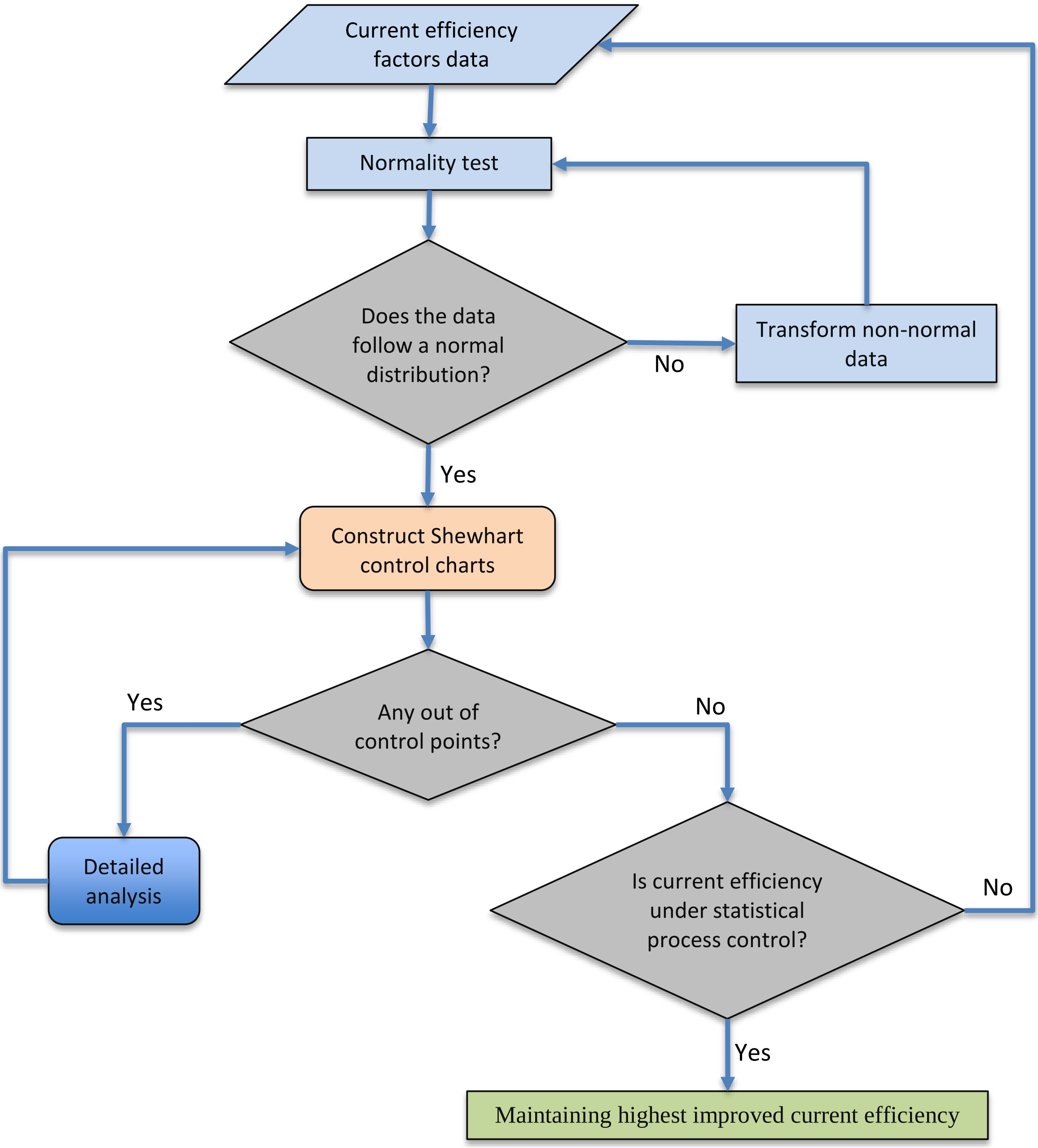


Figure 5.5.2: A simplified continuous quality improvement framework (designed by the author)

6. Conclusion, recommendations and further research

6.1 Conclusion

The work presented in this thesis has proven that it is possible to improve current efficiency from a quality perspective by applying statistical process control. This may be done by using the designed continuous quality improvement framework for improving electrowinning current efficiency. The identified knowledge gap was successfully filled by this research and it has achieved all its objectives. The first research objective was to explore factors that influence current efficiency. This objective was realized because current efficiency factors were explored by conducting an intensive literature review and by conducting a questionnaire-based survey (qualitative research approach). All the current efficiency factors were summarised by making use of a mind map.

On the one hand, based on the reviewed literature the current efficiency factors are temperature, electrolyte quality, rectifier current, cathode weight, electrodes, reagent addition, and contacts. On the other hand, the current efficiency factors explored by using questionnaires are metallurgical short-circuits (hotspots), impurities, electrode condition, electrode alignment (rat patrol), contacts, temperature, reagent addition, acid content, current density, rectifier current, electrode insulators, nodules, copper tenor and flow rate. A Pareto chart was applied to analyze current efficiency factors from questionnaires. After applying the 80-20 rule, the number of factors to be studied was downsized. Because the Pareto chart enables the identification of 20 % of the factors that have 80 % effect on current efficiency. Starting with the factor with the most significant effect on current efficiency, these factors are metallurgical short-circuits (hotspots), electrolyte impurities, electrode condition, electrode alignment (rat patrol), contacts, reagent addition, and electrolyte temperature.

The second research objective was to evaluate the current efficiency factor that has the most significant effect on current efficiency, by applying statistical process control. Amongst all the factors, it was concluded that metallurgical short-circuits (hotspots) seem to have the most significant effect on current efficiency than all other current efficiency factors. This conclusion was made after analyzing statistical control charts, doing a Pearson correlation analysis, process capability analysis and developing an out of control action plan. The same conclusion was also deduced from the qualitative research approach in terms of questionnaires and the Pareto chart (80-20 rule) as mentioned above.

After maintaining hotspots under statistical control, current efficiency improved by 5.40 %. It improved from a minimum value of 89.64 % to a maximum value of 95.04 % (5.40 % difference). This translates to the production of approximately 74 metric tons of 99.999 % pure grade A copper cathode production over a period of 1.5 months. Hence proofing that, it is possible to improve current efficiency from a quality perspective. High correlation coefficient and out of control points alignment between current efficiency and hotspots was a good indication of the significant effect of metallurgical short-circuits (hotspots) on current efficiency. The Pearson correlation analysis proved that the increased number of hotspots is more correlated to the decrease in current efficiency than all other factors. In addition to that, the alignment between the number of hotspots and current efficiency out of control points was high compared to other factors.

Finally, the third objective was achieved by designing a continuous quality improvement framework for improving current efficiency, by applying statistical process control. The framework design consideration include aspects such as current efficiency factors, normality test, transforming non-normal data to fit a normal distribution by using Johnson and Box-Cox transformation, classifying the data type, selecting suitable control charts, Pearson correlation analysis, out of control points alignment analysis, process capability analysis, root cause analysis, developing and implementing an out of control action plan, providing current efficiency training and developing a current efficiency improvement safe working procedure that should be embedded into daily operational activities.

6.2 Recommendations

During the process of designing a continuous quality improvement framework for improving current efficiency, the author has identified a number of potential points to be given as recommendations. The recommendations are aimed at highlighting some of the issues pertaining to the framework:

1. It was observed that the cathode smoothing agent plays a big role. This is because if the cathode smoothing agent make-up is not well monitored and controlled, it can result in the formation of nodules on the cathodes. The formed copper protrusions can result in excessive metallurgical short-circuits (hotspots) that decrease current efficiency drastically. It is recommended that the cathode smoothing agent should be interlocked to the rectifier current. This will allow for increased smoothing agent mass to be applied during make-up when operating at a high rectifier current. This is a process control and instrumentation issue and it requires automation.

2. It is better for the operations team to have an infrared camera (IR camera) instead of utilizing the normal temperature gun. This is because the IR camera is very sensitive and it easily shows metallurgical short-circuits (hotspots) since it is an advanced camera. The IR camera should be used every day for inspecting hotspots over the cells and the findings should be recorded on the log sheet. Thereafter, the identified metallurgical short-circuits (hotspots) should be investigated and rectified immediately.

3. Supervision of the daily operations will be very crucial to ensure the continuous quality improvement of current efficiency. Having the current efficiency continuous improvement procedure in place will not help if there is no strict monitoring, supervision, enforcement, and control over the daily operational activities.

4. It is best for cathode harvesting cranes to have load cells installed. This will allow for cathode weights to be determined for every electrolytic cell during stripping and hence the calculation of current efficiency per cell. The generated current efficiency data per cell can easily allow for easy tracking of the cells that have the lowest current

efficiency and further investigation thereafter per individual cell instead of investigating all electrolytic cells.

5. While collecting information via the questionnaire it was noted that most operational employees and technical staff are not familiar with the concept of current efficiency. However, they have a good idea of the best practice because it is part of the daily operational activities. Therefore, it is recommended to give current efficiency training to the operations and technical team. During training, it is best to share the best practice when it comes to current efficiency improvement so that the team can be very competent and familiar with best practices.

6. The author recommends setting up statistical process control charts in excel so that many current efficiency factors can be tracked on a daily basis. This will ensure that out of control action plans are developed and implemented at the first sign of process out of control.

7. Considering the benefits that the company will get after improving CE it is worth appointing an operator specifically for current efficiency improvement.

8. It was noted that there is no sufficient infrastructure example, overhead cranes at electrowinning to enable investigation of hotspots. The hotspot investigation had to wait. The delays affected the progress on current efficiency improvement. Therefore, it is recommended to install another crane or a manually operated lifting device.

6.3 Further research

The effectiveness of the designed continuous quality improvement framework can further be enhanced by conducting further research. During the current efficiency improvement campaign, a number of issues were observed that need further research. Things that need further research includes, but not limited to:

1. Research on how to accurately quantify the physical factors. Typical physical factors referred to in this case includes, but not limited to the number of metallurgical short-circuits (hotspots), the number of damaged/bend anodes within the electrolytic cells, number of nodules causing hotspots, the degree to which electrode alignment (rat patrol) was done well, etc. Most of the time these factors are determined manually. Which is labour-intensive and not accurate. Therefore, further research should be done to develop a better method to accurately quantify physical factors. An online monitoring system would be best.

2. The analysis done in this report is based on actual commercial electrowinning data. Further research should be done by conducting electrolysis experiments in the lab and also by undertaking computer-based simulation runs. This can allow for the factors to be studied under specific conditions and controlled conditions. This can give a better indication of the effect of the factors on current efficiency.

3. Further research can be done be to study the effect of the interaction between the factors that affect current efficiency. For example, when the impurity concentration is high, and the electrolyte flow is high, it will result in increased impurity mass transfer/plating which can drastically decrease current efficiency. Therefore, multiple factors need to be varied and the effect on current efficiency be investigated. This will be very crucial for better process control and also for maintaining current efficiency under statistical control by reducing process instability.

4. One of the conditions given in the permit to conduct this research was no commercial information should be disclosed, not even indirectly. As a result, no financial implication was analyzed for this research. Further research should be done by

analyzing the cost of continuous quality improvement of current efficiency. The cost of quality is very essential. It will allow one to decide if it is worth investing further in current efficiency improvement. This can be done by conducting financial sensitivity under different conditions.

5. The identified limitations of this research also need to be further researched. The main limitation is the fact that the research was conducted in an unstable electrowinning process. Not all tests could be conducted because it might interrupt copper cathode production. A pilot plant would be the best option for further research. In the pilot plant, the current efficiency factors can easily be studied by varying them and then see how current efficiency will respond to the changes. It can allow for different experimental designs to be executed without interfering with the actual production operation.

6. Further research should be done by applying statistical process control on many current efficiency factors. The multivariate control charts are very crucial for monitoring multiple process variables especially when the process variables correlate. Other control charts such as Cumulative Sum (CUSUM) control charts and Exponentially Weighted Moving Average (EWMA) control charts may also be applied.

7. It may be worth doing further research by applying the design of experiments (DOE) when collecting attribute current efficiency data in the tank house. This will enable the data to be collected in a specific order hence, allowing specific analysis to be conducted.

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8. Appendix

The raw data for the entire research project can be accessed by following this link: https://data.mendeley.com/datasets/r3hf2n9tf9/draft?a=37999064-7ddb-4ad1-b89d-437b02dfd355

Appendix A: Raw data obtained from questionnaires for suggested current efficiency factors and suggested improvement best practices for improving current efficiency

Table 8.1: Questionnaire results for suggested current efficiency factors (compiled by the author)

Current efficiency factors suggested	Frequency of suggestion	Cumulative percent
Current density	6	2.5 %
Plating time	1	0.4 %
Mass transport coefficient	1	0.4 %
Electrolyte impurities concentration	28	11.5 %
Electrode condition	6	2.5 %
Electrolyte conductivity	4	1.6 %
Electrolyte temperature	17	7.0 %
EQ bar condition	2	0.8 %
Dirty electrode contacts	24	9.8 %
Electrode alignment (Rat patrol)	26	10.7 %
Electrolyte acid concentration	8	3.3 %
Metallurgical short-circuits (Hotspot)	48	19.7 %
Missing electrode insulators	6	2.5 %
Electrolyte copper tenor	4	1.6 %
Anode cleaning/inspection	5	2.0 %
Reagent addition	5	2.0 %
Organic entrainment	3	1.2 %
Flocculant addition	5	2.0 %
Formation of nodules	6	2.5 %
Bend and corroded anodes	11	4.5 %
Anode age	3	1.2 %
Rectifier current	1	0.4 %
Anode preparation	2	0.8 %

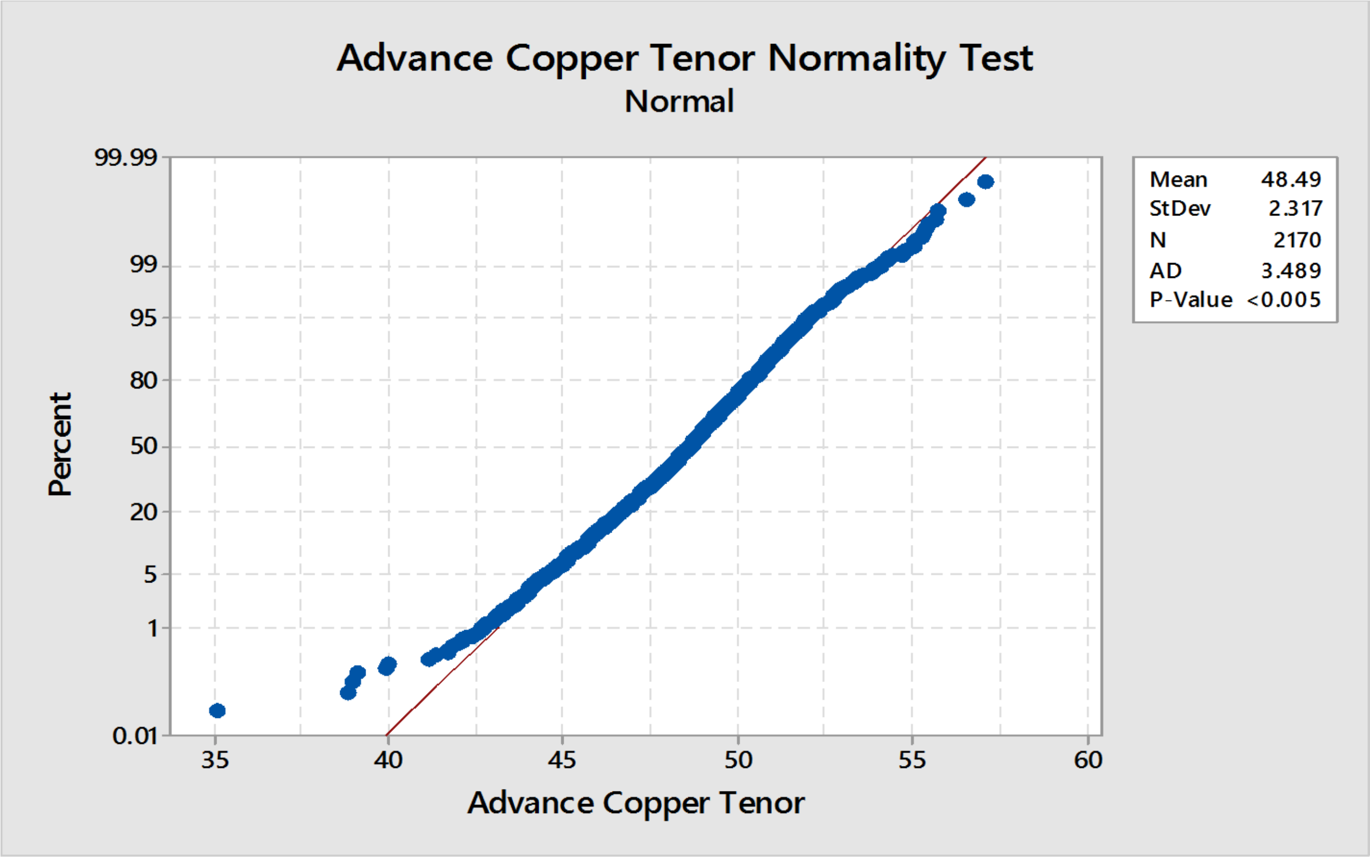
Stray current	2	0.8 %
Leakage current	2	0.8 %
Cathode corrosion	1	0.4 %
Imbalanced voltage	1	0.4 %
Electrolyte flow control	3	1.2 %
Anode polarization	1	0.4 %
Cathode brushing	1	0.4 %
Sulphate balance	1	0.4 %
Salt addition	1	0.4 %
Rectifier efficiency	6	2.5 %
Current efficiency calculation method	1	0.4 %
Loose contact connections	1	0.4 %
Total suspended solids	1	0.4 %
Total	**244**	**100%**

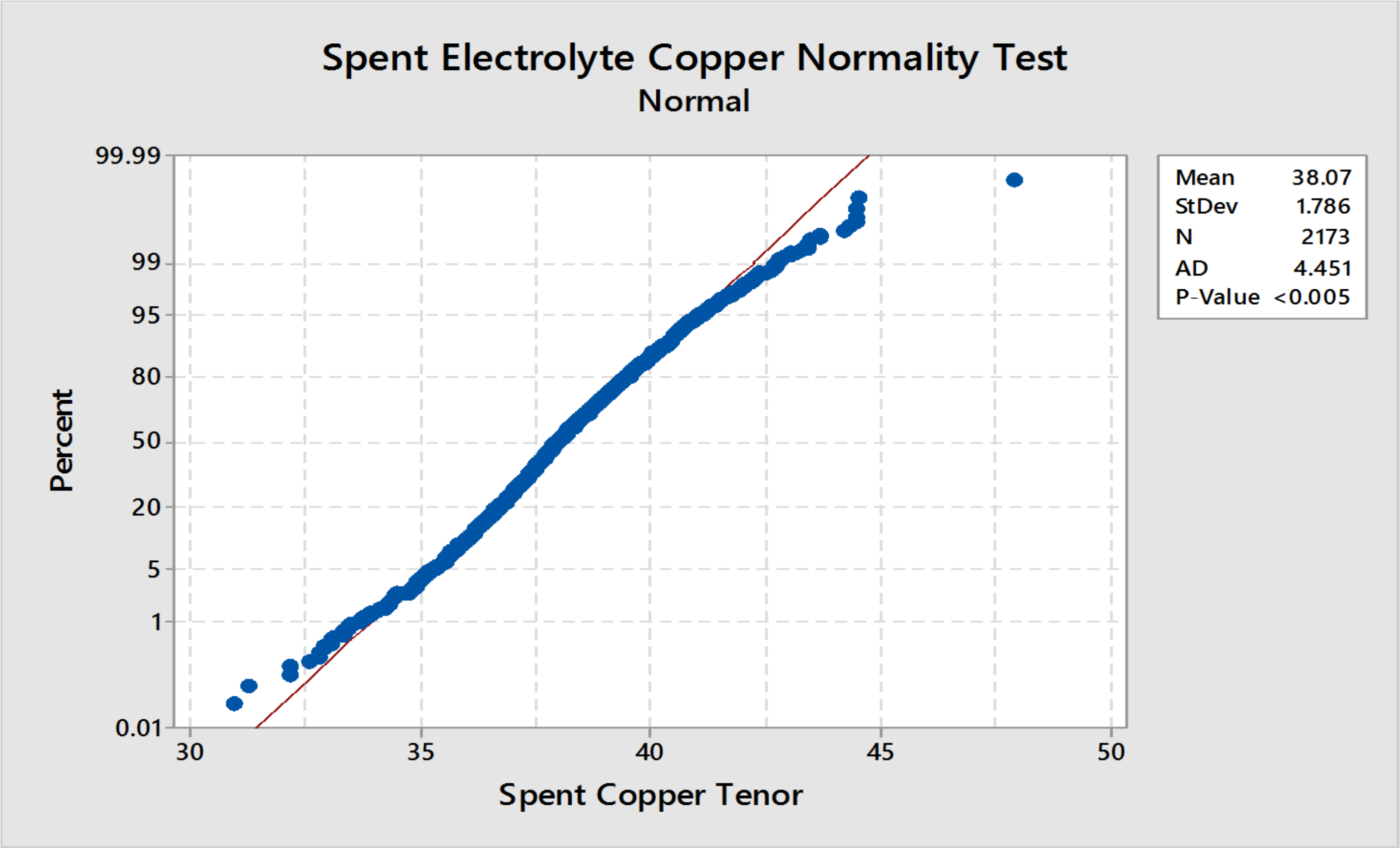
Table 8.2: Questionnaire results for suggested best practice for improving current efficiency (compiled by the author)

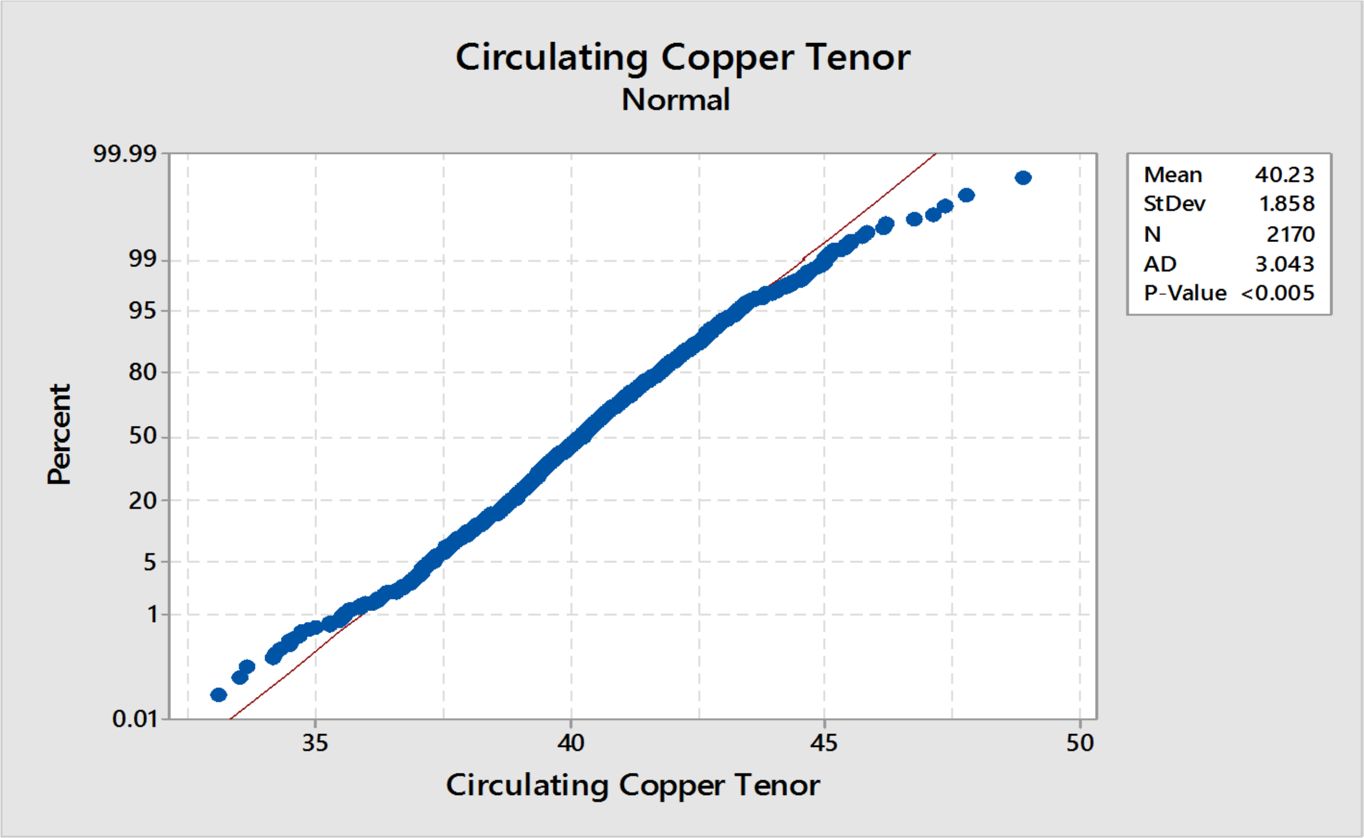
Best practice suggested	**Frequency of suggestion**	**Cumulative percent**
Reduce cathode passivation	1	0.3 %
Electrode replacement	17	5.7 %
Electrolyte impurity monitoring and control	26	8.8 %
Optimum operating current density	3	1.0 %
Regular anode cleaning	6	2.0 %
Metallurgical short-circuits (Hotspot) monitoring & correction	48	16.2 %
Monitor & control electrolyte temperature	7	2.4 %
Current efficiency training	45	15.2 %
Current efficiency improvement procedure	43	14.5 %
Regular electrode alignment (Rat patrol)	26	8.8 %
Cleaning contacts regularly	19	6.4 %

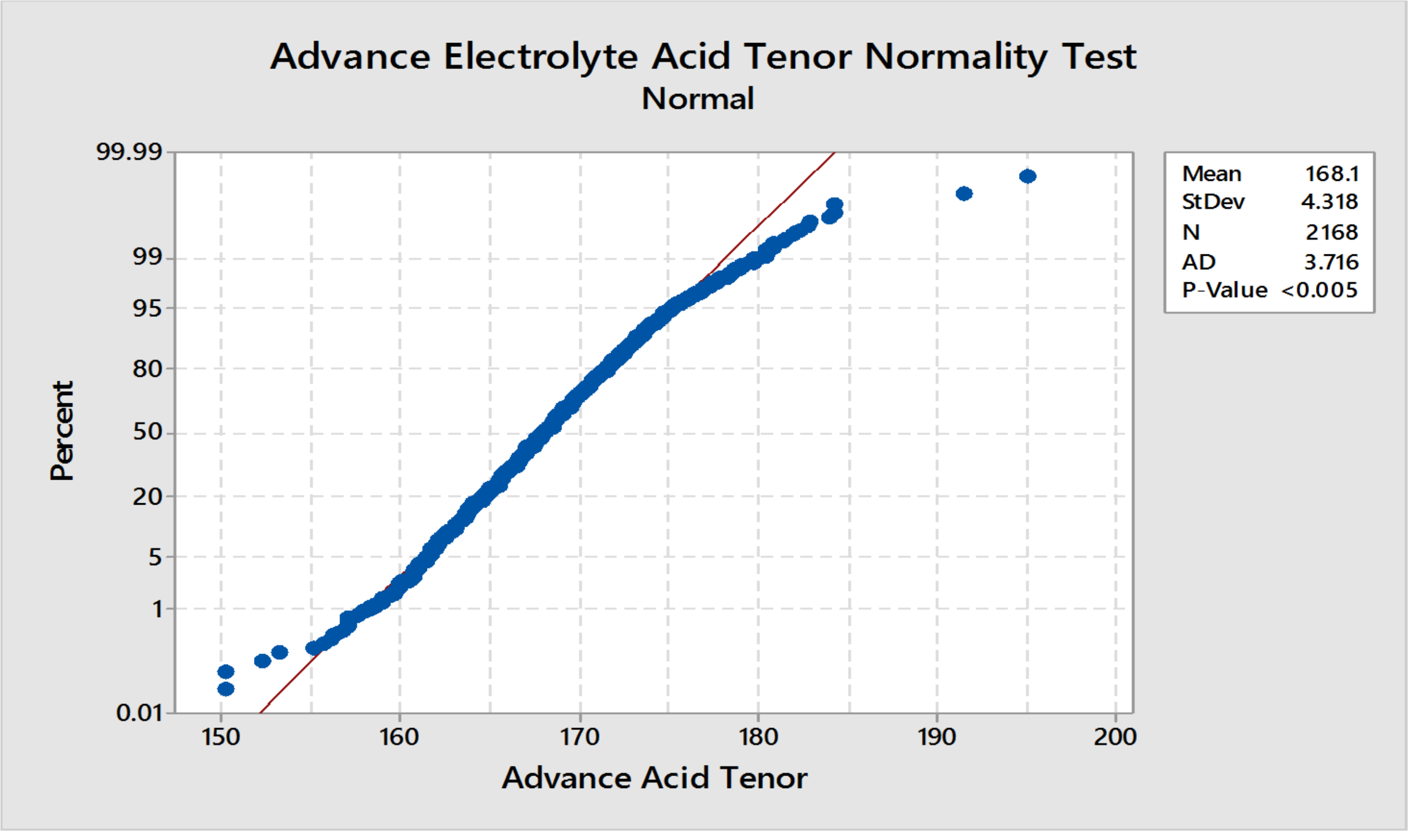
Replace missing insulators	7	2.4 %
Monitor & control reagent addition	8	2.7 %
Monitor & control copper tenor	2	0.7 %
Regular cell cleaning	7	2.4 %
Monitor & control flocculant addition	8	2.7 %
Monitor & control acid tenor	6	2.0 %
Skimming off entrained organic	1	0.3 %
Monitor & control electrolyte flow	1	0.3 %
Cell monitoring system	1	0.3 %
Regular organic removal from cells	1	0.3 %
Electrolyte pipes inspection	1	0.3 %
Brush cathodes regularly	1	0.3 %
Monitor and control heat exchanger efficiency	2	0.7 %
Straighten bend anodes	2	0.7 %
Review CE calculations	2	0.7 %
Ripple control on VDC line	1	0.3 %
Inspect for loose contact connections	1	0.3 %
Regular replacement of electrolyte filtration media	2	0.7 %
Improved control of rectifier current	1	0.3 %
Total	**296**	**100 %**

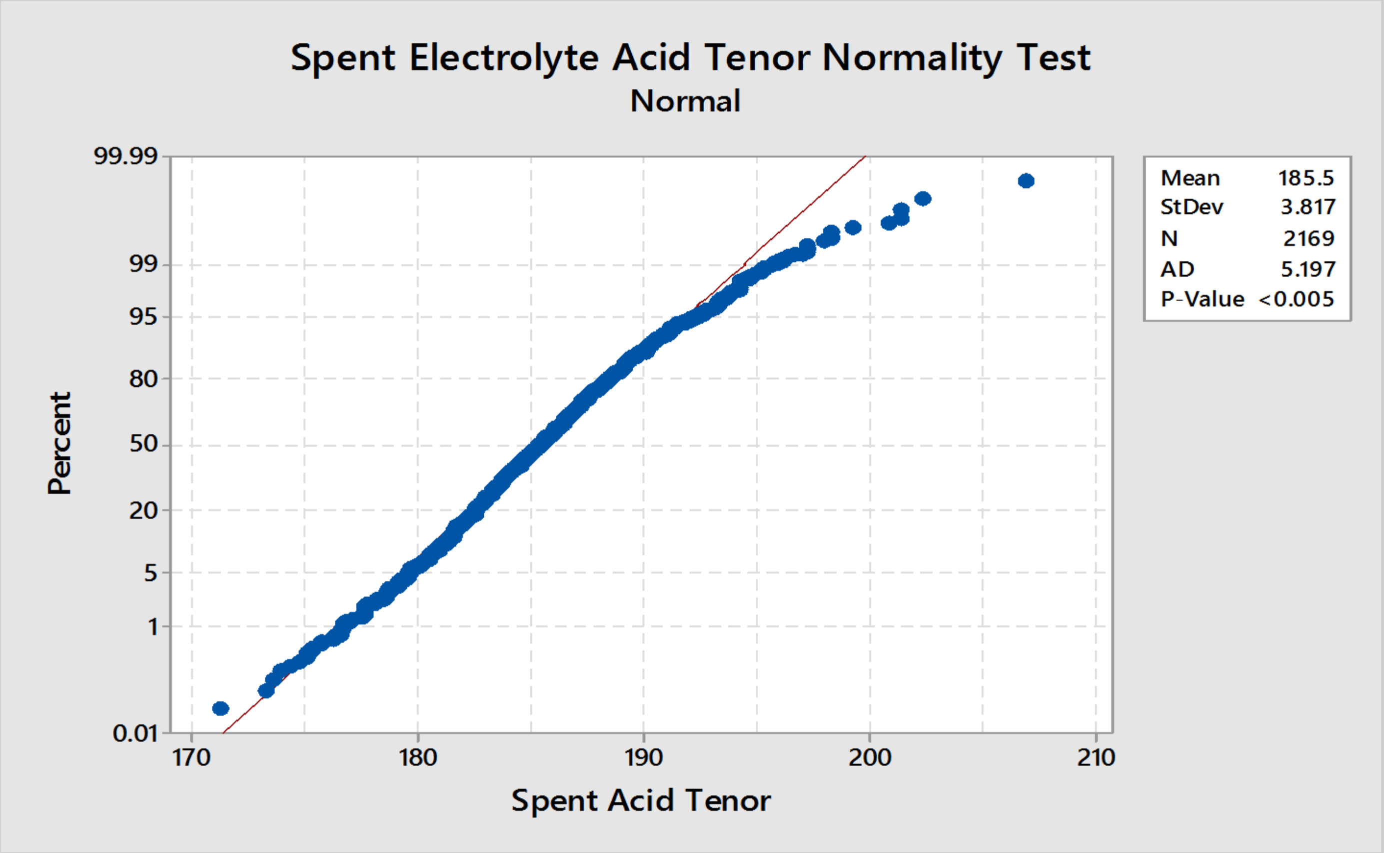
Appendix B: Anderson Darlington normality test charts created using Minitab statistical software for current efficiency factors data

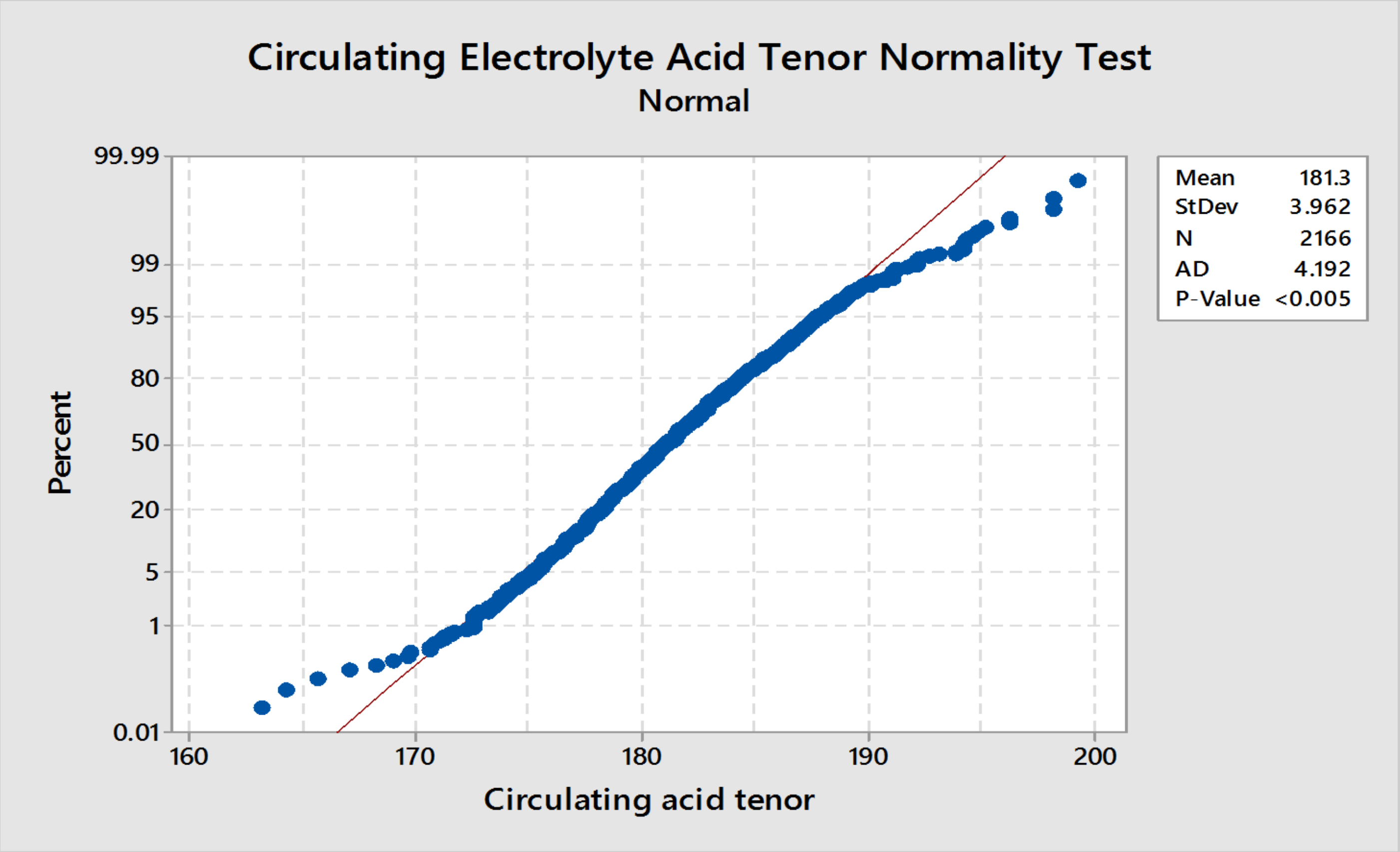


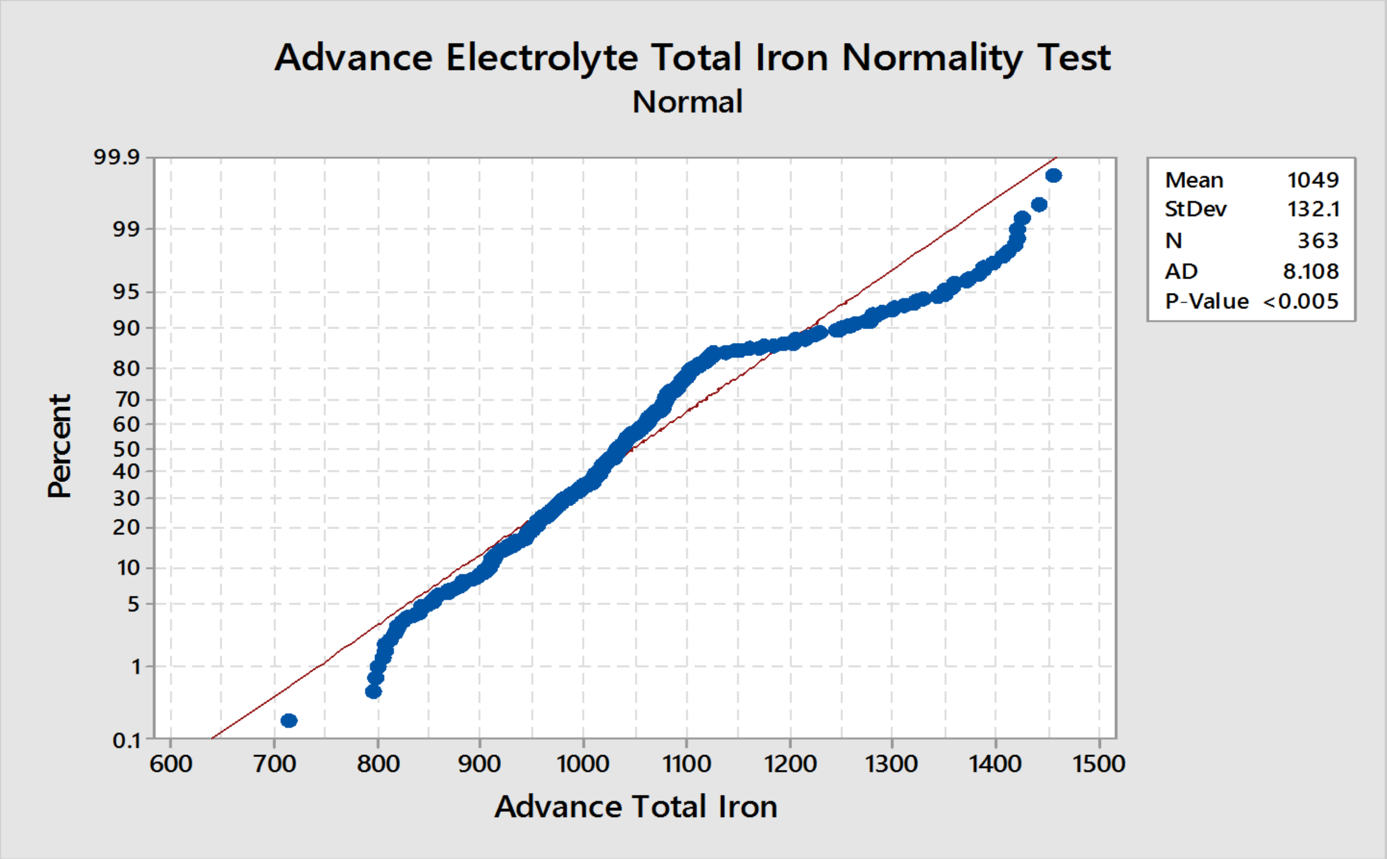


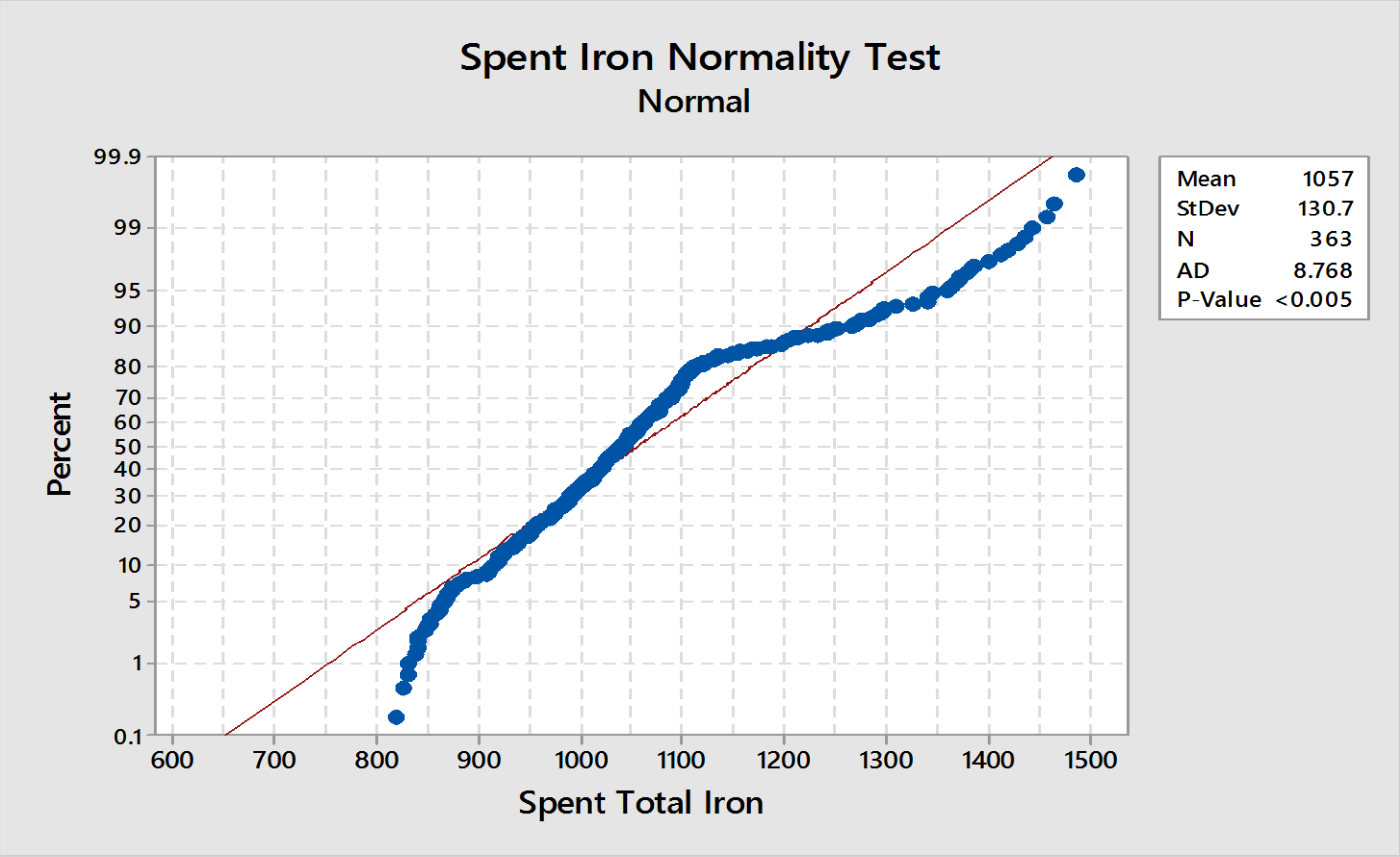


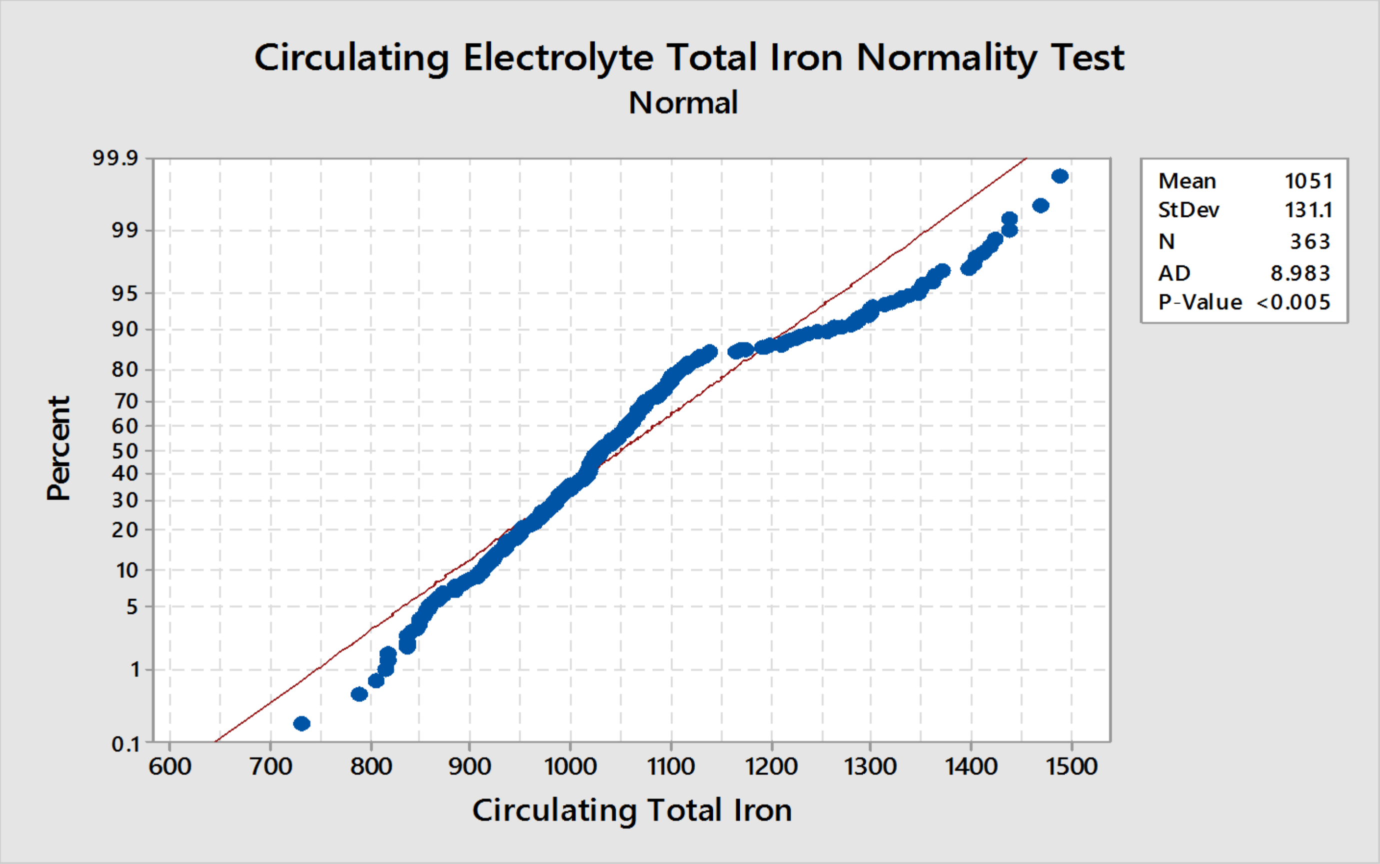


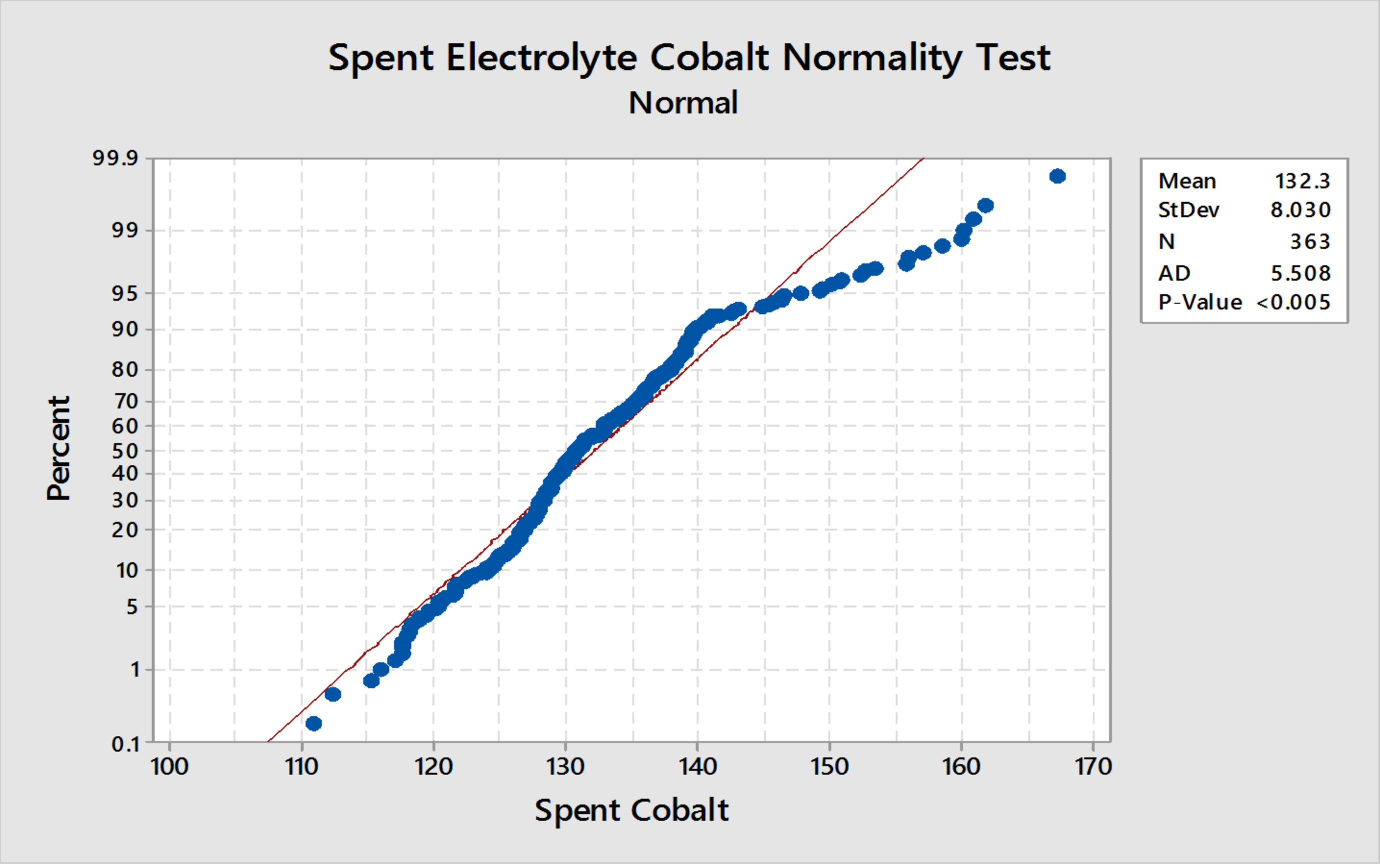

Spent Electrolyte Acid Tenor Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
170
180
190
200
210
Spent Acid Tenor
Mean 185.5
StDev 3.817
N 2169
AD 5.197
P-Value <0.005

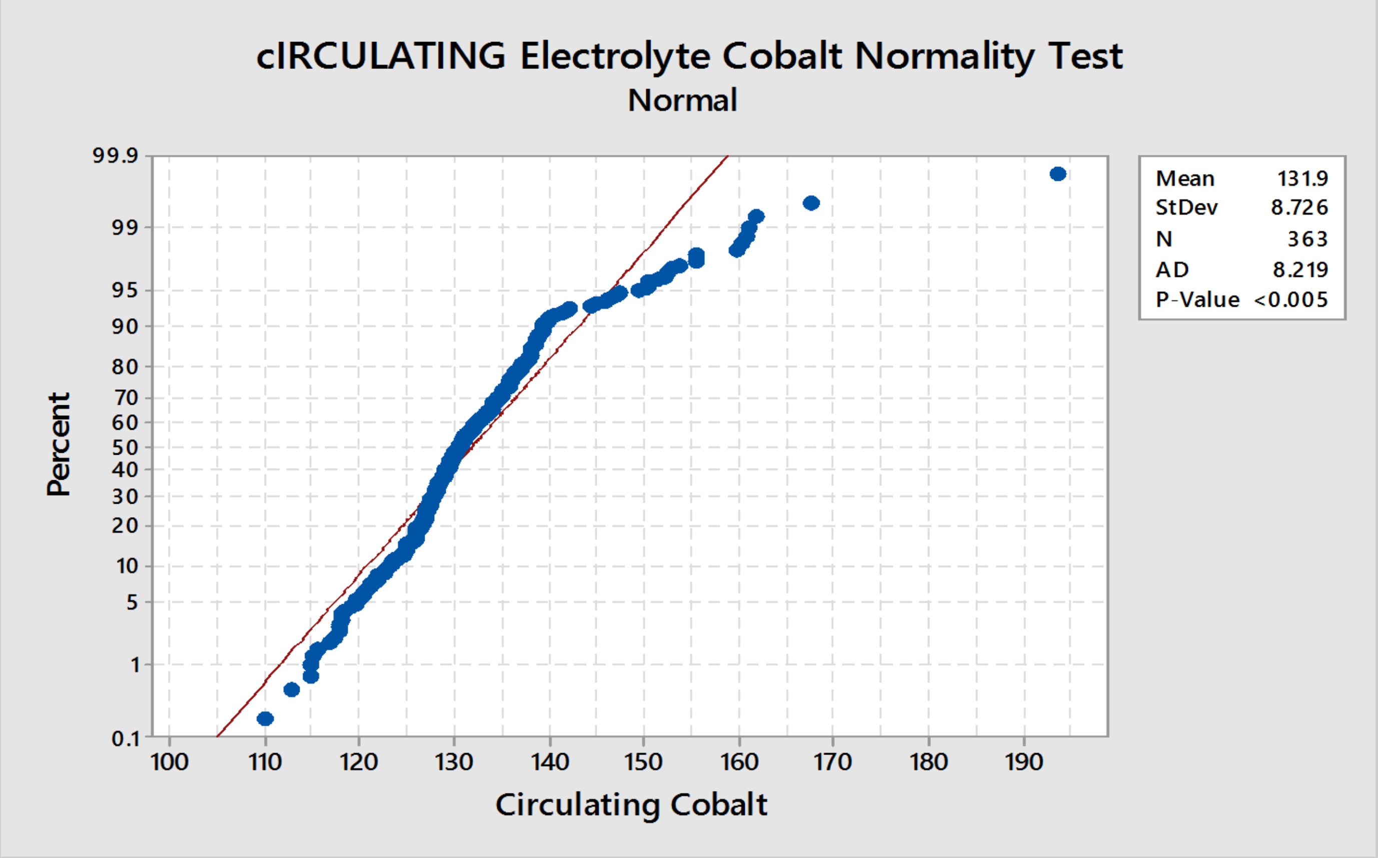

Circulating Electrolyte Acid Tenor Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
160
170
180
190
200
Circulating acid tenor
Mean 181.3
StDev 3.962
N 2166
AD 4.192
P-Value <0.005

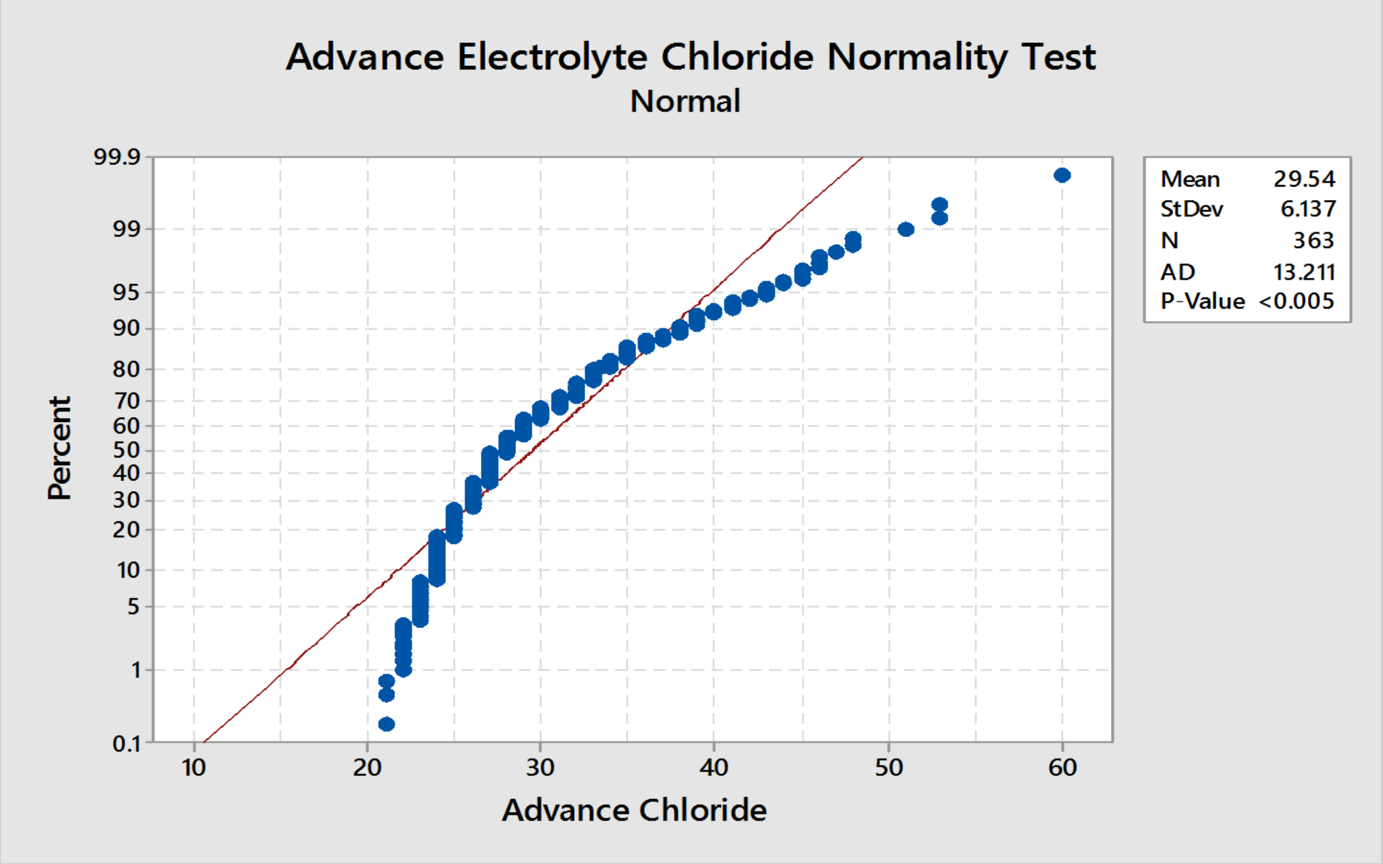

Advance Electrolyte Total Iron Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
600
700
800
900
1000
1100
1200
1300
1400
1500
Advance Total Iron
Mean 1049
StDev 132.1
N 363
AD 8.108
P-Value <0.005

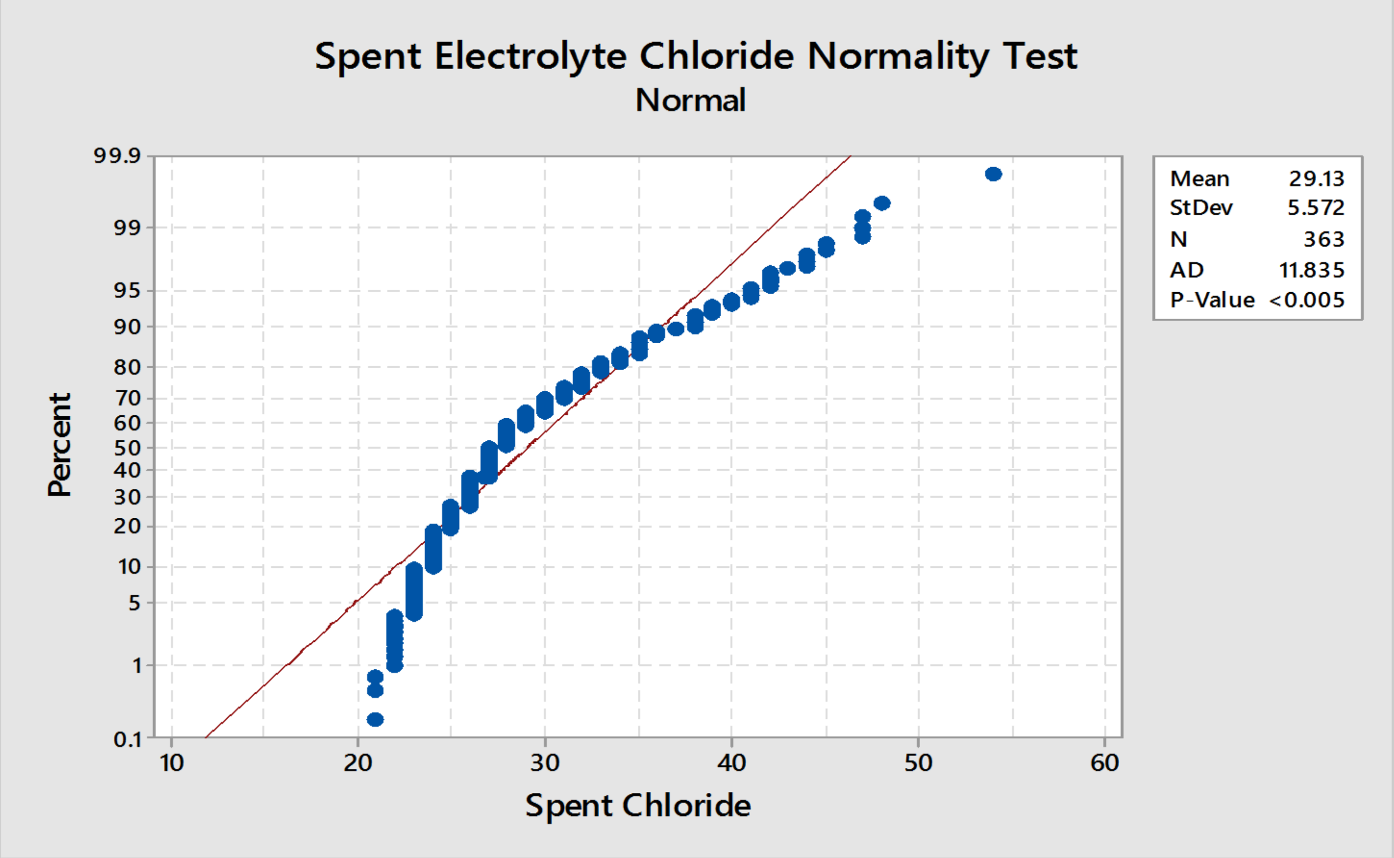

Spent Iron Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
600
700
800
900
1000
1100
1200
1300
1400
1500
Spent Total Iron
Mean 1057
StDev 130.7
N 363
AD 8.768
P-Value <0.005


Circulating Electrolyte Total Iron Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
600
700
800
900
1000
1100
1200
1300
1400
1500
Circulating Total Iron
Mean 1051
StDev 131.1
N 363
AD 8.983
P-Value <0.005

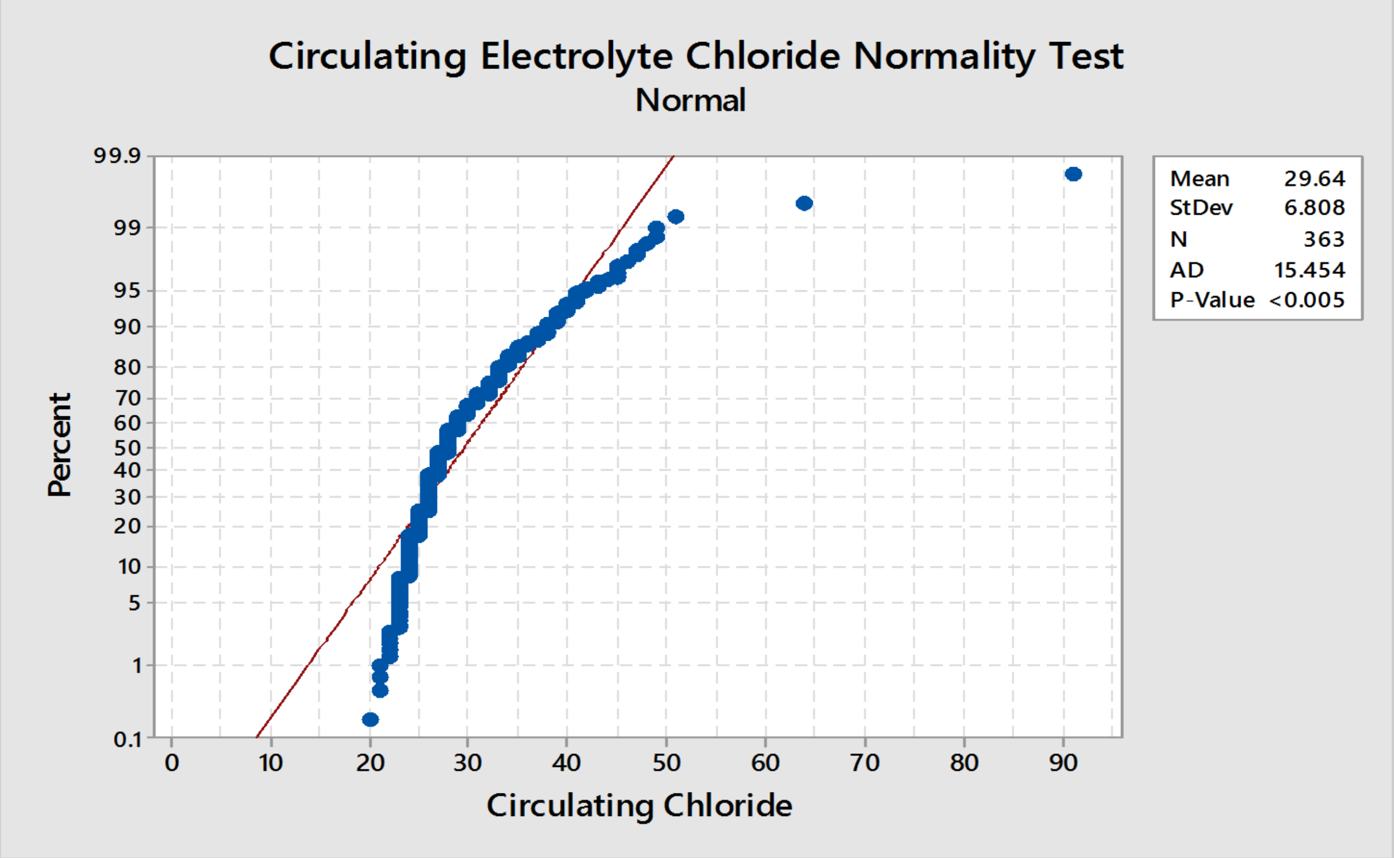

Spent Electrolyte Cobalt Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
100
110
120
130
140
150
160
170
Spent Cobalt
Mean 132.3
StDev 8.030
N 363
AD 5.508
P-Value <0.005


cIRCULATING Electrolyte Cobalt Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
100
110
120
130
140
150
160
170
180
190
Circulating Cobalt
Mean 131.9
StDev 8.726
N 363
AD 8.219
P-Value <0.005

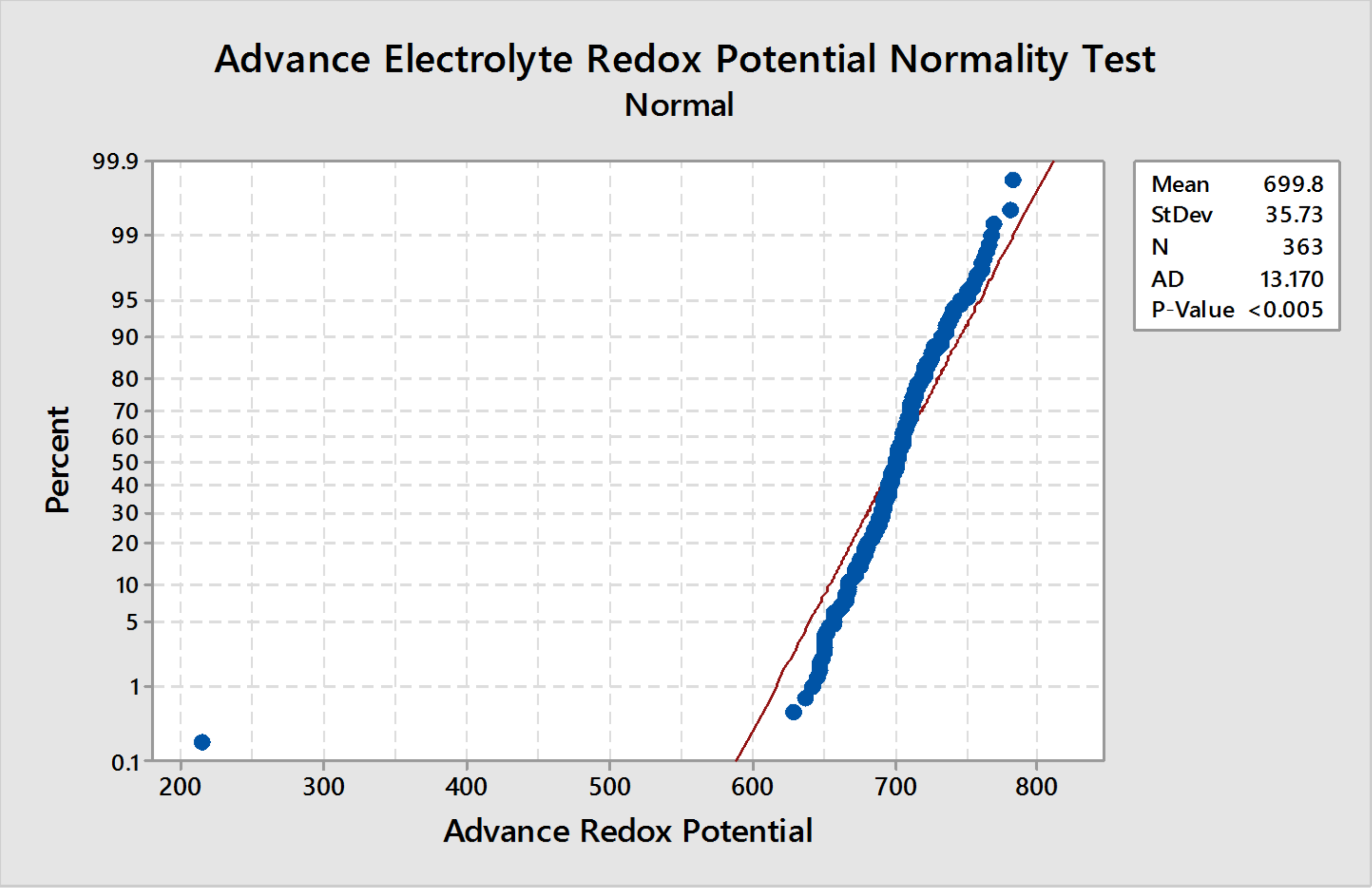

Advance Electrolyte Chloride Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
10
20
30
40
50
60
Advance Chloride
Mean 29.54
StDev 6.137
N 363
AD 13.211
P-Value <0.005



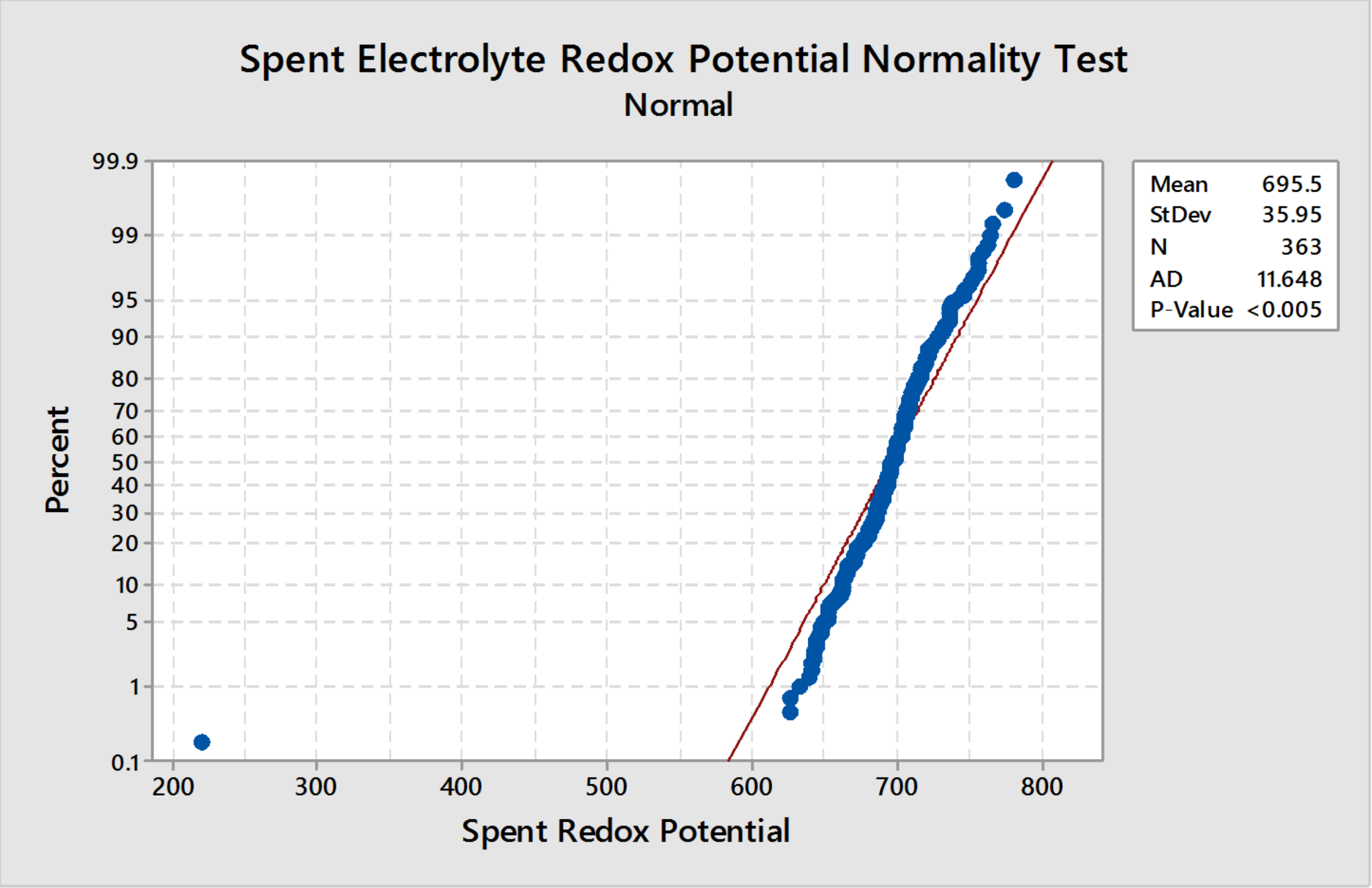
Spent Electrolyte Chloride Normality Test
Normal



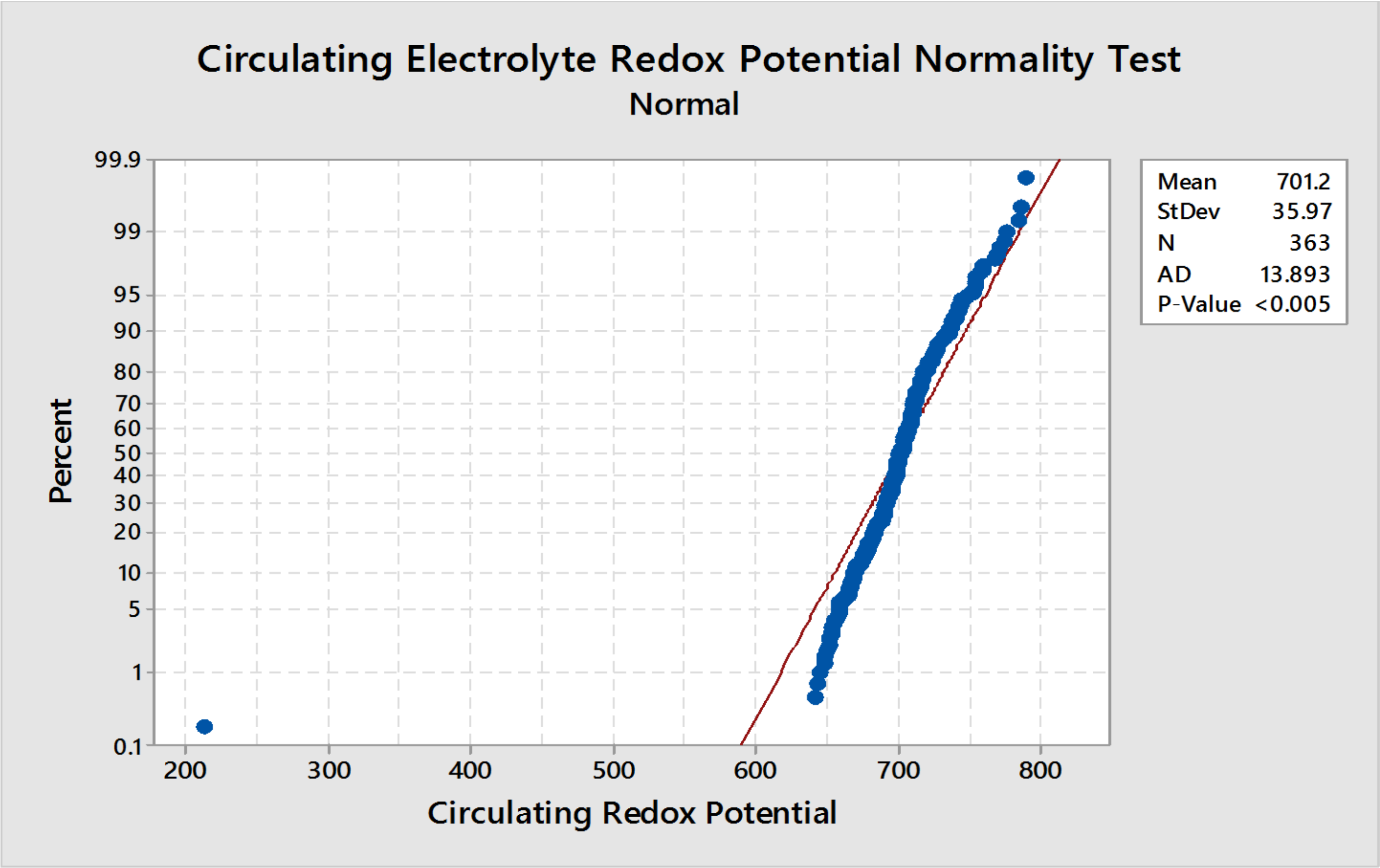
Circulating Electrolyte Chloride Normality Test
Normal

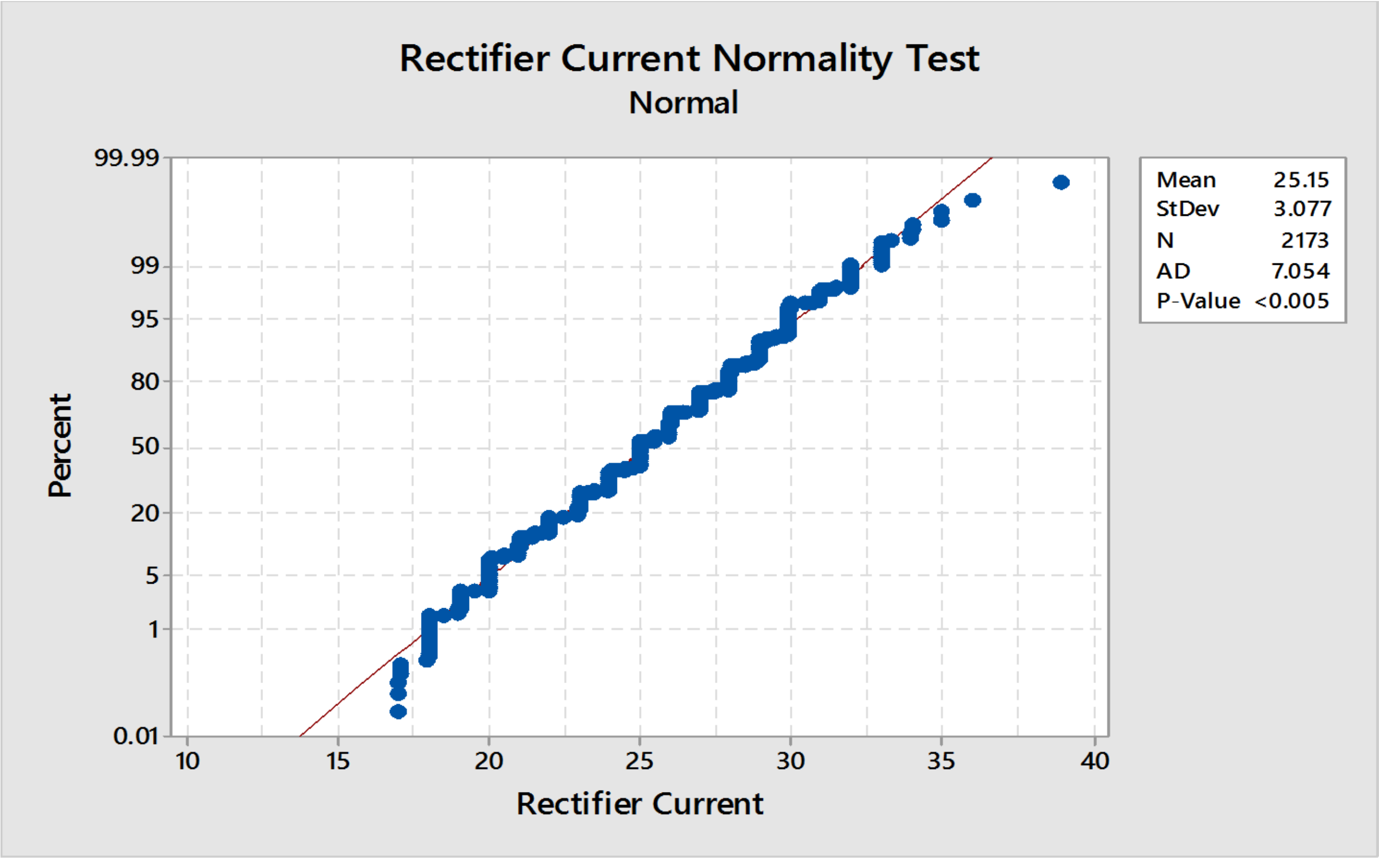


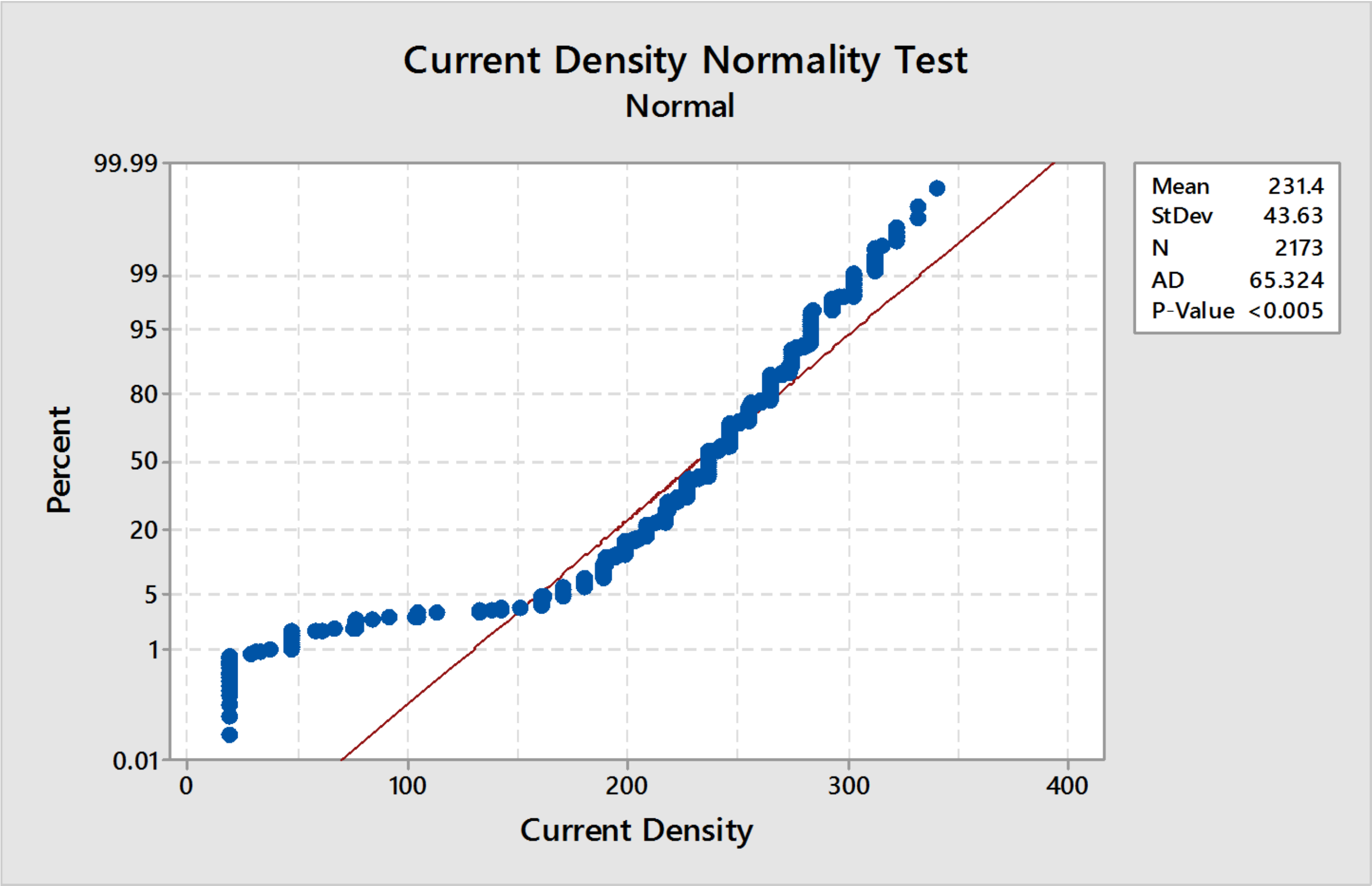
Advance Electrolyte Redox Potential Normality Test
Normal

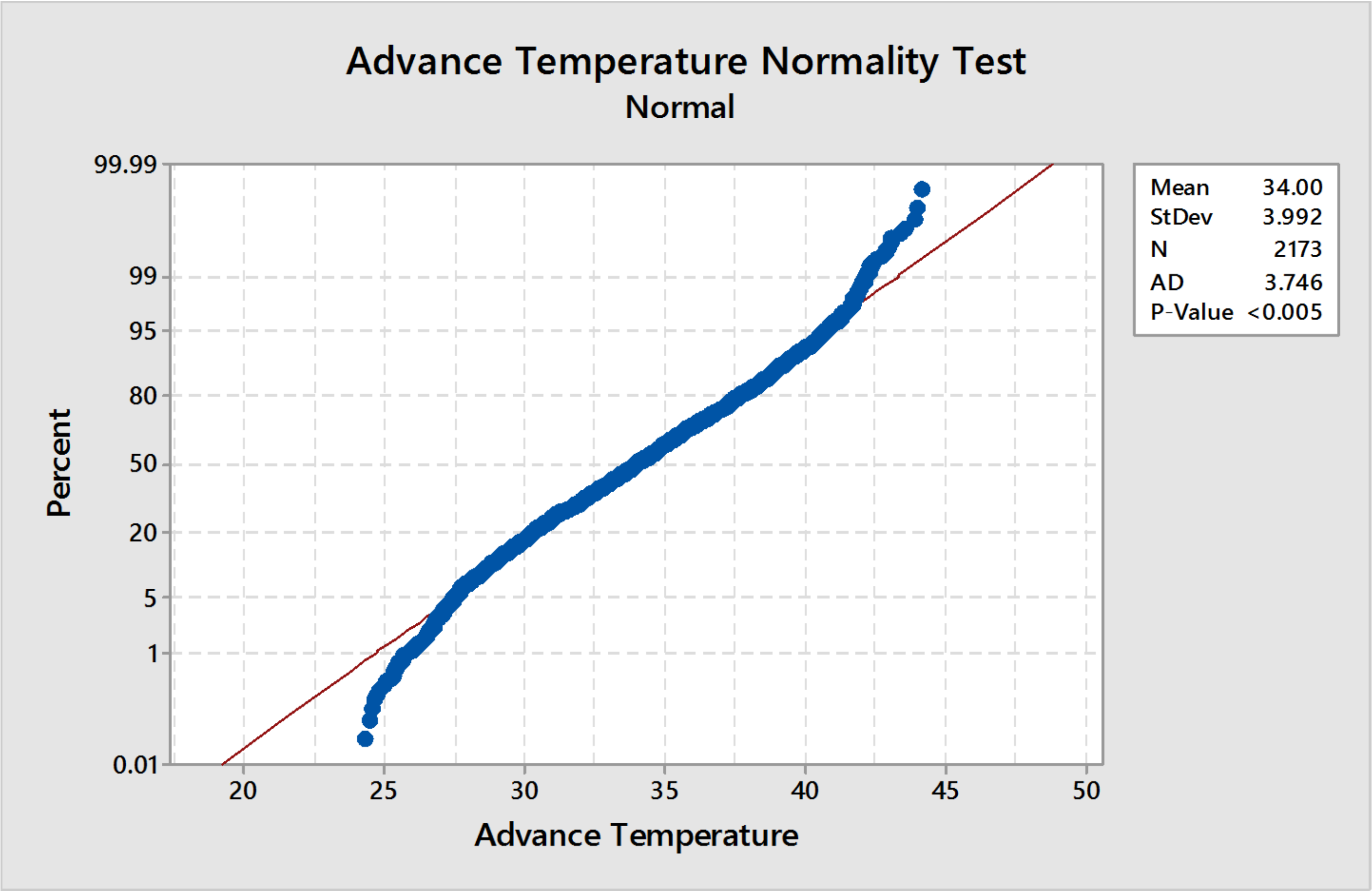


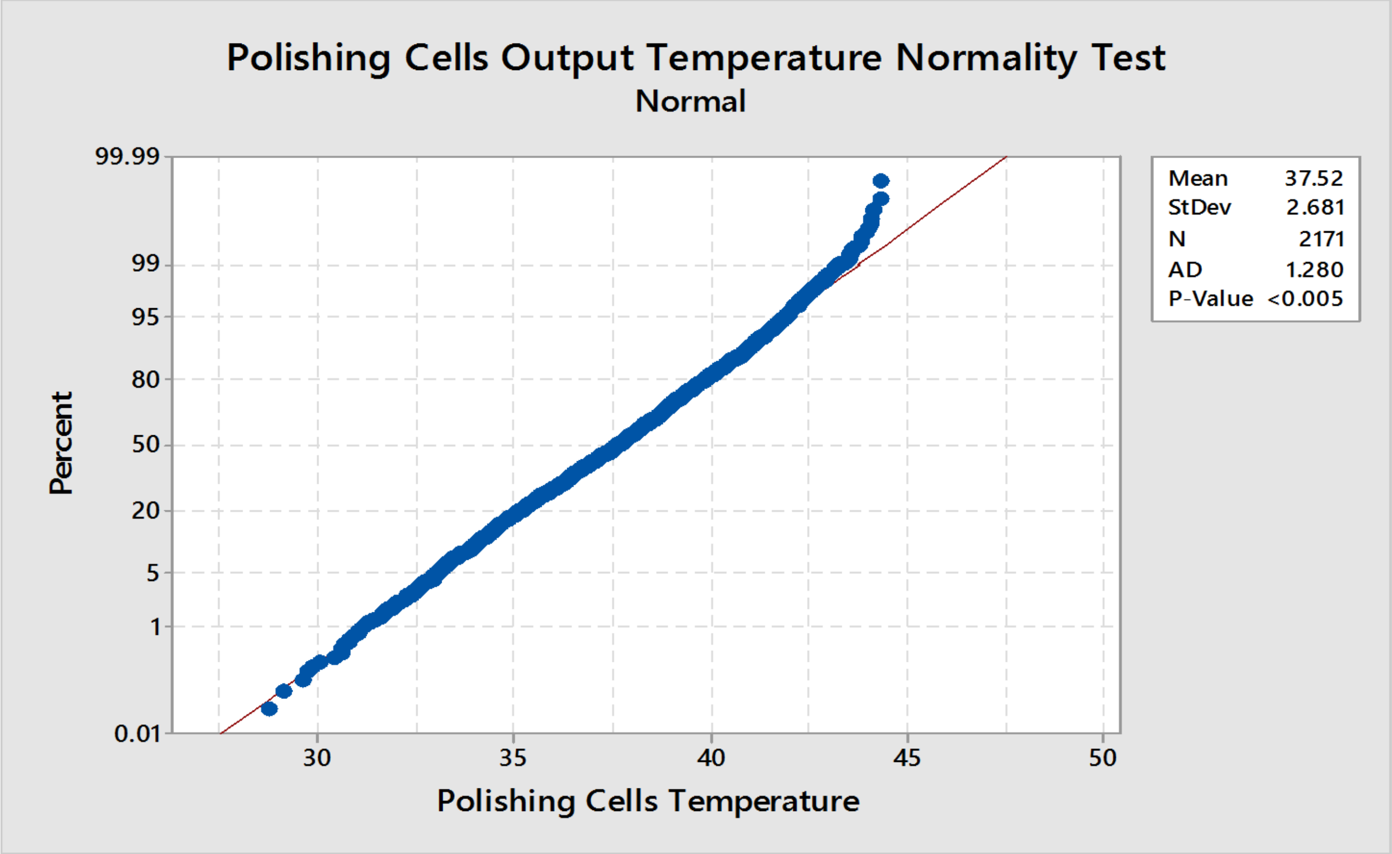
Spent Electrolyte Redox Potential Normality Test
Normal

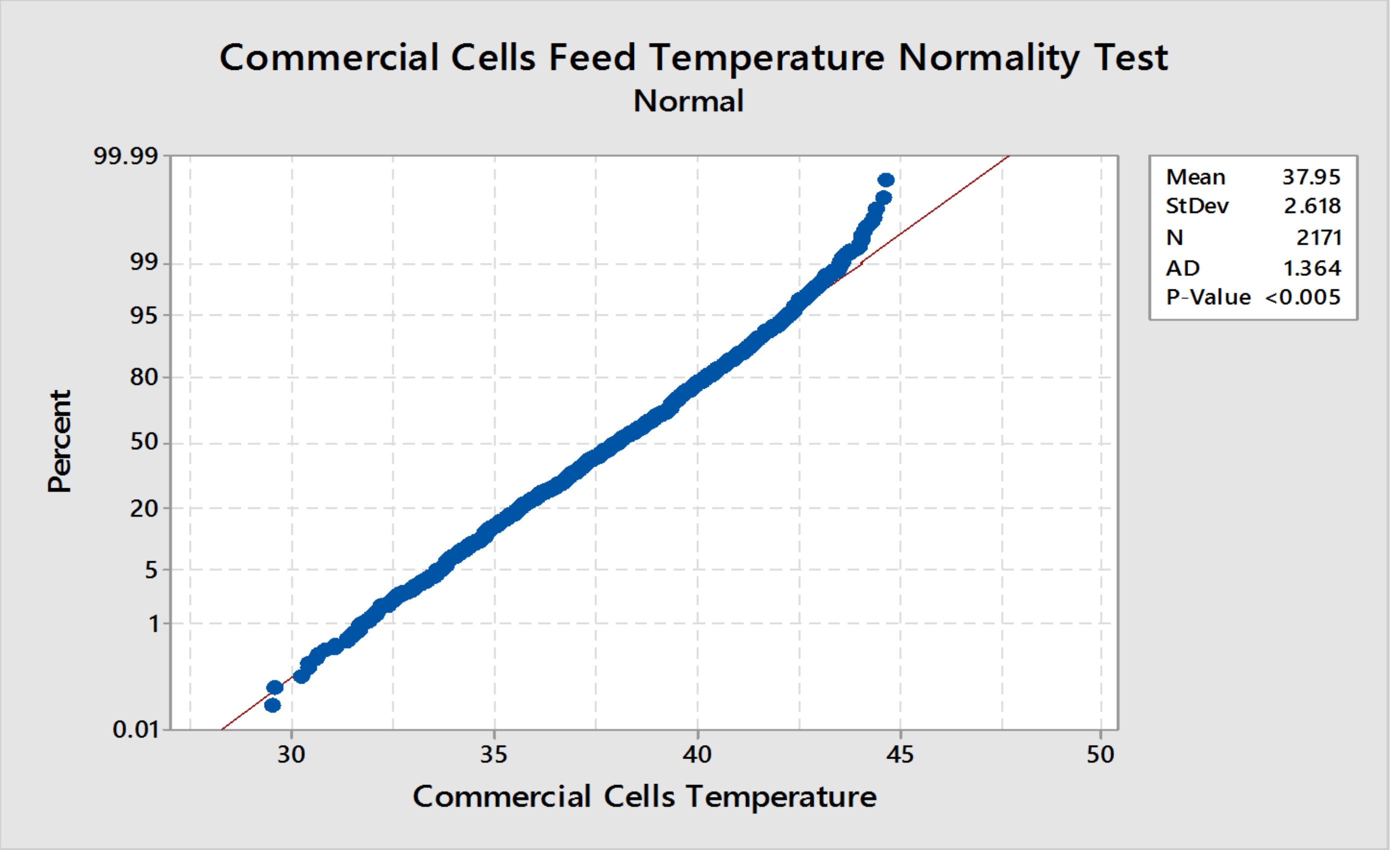

Circulating Electrolyte Redox Potential Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
200
300
400
500
600
700
800
Circulating Redox Potential
Mean 701.2
StDev 35.97
N 363
AD 13.893
P-Value <0.005

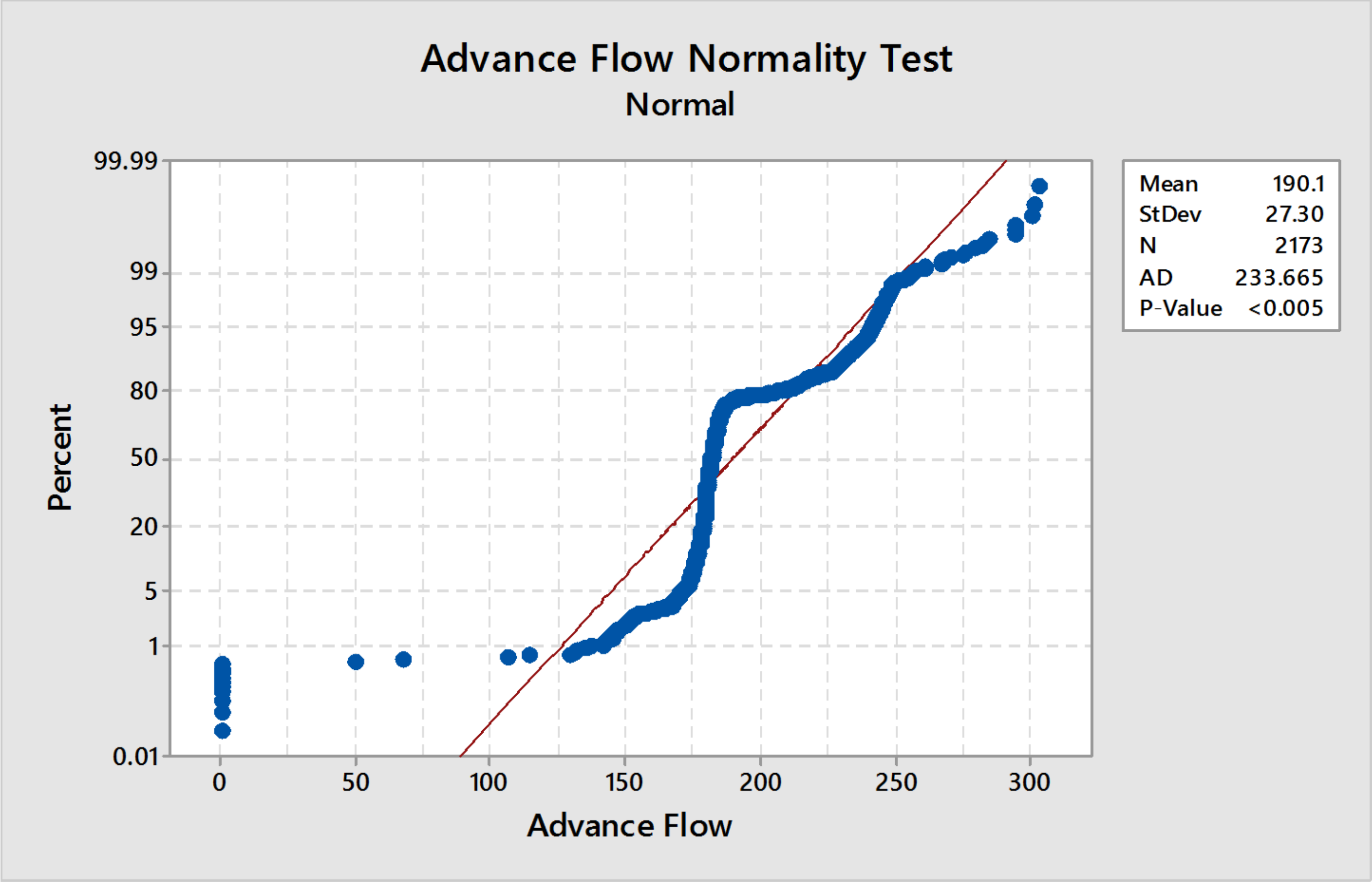

Rectifier Current Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
10
15
20
25
30
35
40
Rectifier Current
Mean 25.15
StDev 3.077
N 2173
AD 7.054
P-Value <0.005

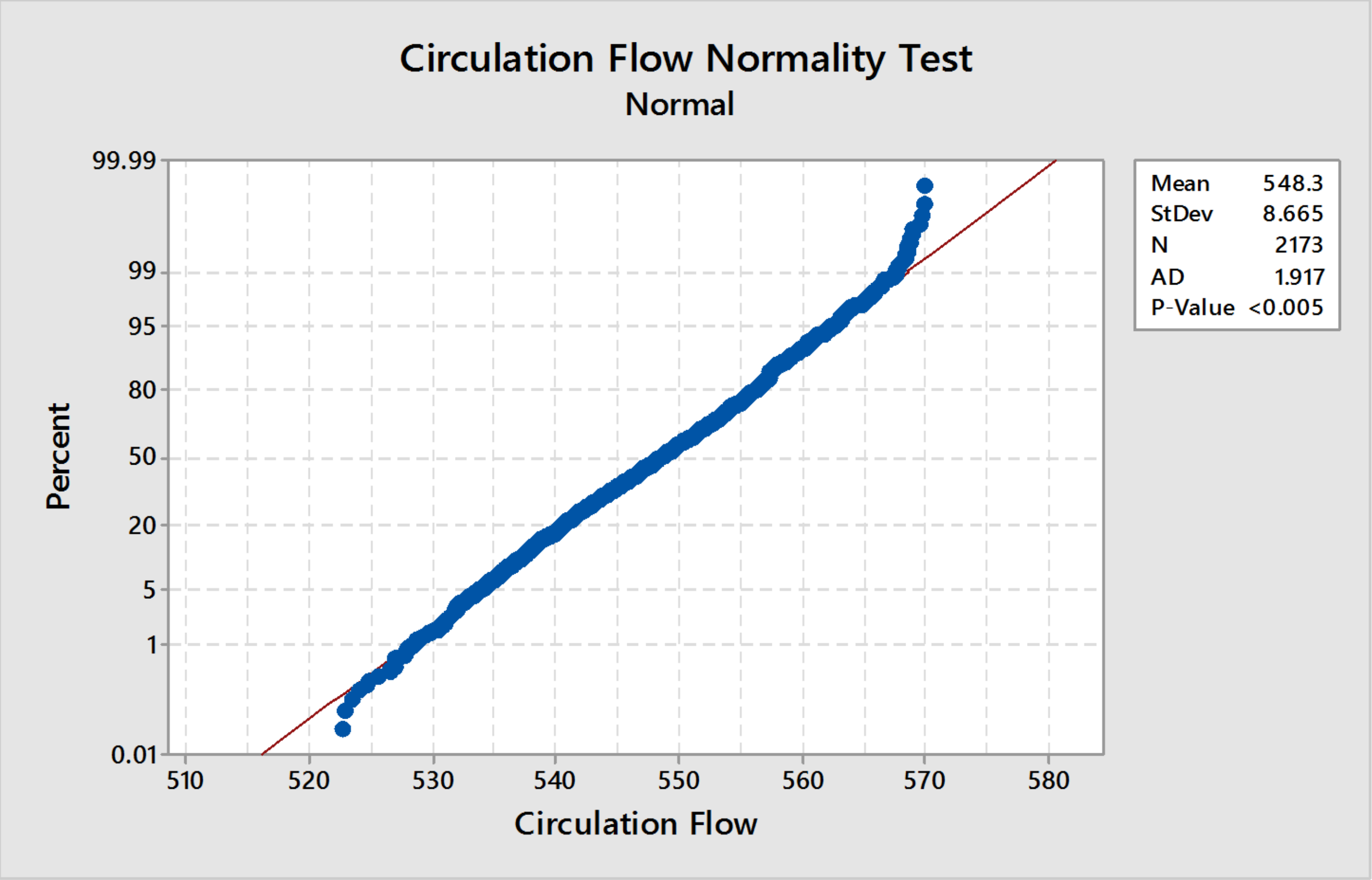

Current Density Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
0
100
200
300
400
Current Density
Mean 231.4
StDev 43.63
N 2173
AD 65.324
P-Value <0.005


Advance Temperature Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
20
25
30
35
40
45
50
Advance Temperature
Mean 34.00
StDev 3.992
N 2173
AD 3.746
P-Value <0.005


Polishing Cells Output Temperature Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
30
35
40
45
50
Polishing Cells Temperature
Mean 37.52
StDev 2.681
N 2171
AD 1.280
P-Value <0.005


Commercial Cells Feed Temperature Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
30
35
40
45
50
Commercial Cells Temperature
Mean 37.95
StDev 2.618
N 2171
AD 1.364
P-Value <0.005


Advance Flow Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
0
50
100
150
200
250
300
Advance Flow
Mean 190.1
StDev 27.30
N 2173
AD 233.665
P-Value <0.005


Circulation Flow Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
510
520
530
540
550
560
570
580
Circulation Flow
Mean 548.3
StDev 8.665
N 2173
AD 1.917
P-Value <0.005

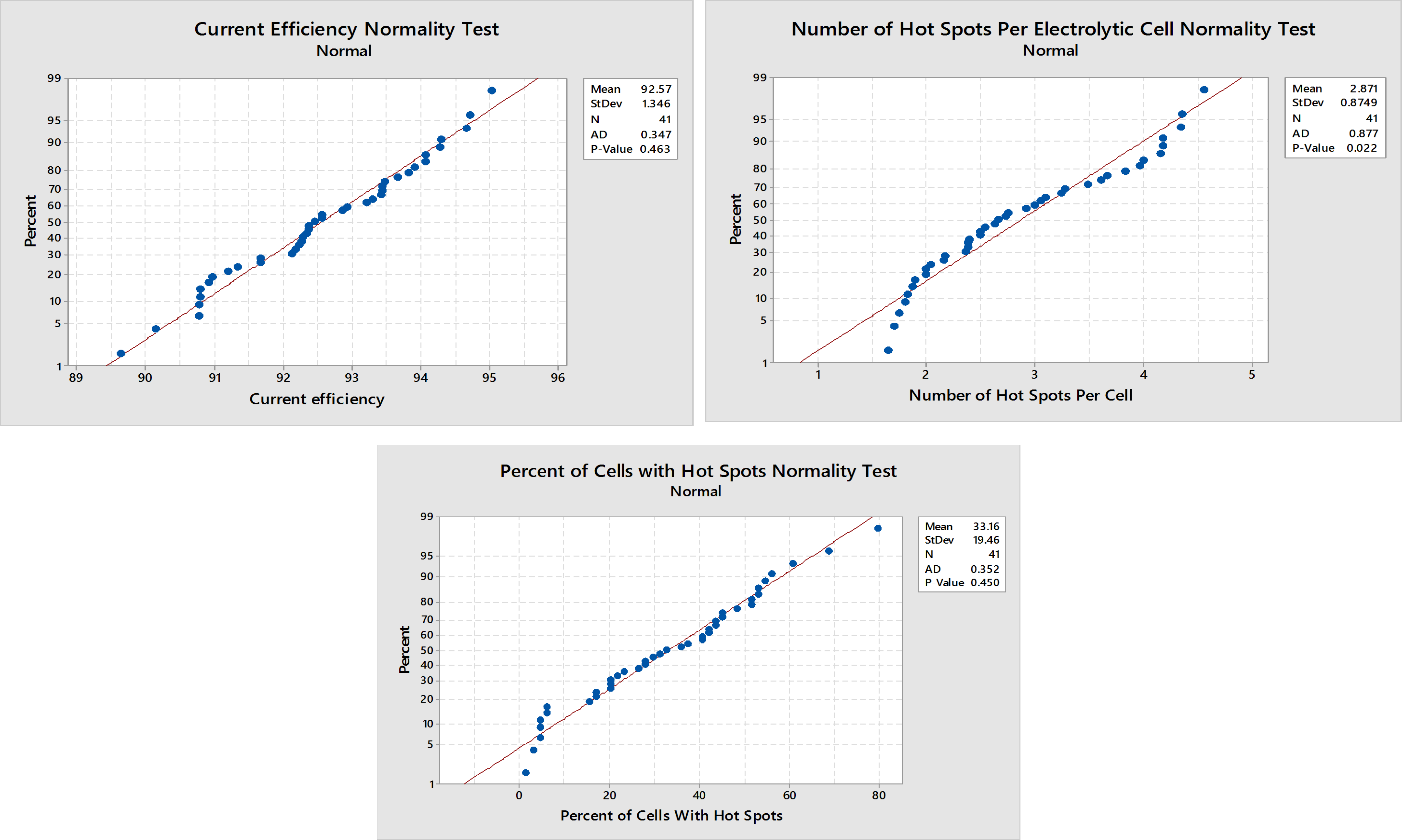
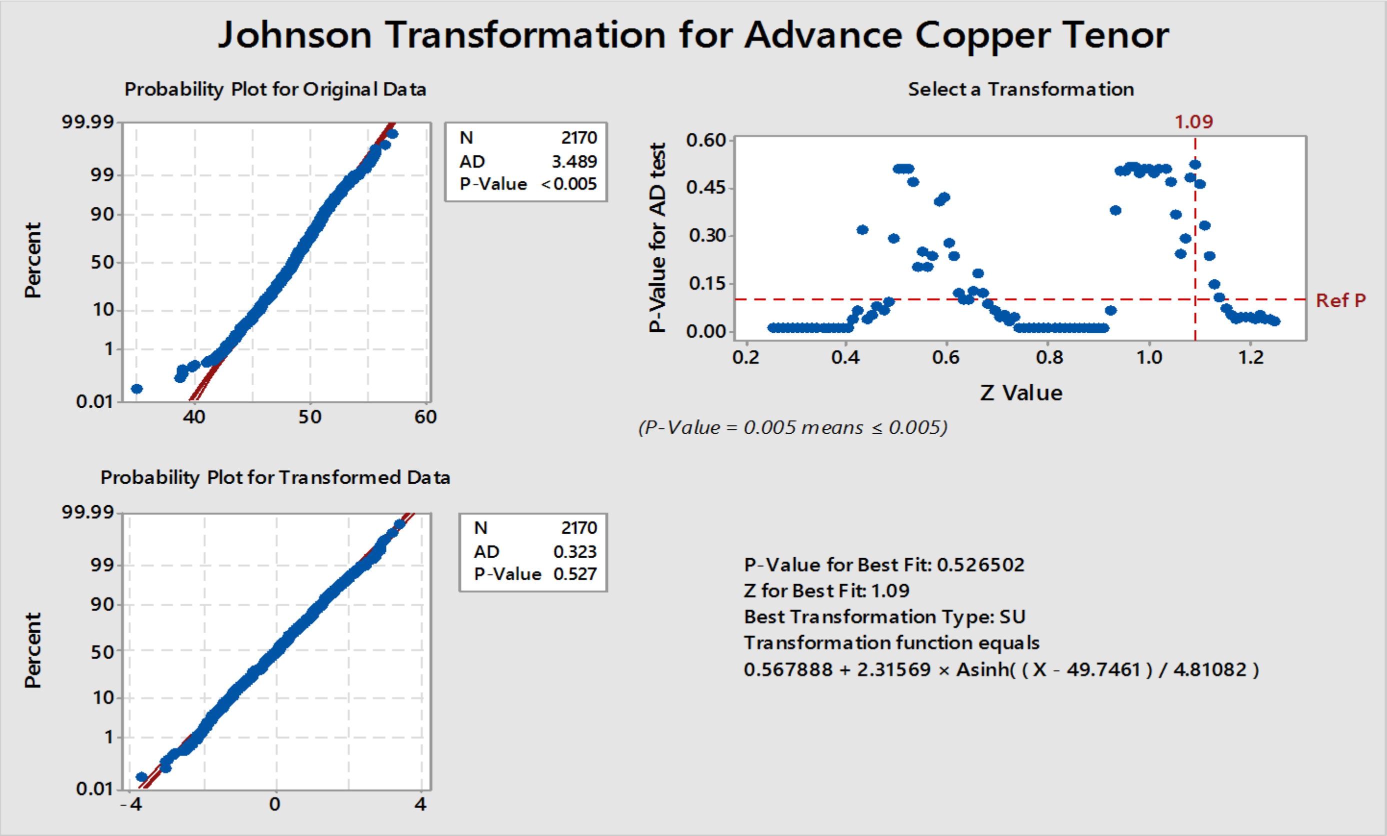


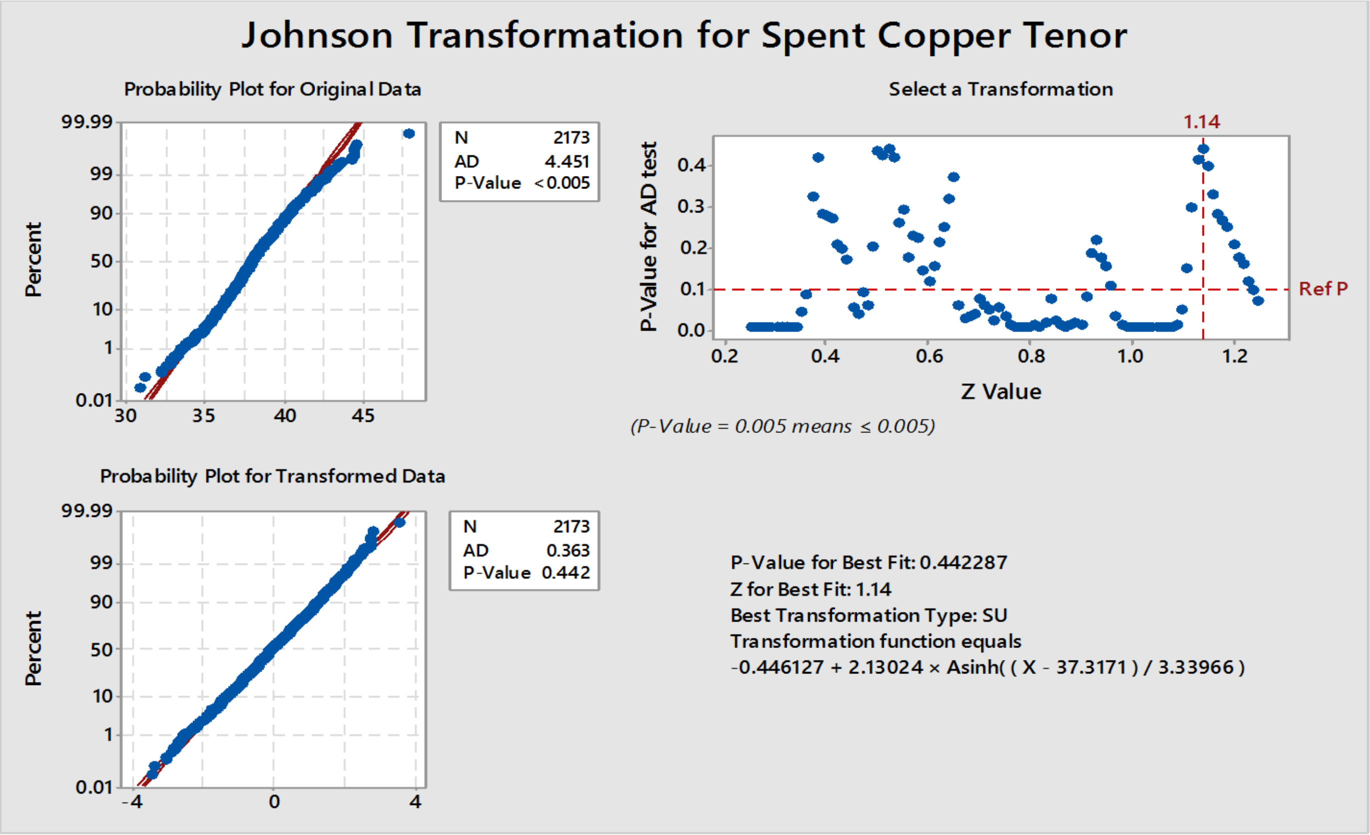
Figure 8.1: Initial current efficiency factor normality test Minitab output (created by the author)

Appendix C: Charts for transformation of non-normal data by applying Johnson and Box-Cox transformation created using Minitab statistical software for current efficiency factors data


Johnson Transformation for Advance Copper Tenor

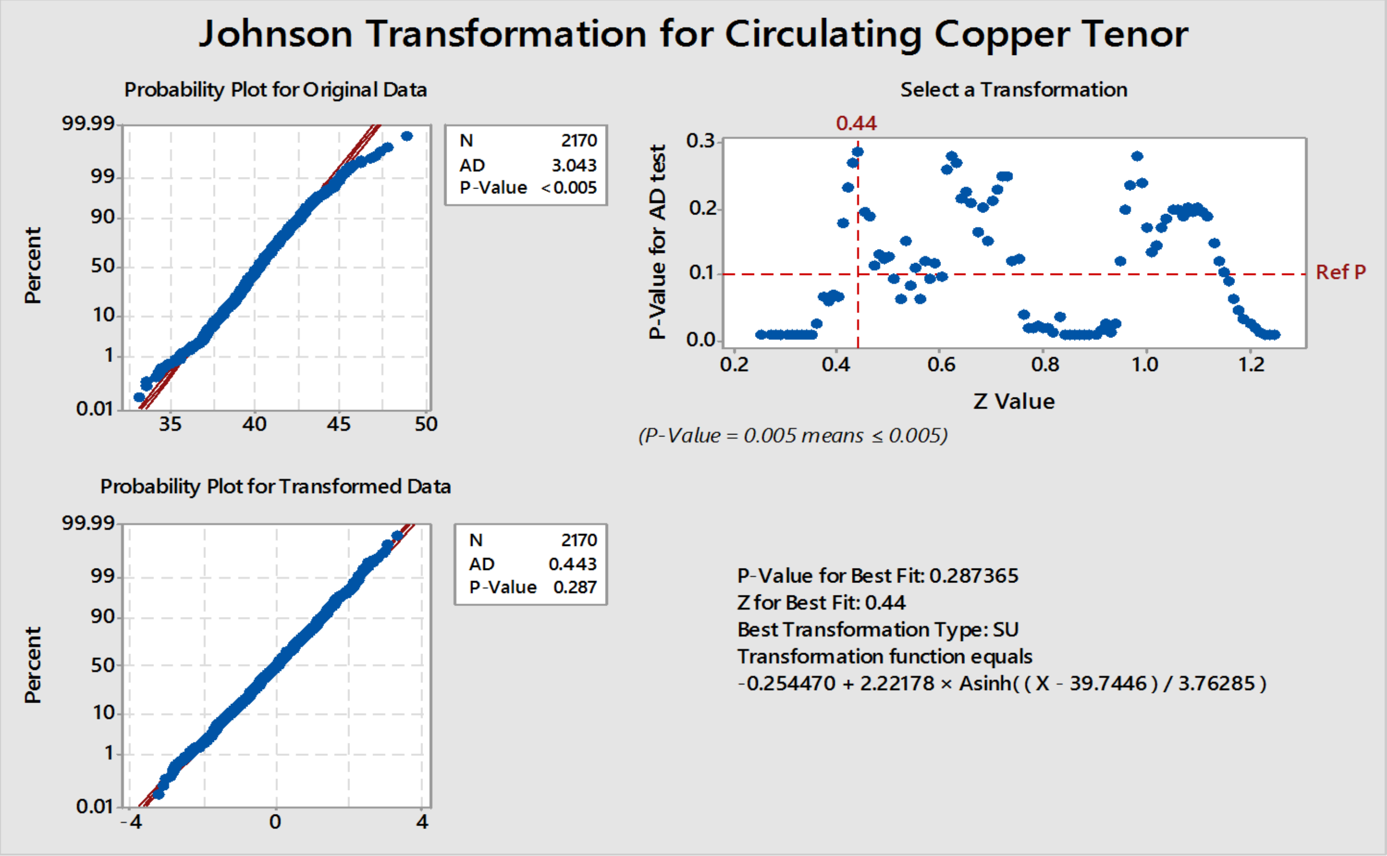
(P-Value = 0.005 means ≤ 0.005)

P-Value for Best Fit: 0.526502
Z for Best Fit: 1.09
Best Transformation Type: SU
Transformation function equals
0.567888 + 2.31569 × Asinh((X - 49.7461) / 4.81082)


Johnson Transformation for Spent Copper Tenor

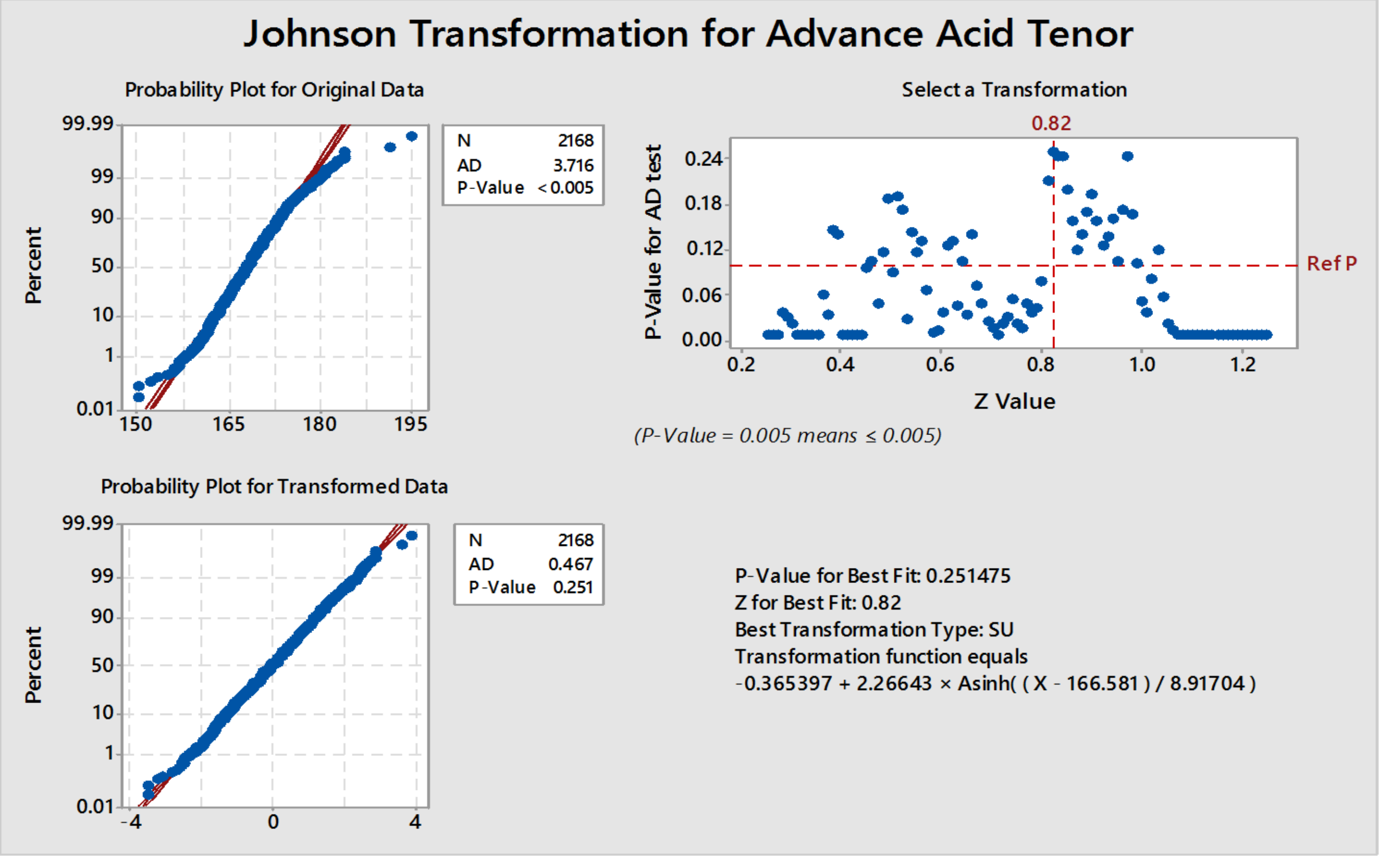
(P-Value = 0.005 means ≤ 0.005)

P-Value for Best Fit: 0.442287
Z for Best Fit: 1.14
Best Transformation Type: SU
Transformation function equals
-0.446127 + 2.13024 × Asinh((X - 37.3171) / 3.33966)


Johnson Transformation for Circulating Copper Tenor

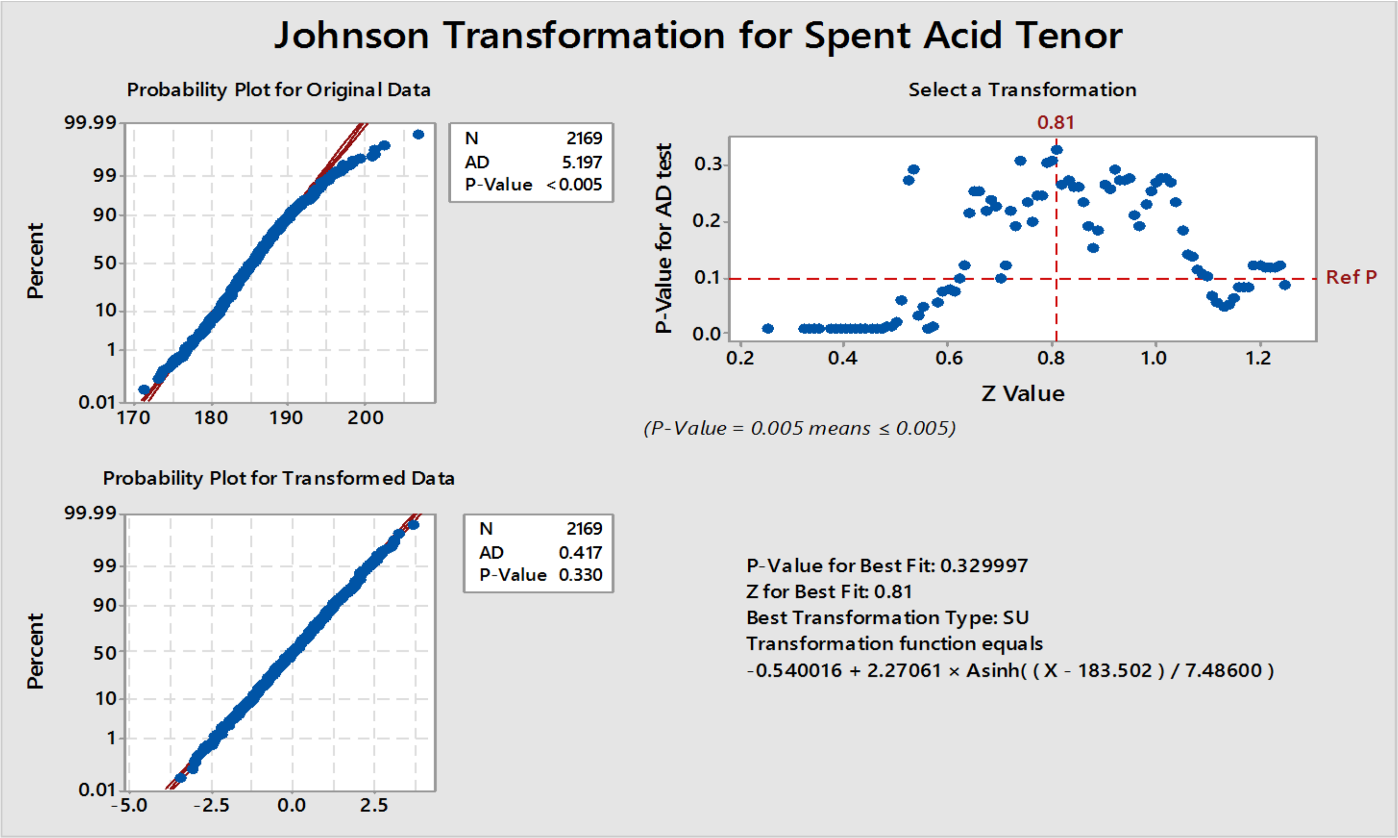
(P-Value = 0.005 means ≤ 0.005)

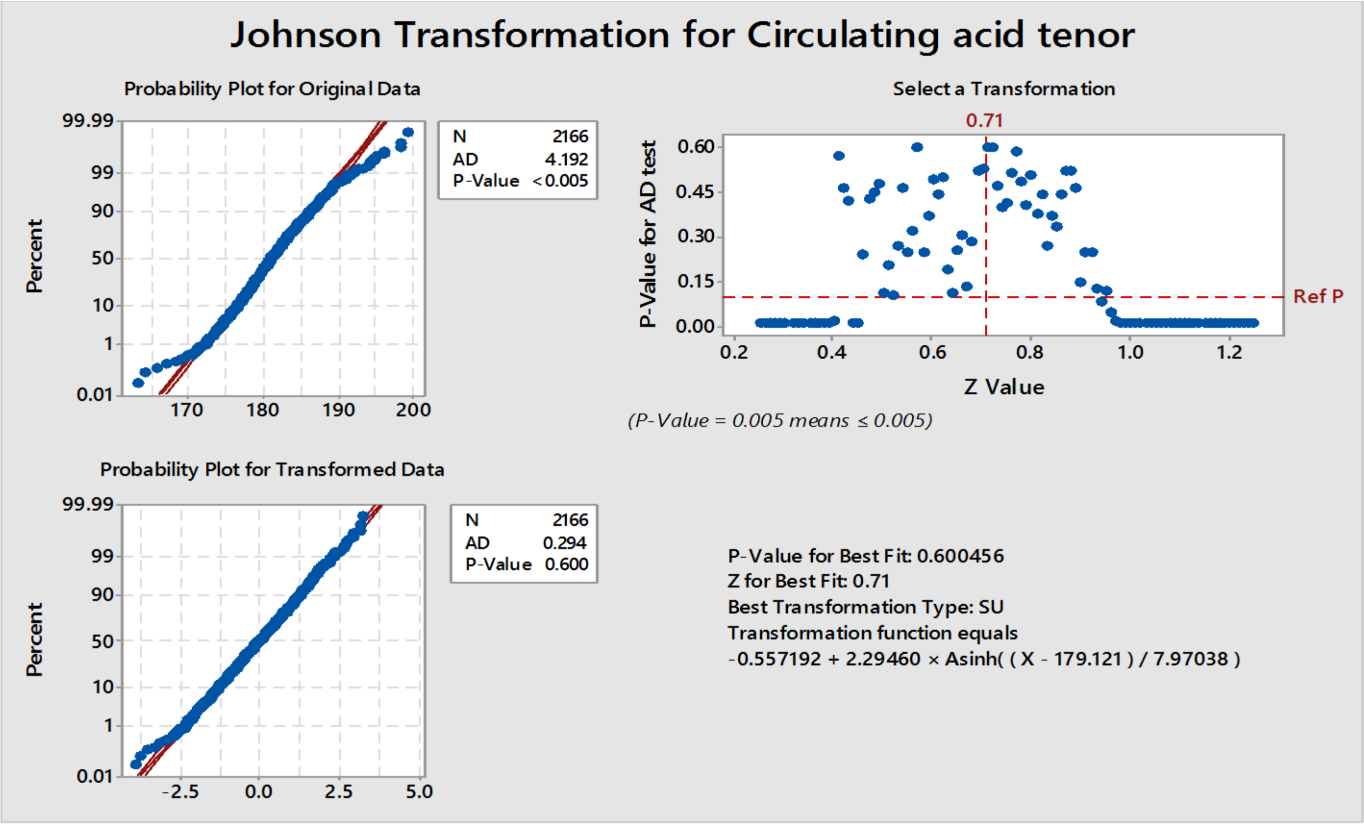
P-Value for Best Fit: 0.287365
Z for Best Fit: 0.44
Best Transformation Type: SU
Transformation function equals
-0.254470 + 2.22178 × Asinh((X - 39.7446) / 3.76285)

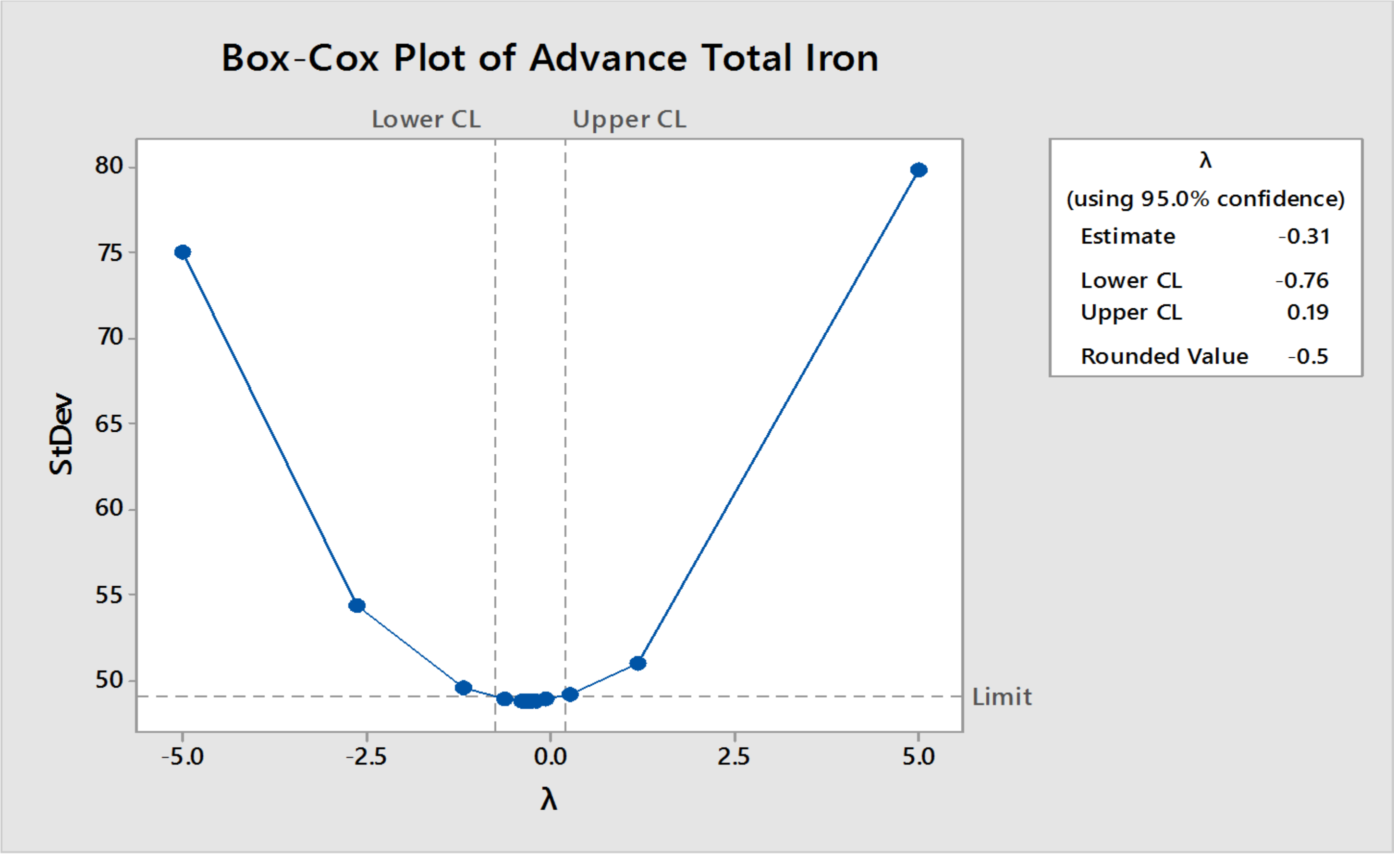

Johnson Transformation for Advance Acid Tenor

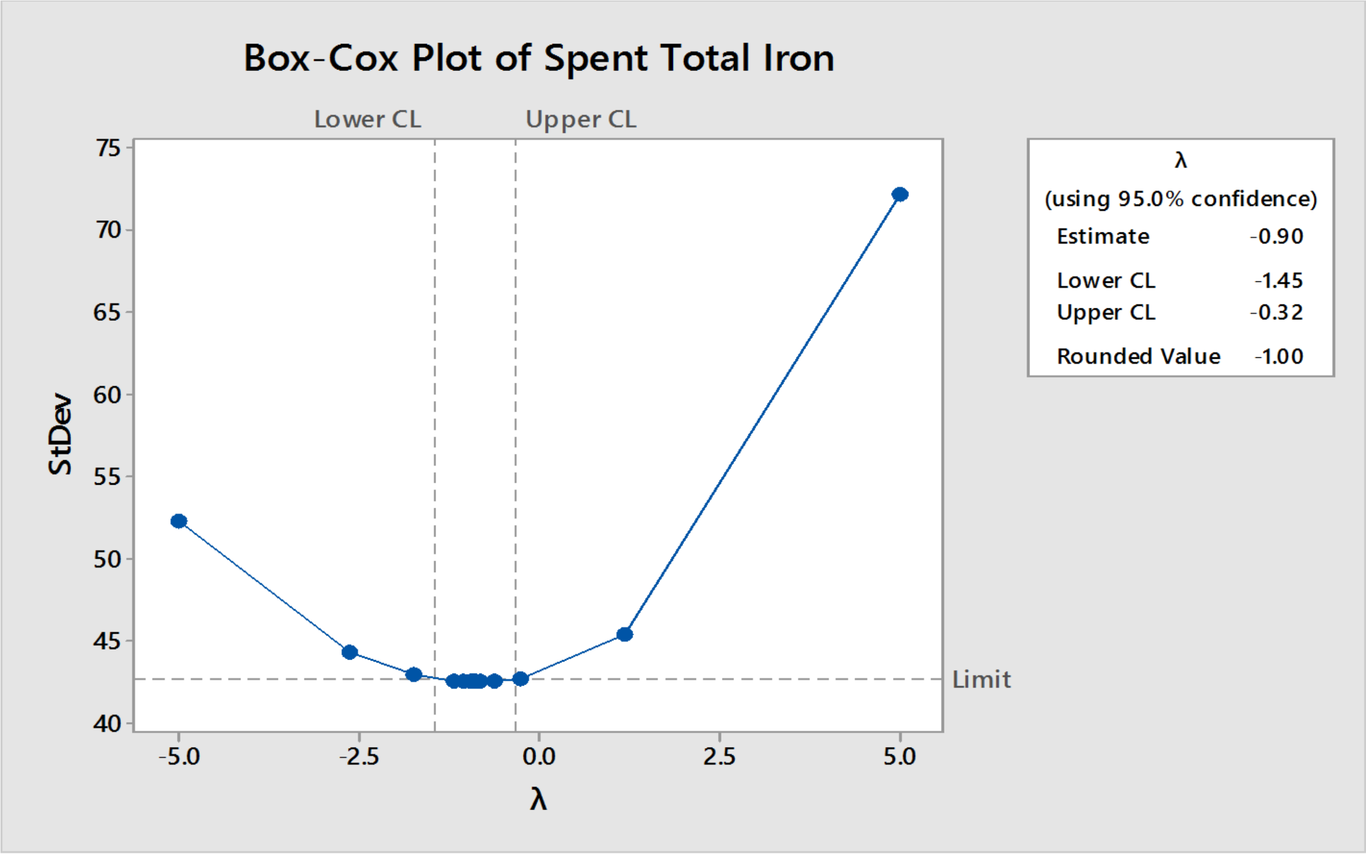
(P-Value = 0.005 means ≤ 0.005)

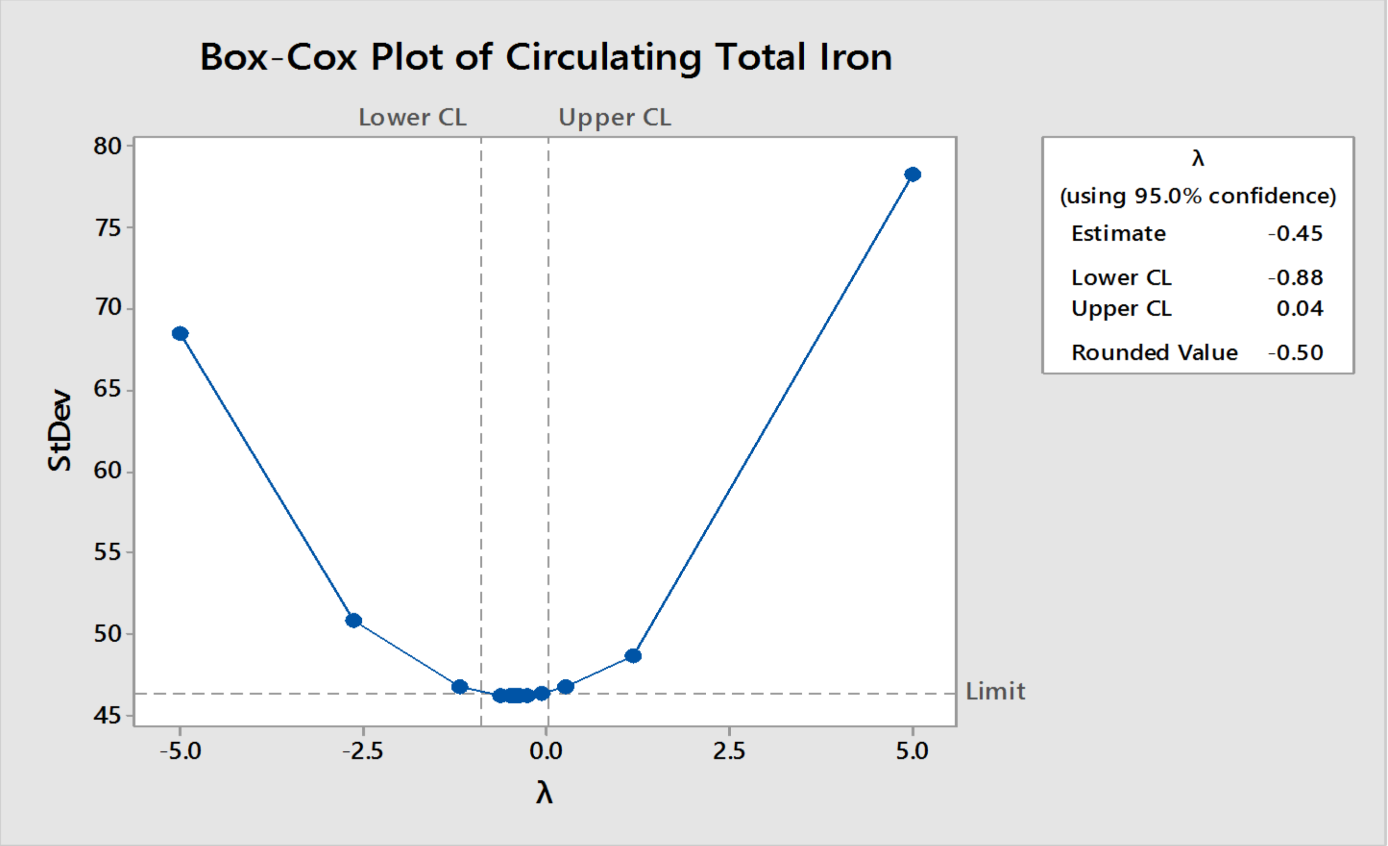
P-Value for Best Fit: 0.251475
Z for Best Fit: 0.82
Best Transformation Type: SU
Transformation function equals
-0.365397 + 2.26643 × Asinh((X - 166.581) / 8.91704)

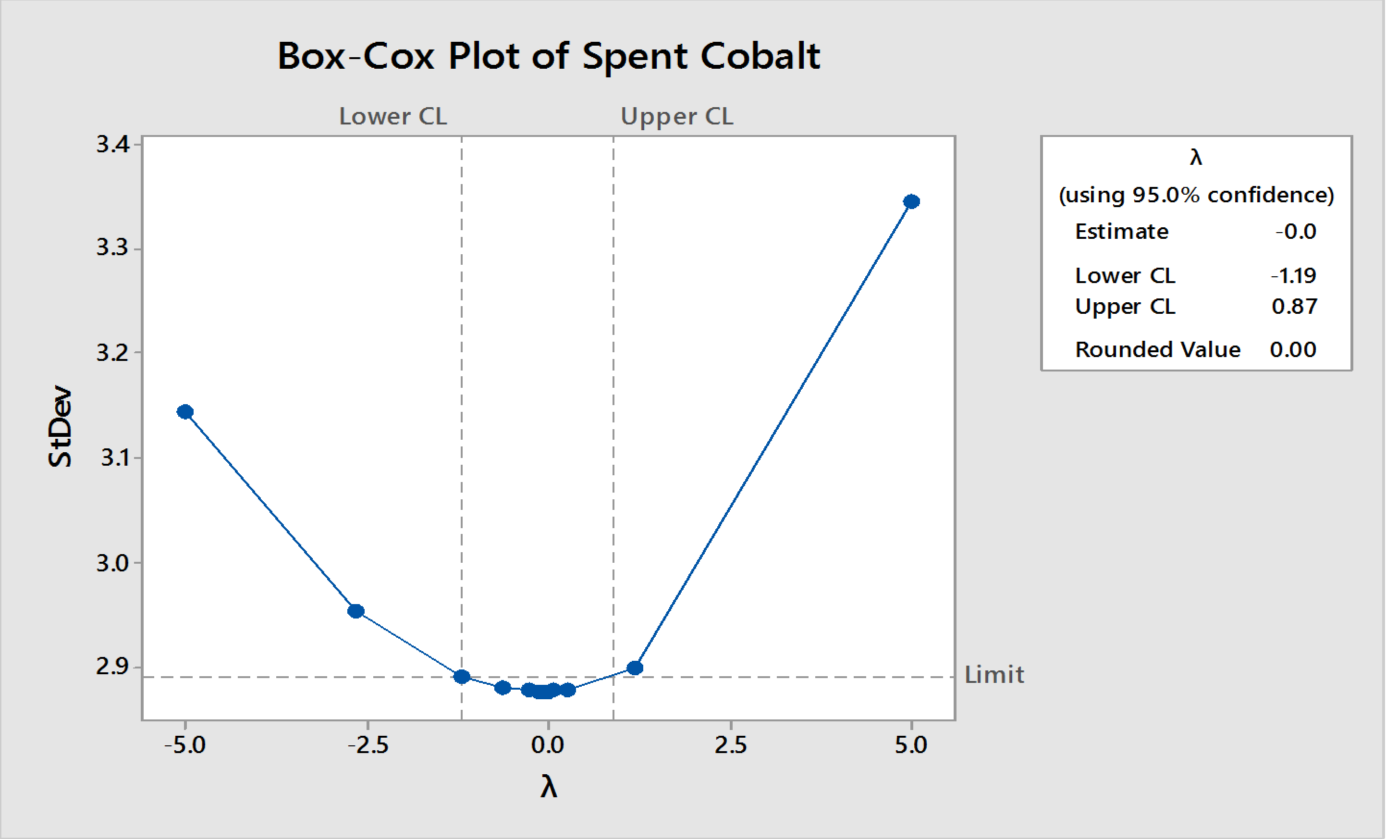

Johnson Transformation for Spent Acid Tenor
Probability Plot for Original Data
Percent
99.99
99
90
50
10
1
0.01
170
180
190
200
N 2169
AD 5.197
P-Value <0.005
Select a Transformation
0.81
P-Value for AD test
0.3
0.2
0.1
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Ref P
Z Value
(P-Value = 0.005 means ≤ 0.005)
Probability Plot for Transformed Data
Percent
99.99
99
90
50
10
1
0.01
-5.0
-2.5
0.0
2.5
N 2169
AD 0.417
P-Value 0.330
P-Value for Best Fit: 0.329997
Z for Best Fit: 0.81
Best Transformation Type: SU
Transformation function equals
-0.540016 + 2.27061 × Asinh((X - 183.502) / 7.48600)

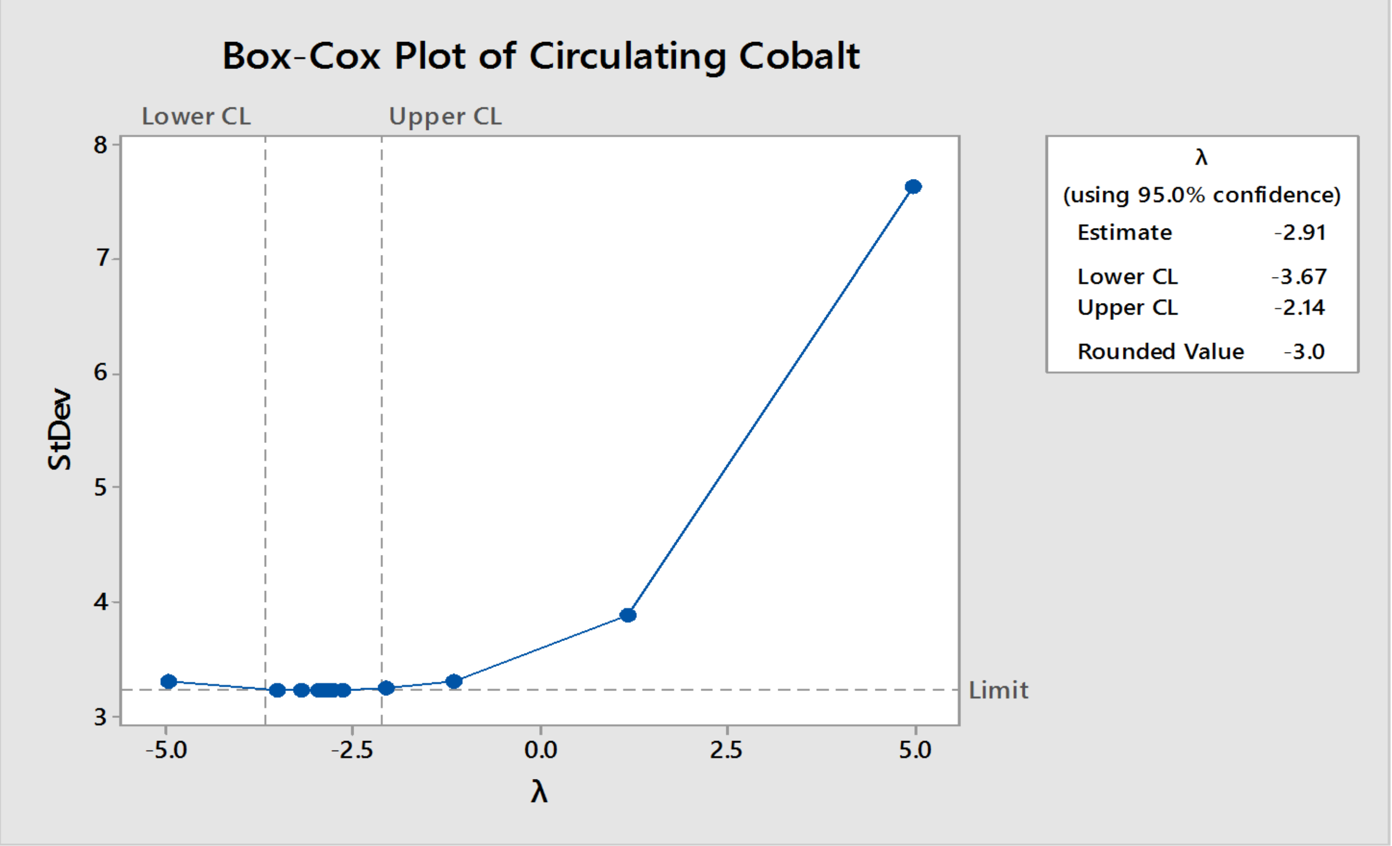

Johnson Transformation for Circulating acid tenor
Probability Plot for Original Data
Percent
99.99
99
90
50
10
1
0.01
170
180
190
200
N 2166
AD 4.192
P-Value <0.005
Select a Transformation
0.71
P-Value for AD test
0.60
0.45
0.30
0.15
0.00
0.2
0.4
0.6
0.8
1.0
1.2
Ref P
Z Value
(P-Value = 0.005 means ≤ 0.005)
Probability Plot for Transformed Data
Percent
99.99
99
90
50
10
1
0.01
-2.5
0.0
2.5
5.0
N 2166
AD 0.294
P-Value 0.600
P-Value for Best Fit: 0.600456
Z for Best Fit: 0.71
Best Transformation Type: SU
Transformation function equals
-0.557192 + 2.29460 × Asinh((X - 179.121) / 7.97038)

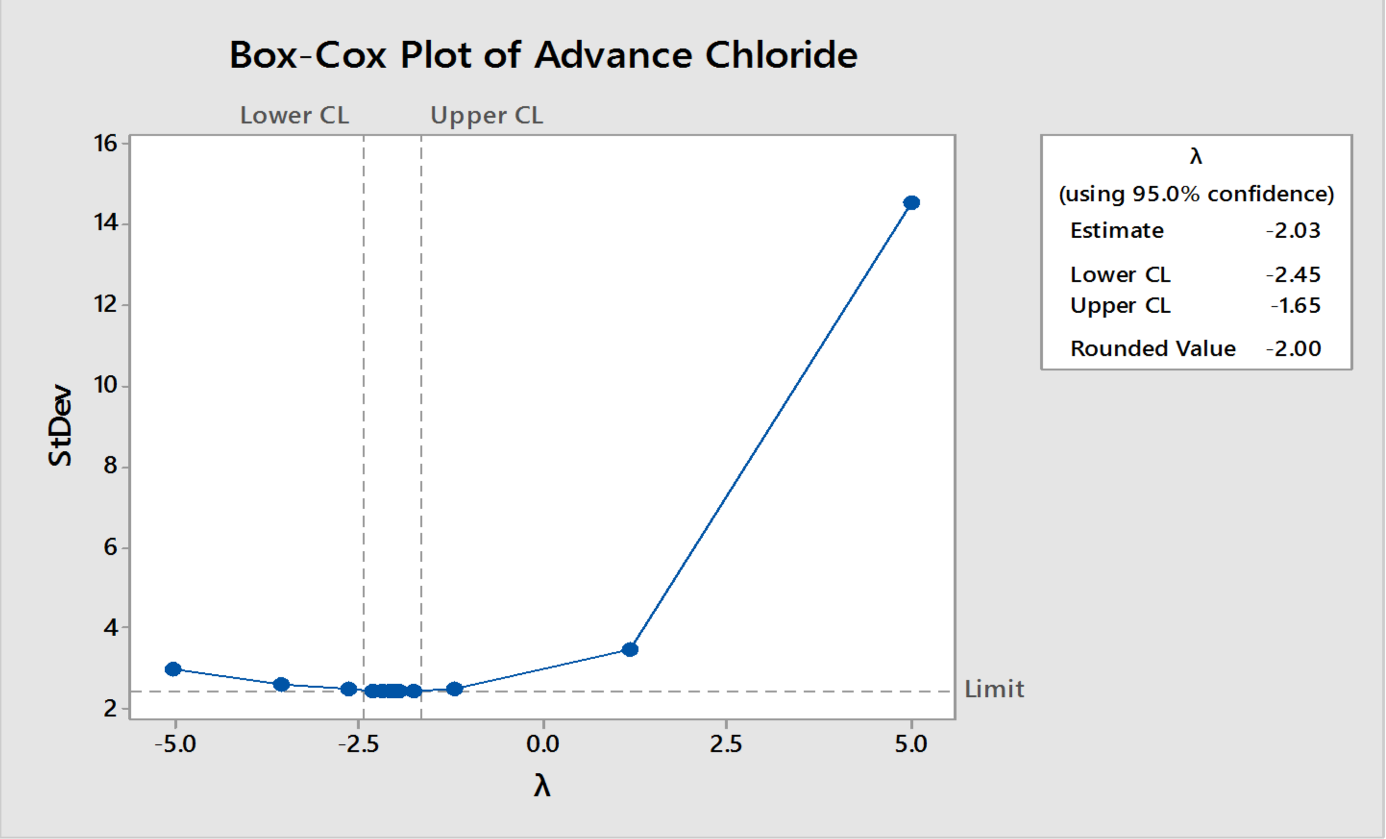

Box-Cox Plot of Advance Total Iron
Lower CL
Upper CL
StDev
80
75
70
65
60
55
50
Limit
-5.0
-2.5
0.0
2.5
5.0
λ
λ
(using 95.0% confidence)
Estimate -0.31
Lower CL -0.76
Upper CL 0.19
Rounded Value -0.5

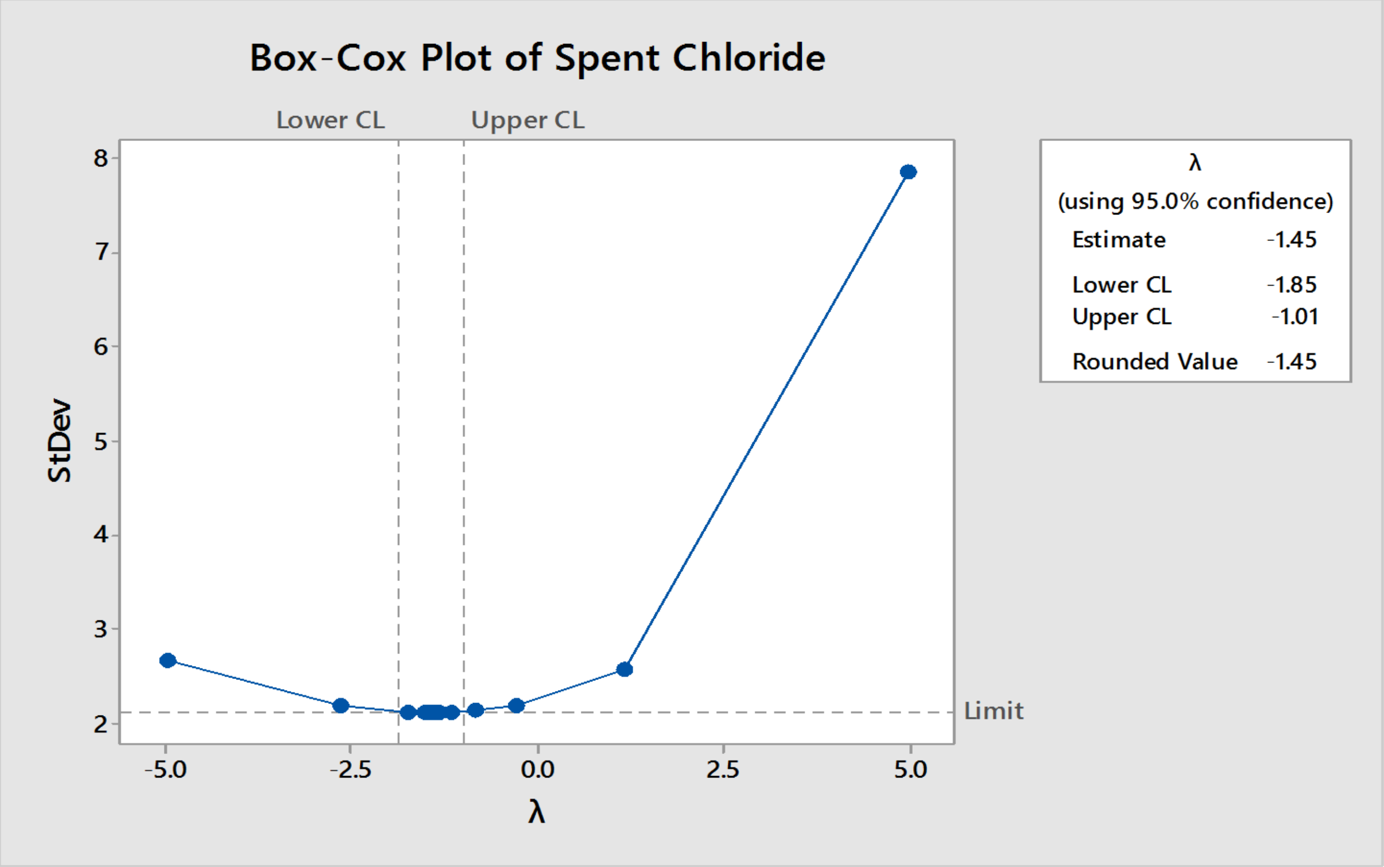

Box-Cox Plot of Spent Total Iron
Lower CL
Upper CL
StDev
75
70
65
60
55
50
45
40
Limit
-5.0
-2.5
0.0
2.5
5.0
λ
λ
(using 95.0% confidence)
Estimate -0.90
Lower CL -1.45
Upper CL -0.32
Rounded Value -1.00


Box-Cox Plot of Circulating Total Iron
Lower CL
Upper CL
80
75
70
65
60
55
50
45
StDev
-5.0
-2.5
0.0
2.5
5.0
λ
Limit
λ
(using 95.0% confidence)
Estimate -0.45
Lower CL -0.88
Upper CL 0.04
Rounded Value -0.50

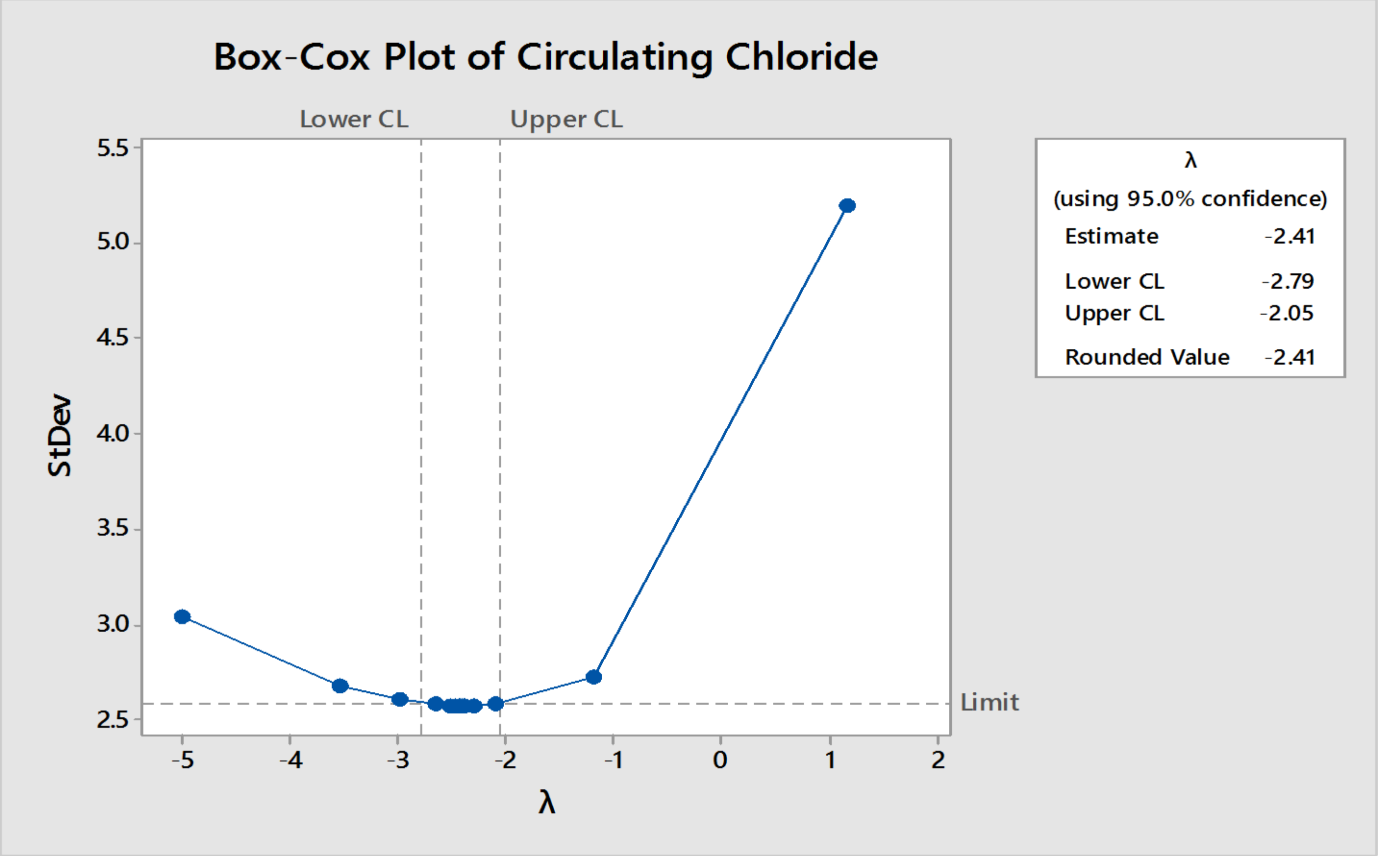

Box-Cox Plot of Spent Cobalt
Lower CL
Upper CL
3.4
3.3
3.2
3.1
3.0
2.9
StDev
-5.0
-2.5
0.0
2.5
5.0
λ
Limit
λ
(using 95.0% confidence)
Estimate -0.0
Lower CL -1.19
Upper CL 0.87
Rounded Value 0.00


Box-Cox Plot of Circulating Cobalt
Lower CL
Upper CL
8
7
6
5
4
3
StDev
-5.0
-2.5
0.0
2.5
5.0
λ
Limit
λ
(using 95.0% confidence)
Estimate -2.91
Lower CL -3.67
Upper CL -2.14
Rounded Value -3.0

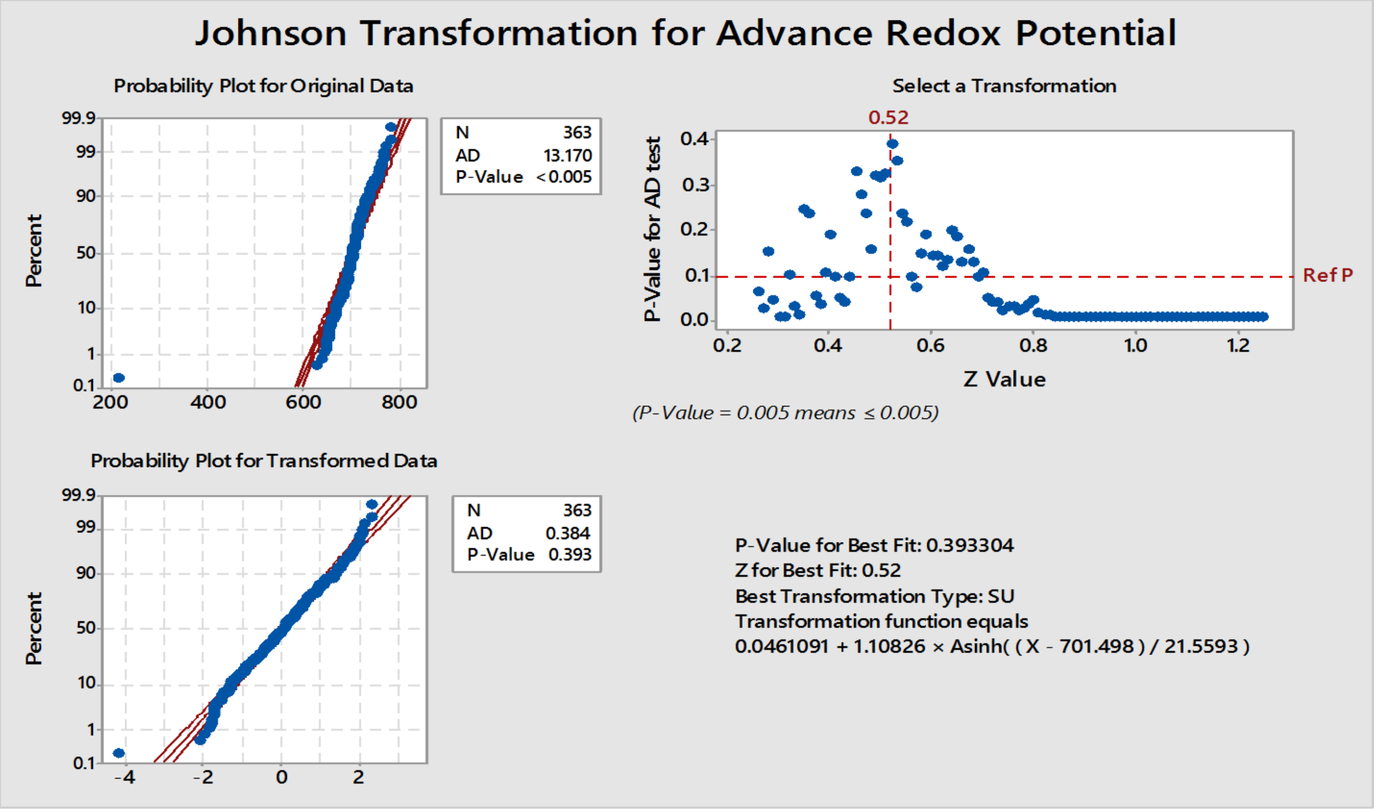

Box-Cox Plot of Advance Chloride
Lower CL
Upper CL
16
14
12
10
8
6
4
2
StDev
-5.0
-2.5
0.0
2.5
5.0
λ
Limit
λ
(using 95.0% confidence)
Estimate -2.03
Lower CL -2.45
Upper CL -1.65
Rounded Value -2.00



```
λ
(using 95.0% confidence)
Estimate         -1.45
Lower CL         -1.85
Upper CL         -1.01
Rounded Value    -1.45
```



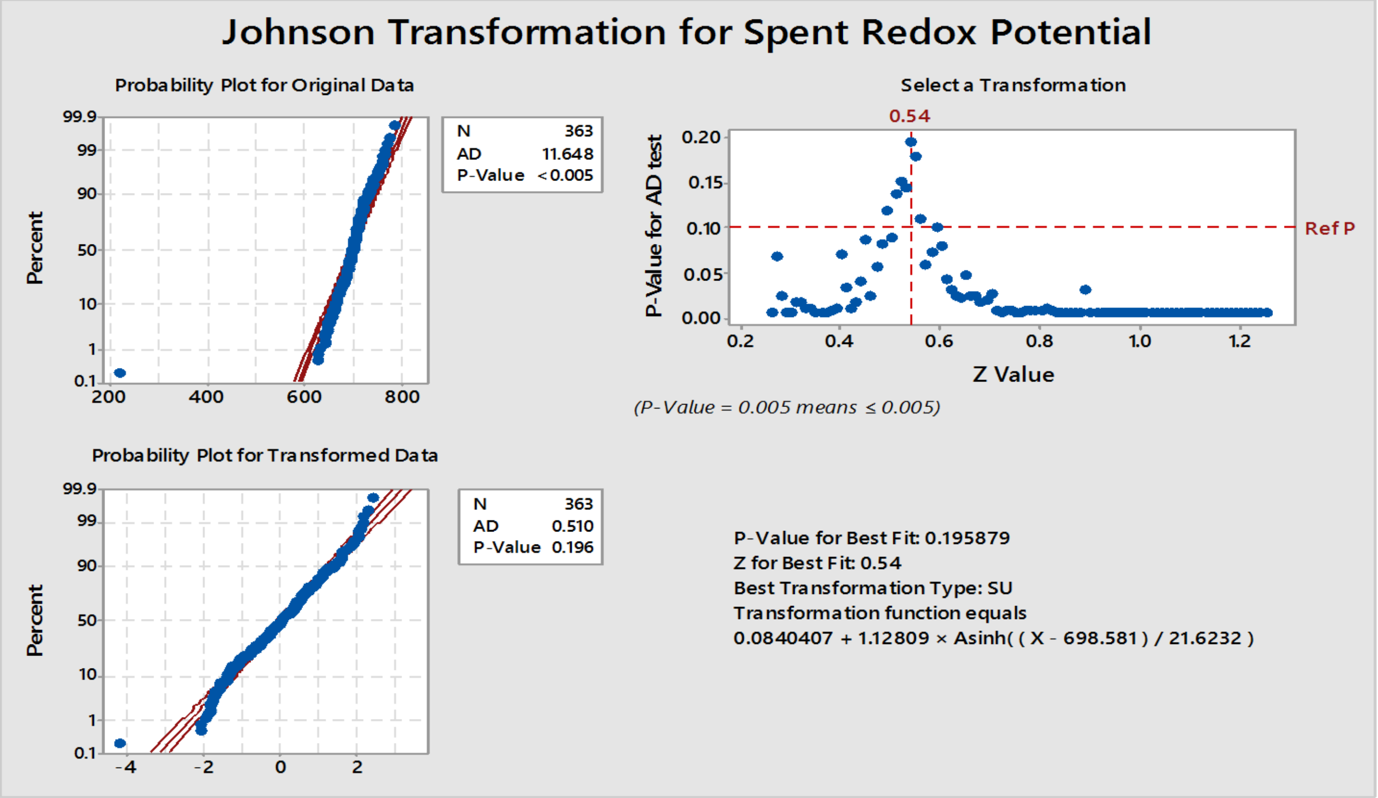
```
λ
(using 95.0% confidence)
Estimate         -2.41
Lower CL         -2.79
Upper CL         -2.05
Rounded Value    -2.41
```



```
N           363
AD       13.170
P-Value  <0.005
```

```
N           363
AD        0.384
P-Value   0.393
```

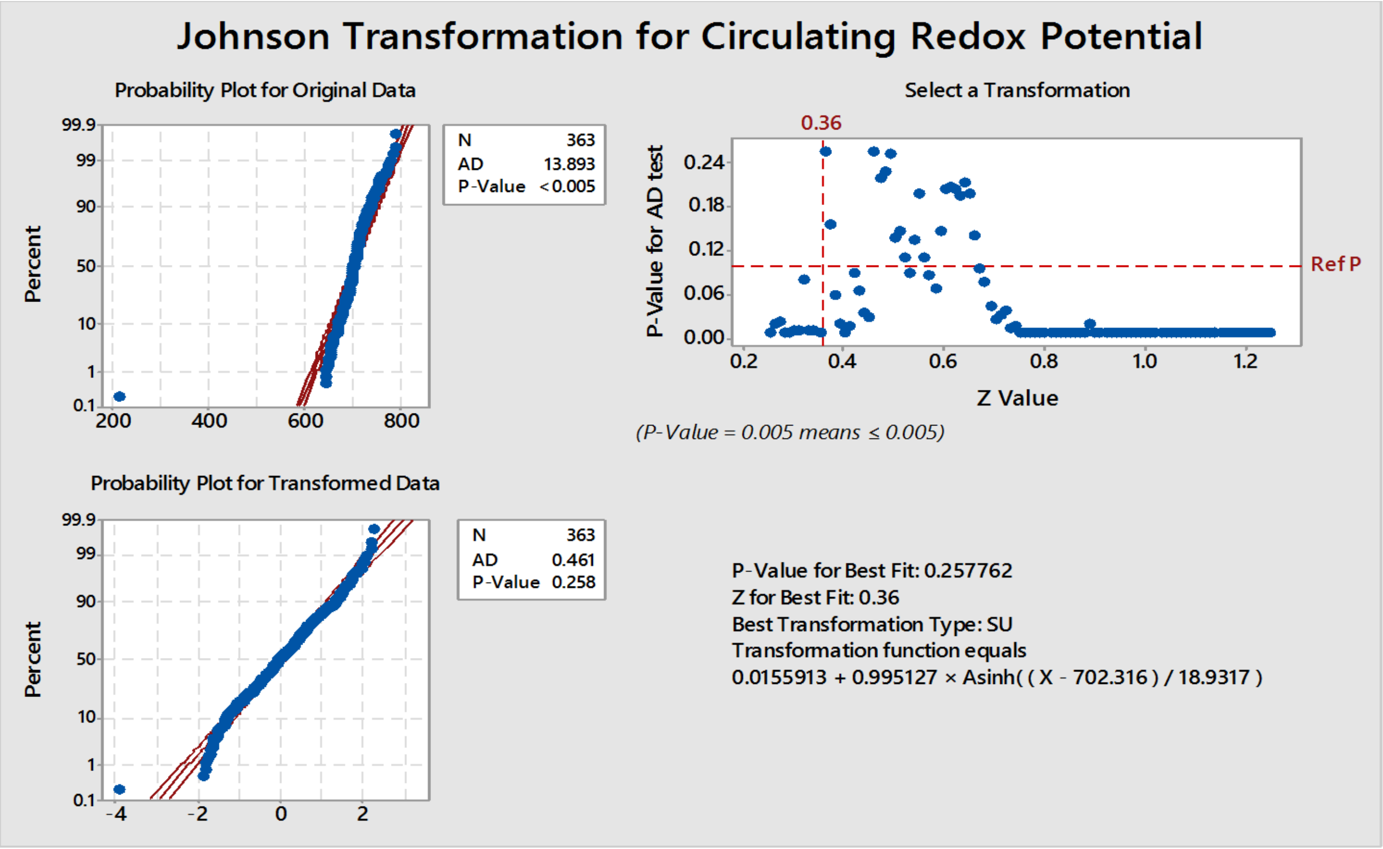
```
P-Value for Best Fit: 0.393304
Z for Best Fit: 0.52
Best Transformation Type: SU
Transformation function equals
0.0461091 + 1.10826 × Asinh( ( X - 701.498 ) / 21.5593 )
```

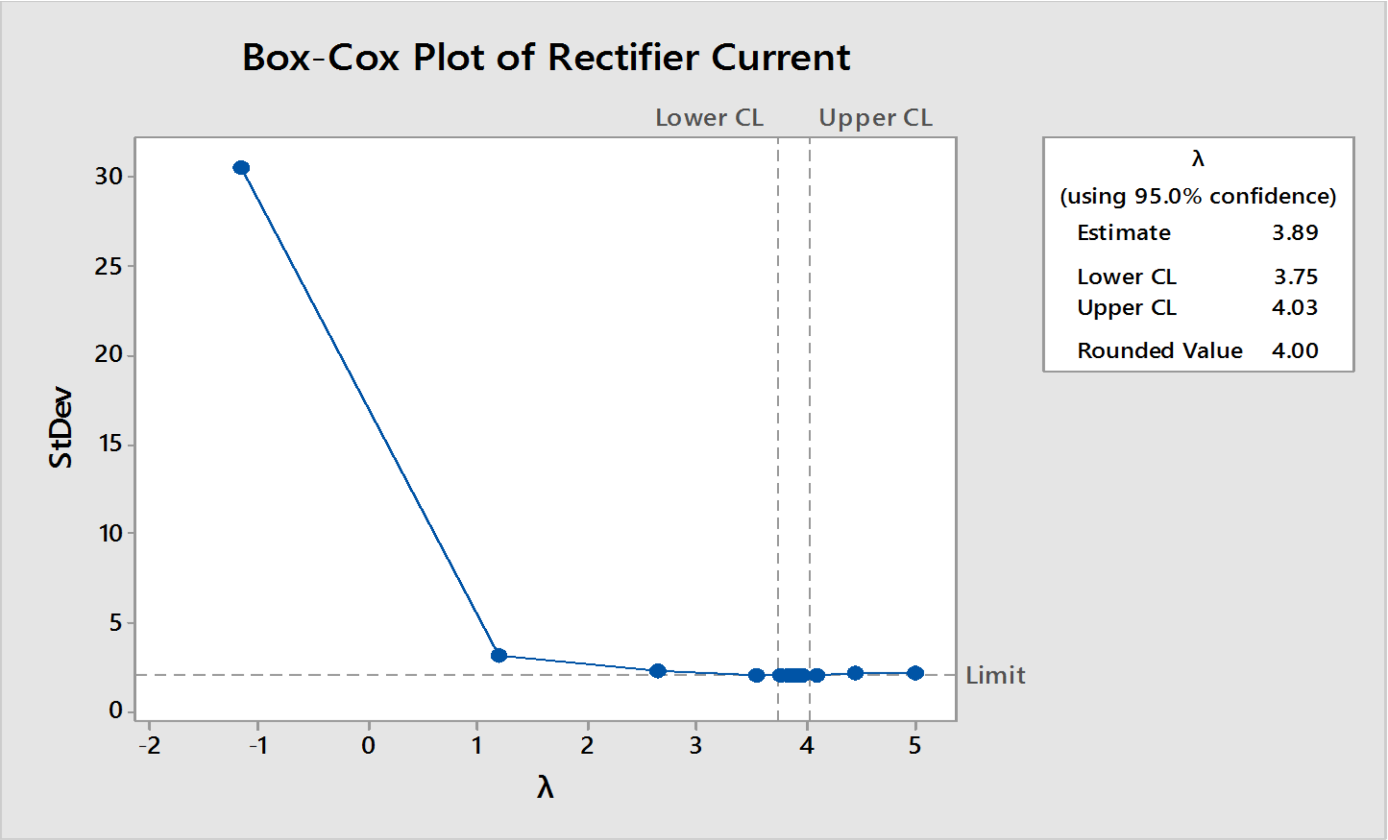


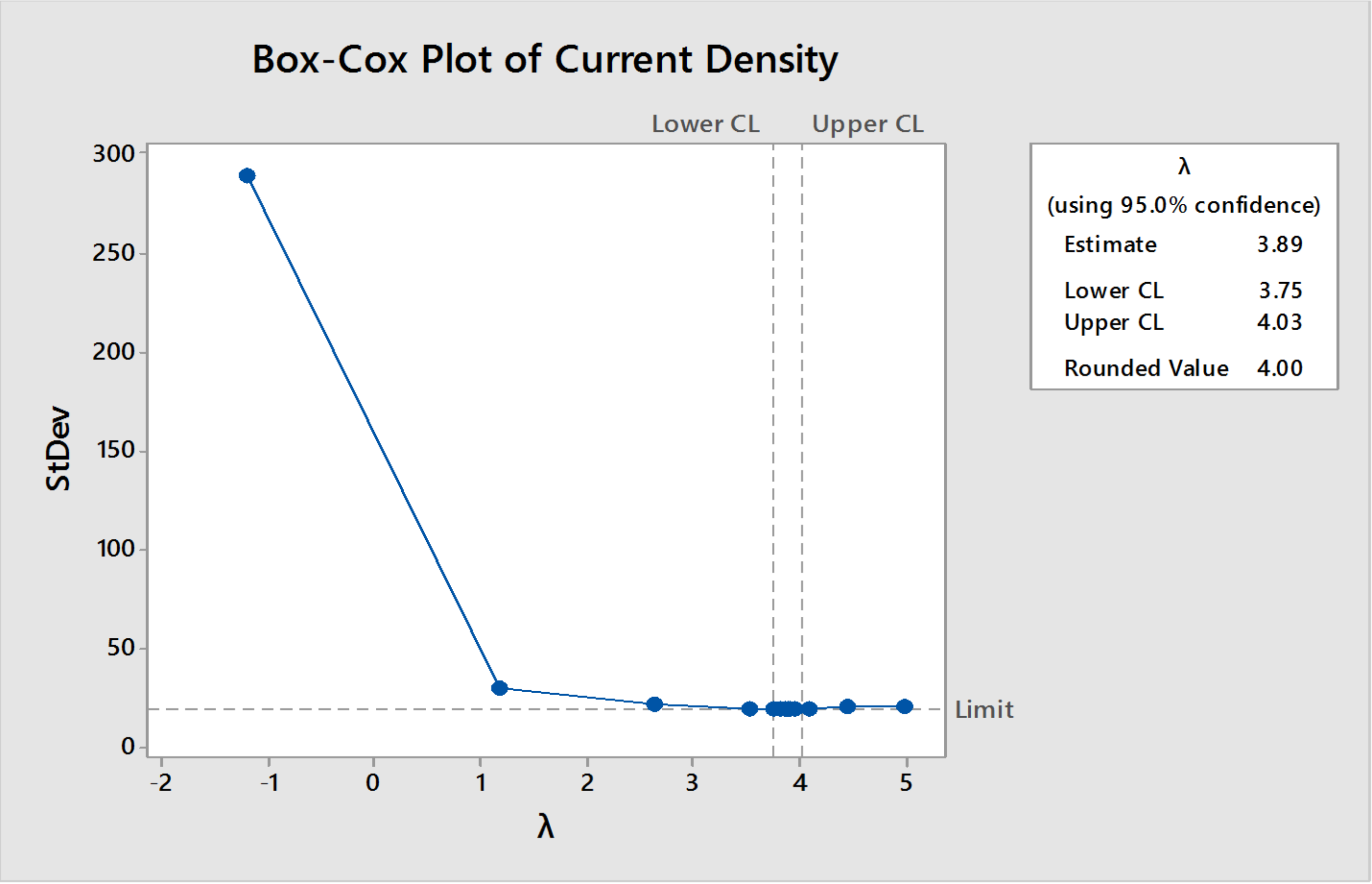
```
N           363
AD       11.648
P-Value  <0.005
```

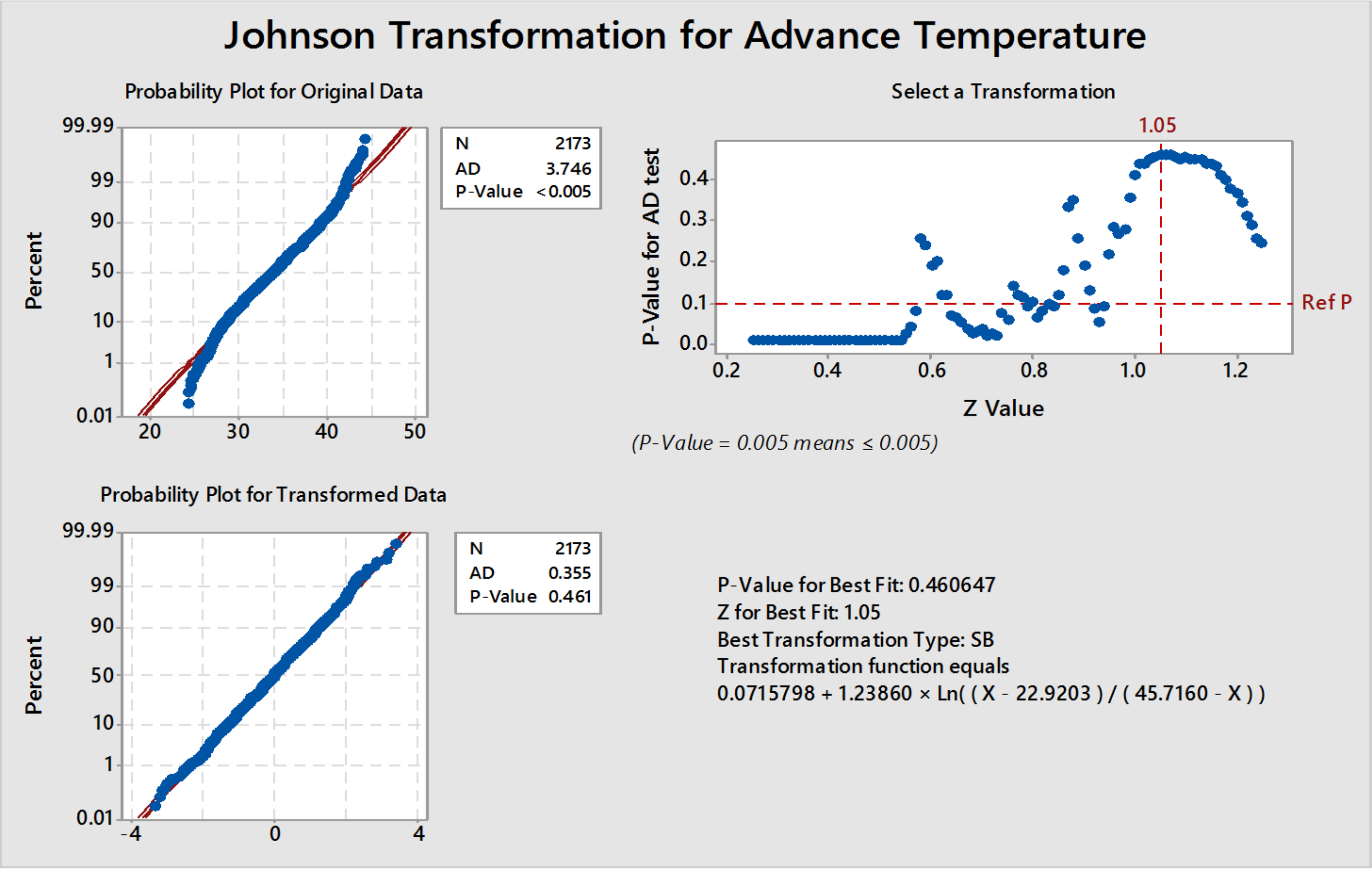
```
N           363
AD        0.510
P-Value   0.196
```

```
P-Value for Best Fit: 0.195879
Z for Best Fit: 0.54
Best Transformation Type: SU
Transformation function equals
0.0840407 + 1.12809 × Asinh( ( X - 698.581 ) / 21.6232 )
```


Johnson Transformation for Circulating Redox Potential
Probability Plot for Original Data
Percent
99.9
99
90
50
10
1
0.1
200
400
600
800
N 363
AD 13.893
P-Value <0.005
Select a Transformation
0.36
P-Value for AD test
0.24
0.18
0.12
0.06
0.00
0.2
0.4
0.6
0.8
1.0
1.2
Z Value
Ref P
(P-Value = 0.005 means ≤ 0.005)
Probability Plot for Transformed Data
Percent
-4
-2
0
2
N 363
AD 0.461
P-Value 0.258
P-Value for Best Fit: 0.257762
Z for Best Fit: 0.36
Best Transformation Type: SU
Transformation function equals
0.0155913 + 0.995127 × Asinh((X - 702.316) / 18.9317)


Box-Cox Plot of Rectifier Current
Lower CL
Upper CL
StDev
30
25
20
15
10
5
0
-2
-1
0
1
2
3
4
5
λ
Limit
λ
(using 95.0% confidence)
Estimate 3.89
Lower CL 3.75
Upper CL 4.03
Rounded Value 4.00


Box-Cox Plot of Current Density
Lower CL
Upper CL
StDev
300
250
200
150
100
50
0
-2
-1
0
1
2
3
4
5
λ
Limit
λ
(using 95.0% confidence)
Estimate 3.89
Lower CL 3.75
Upper CL 4.03
Rounded Value 4.00


Johnson Transformation for Advance Temperature
Probability Plot for Original Data
Percent
99.99
99
90
50
10
1
0.01
20
30
40
50
N 2173
AD 3.746
P-Value <0.005
Select a Transformation
1.05
P-Value for AD test
0.4
0.3
0.2
0.1
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Z Value
Ref P
(P-Value = 0.005 means ≤ 0.005)
Probability Plot for Transformed Data
Percent
-4
0
4
N 2173
AD 0.355
P-Value 0.461
P-Value for Best Fit: 0.460647
Z for Best Fit: 1.05
Best Transformation Type: SB
Transformation function equals
0.0715798 + 1.23860 × Ln((X - 22.9203) / (45.7160 - X))

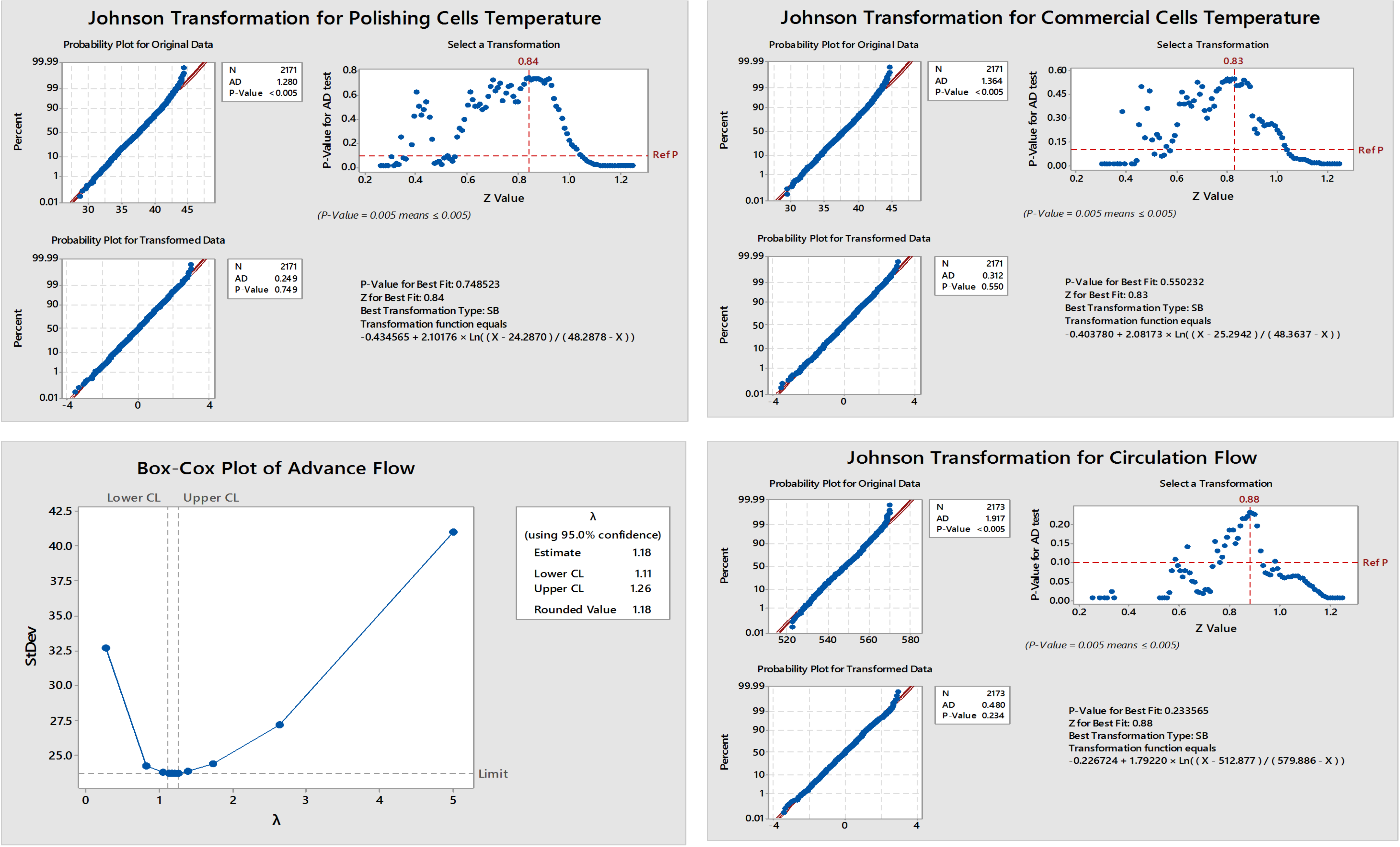
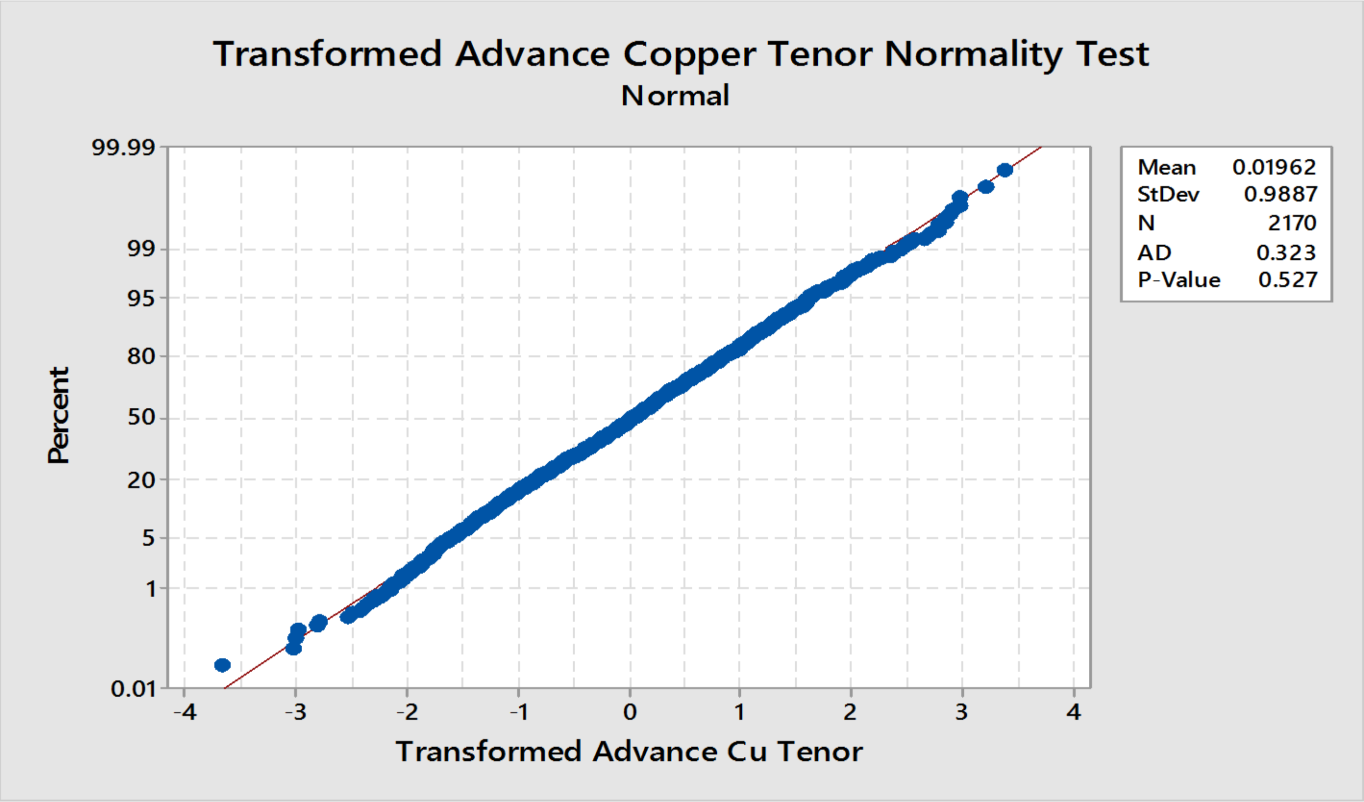
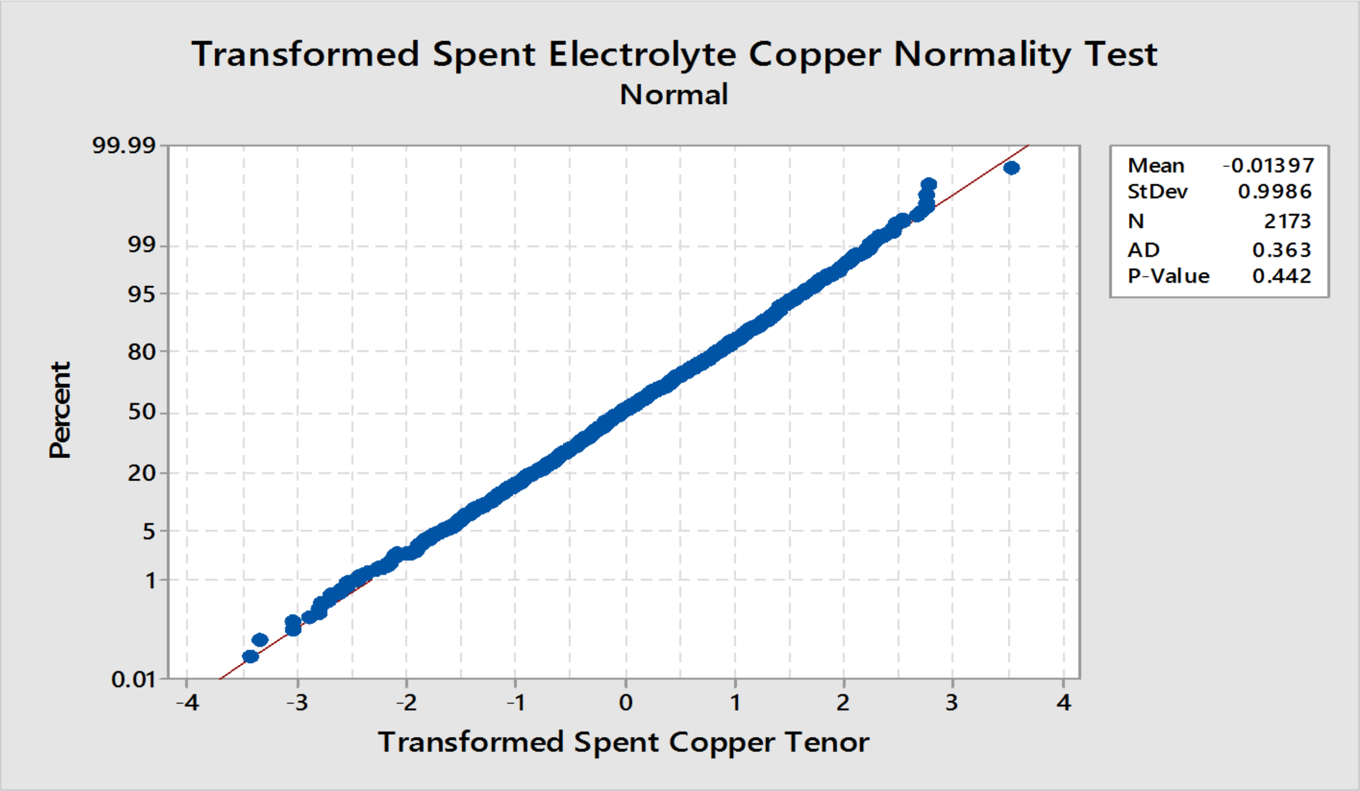
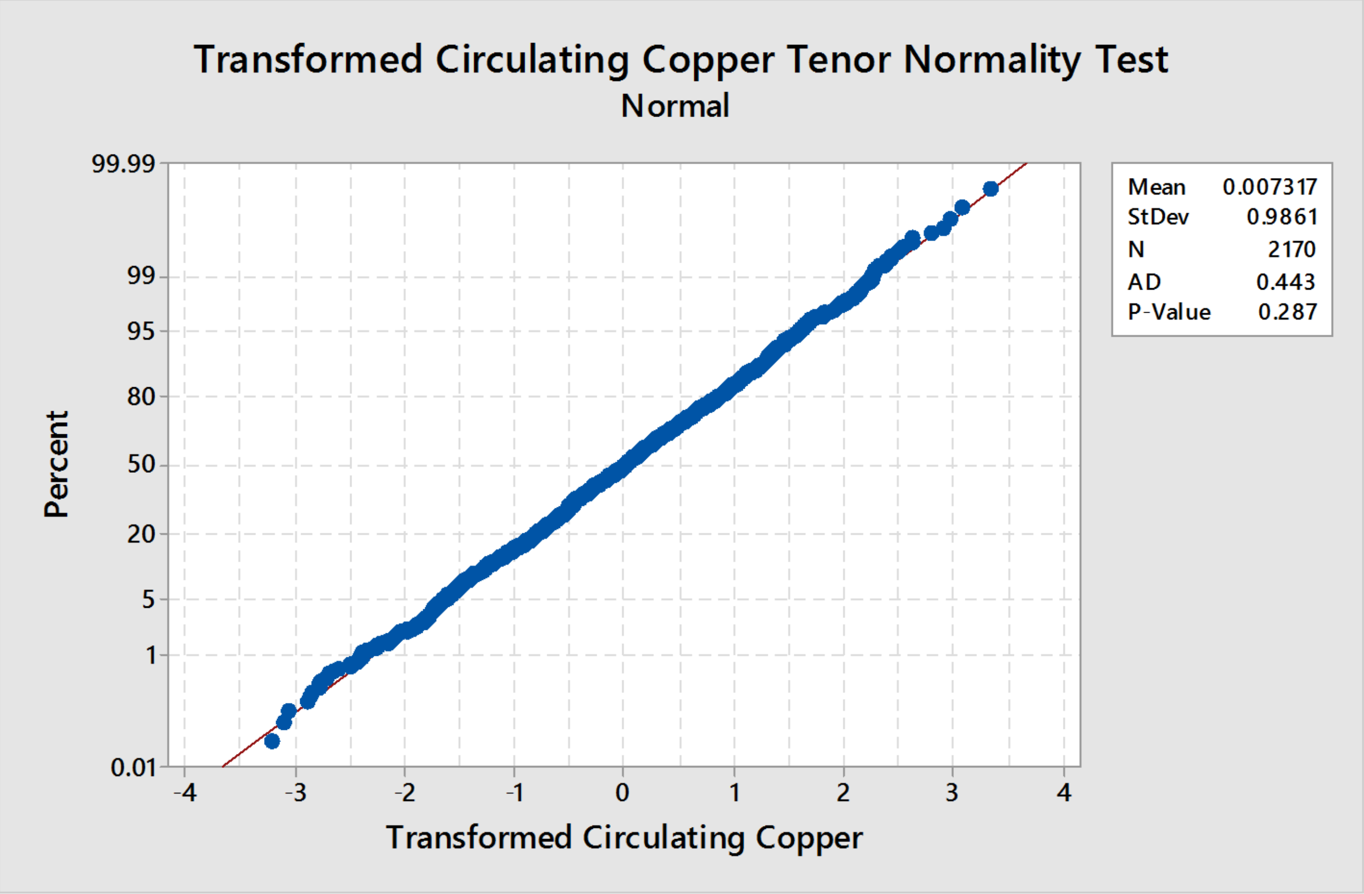


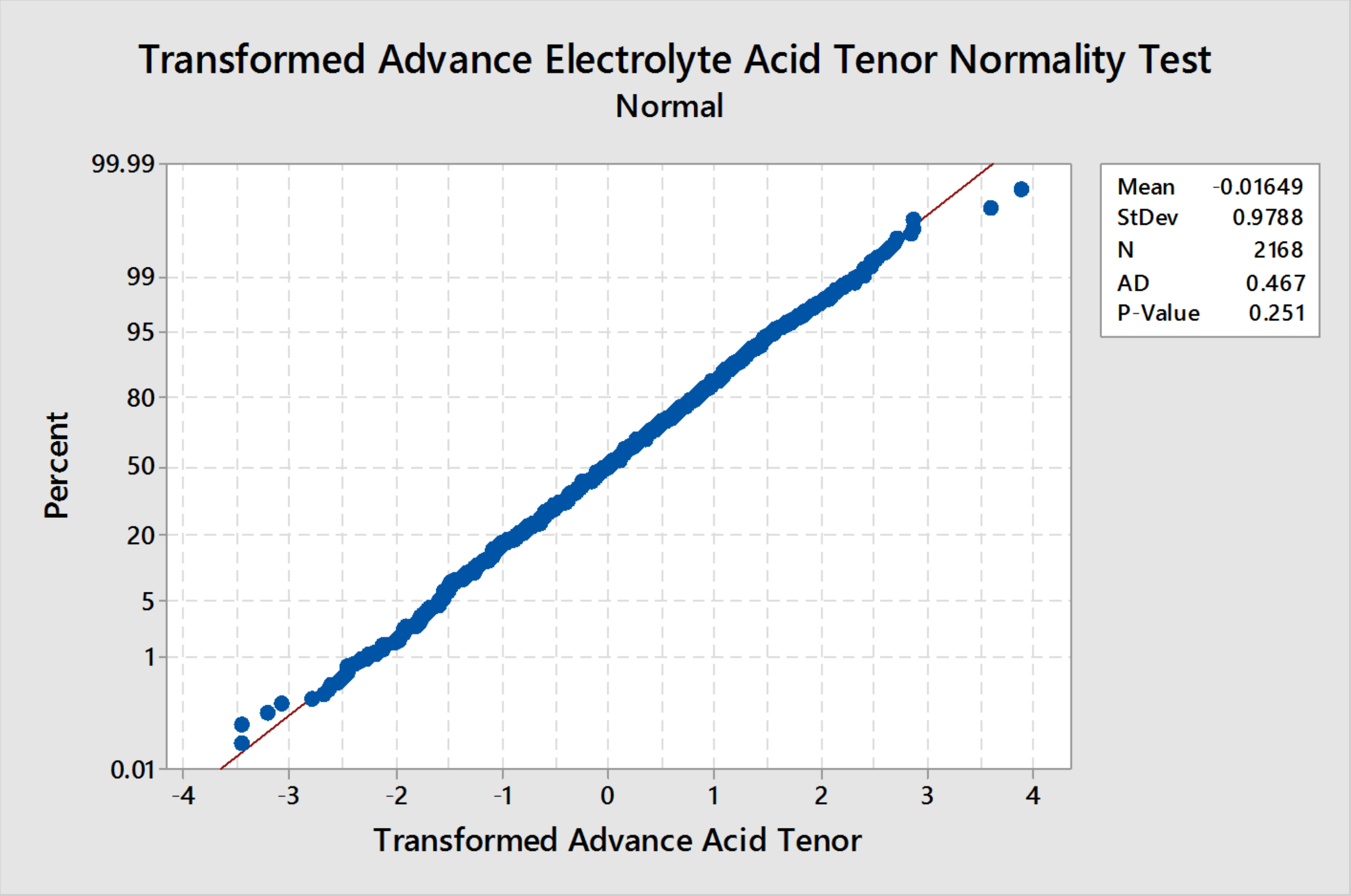
Figure 8.2: Minitab output for Johnson and Box-Cox transformation for CE factors (created by the author)

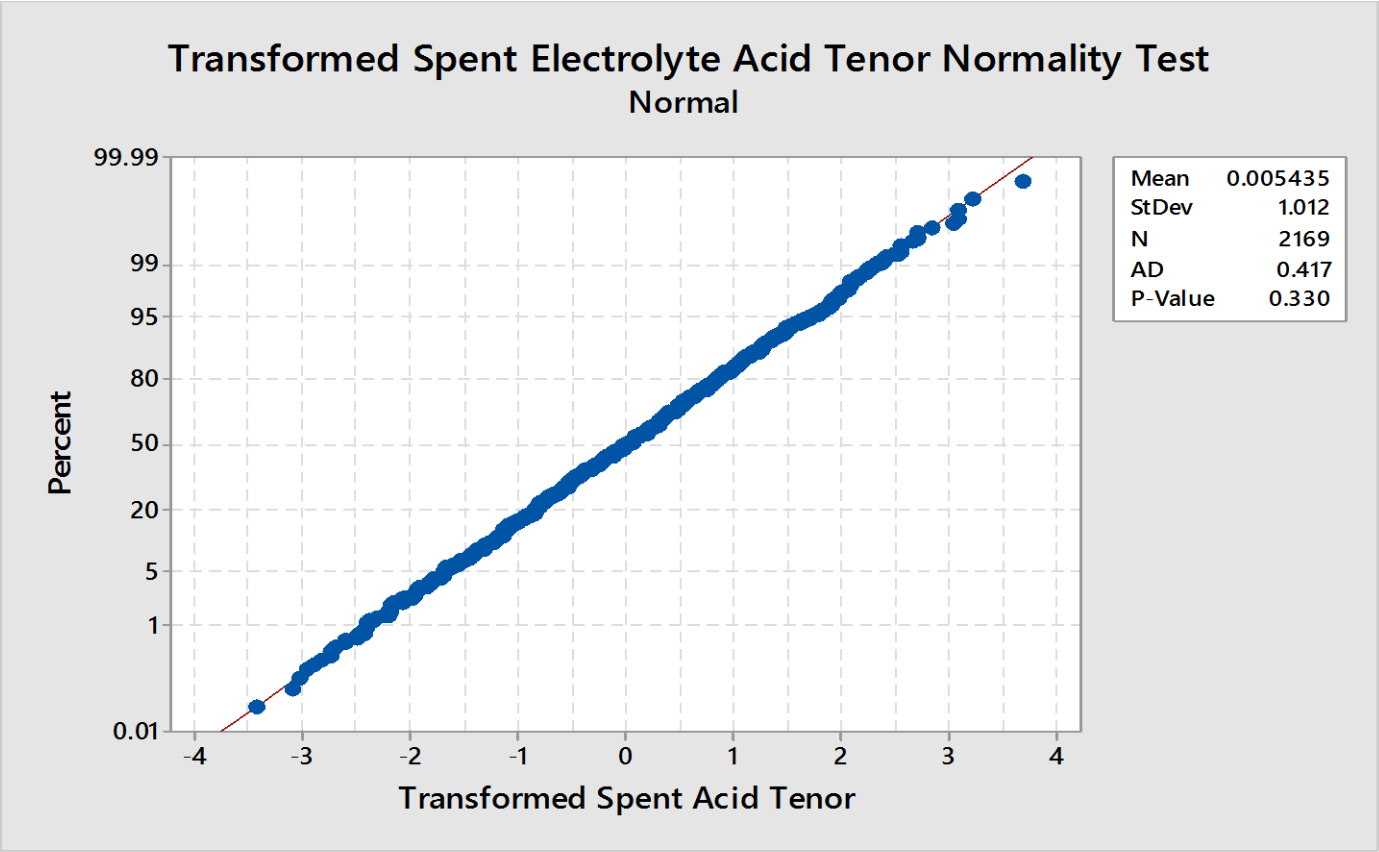
Appendix D: Anderson Darlington normality test results for the transformed current efficiency factors data created using Minitab statistical software

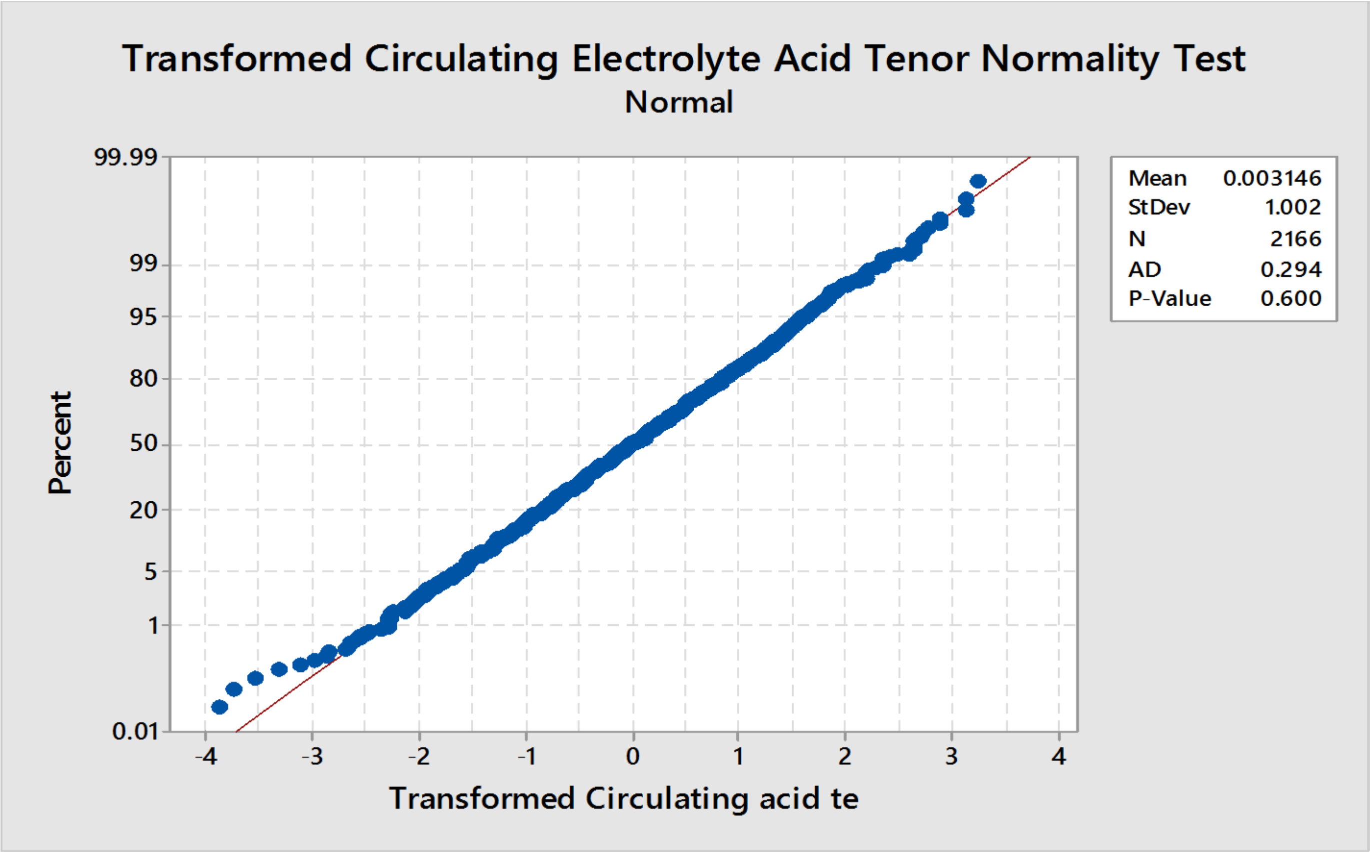


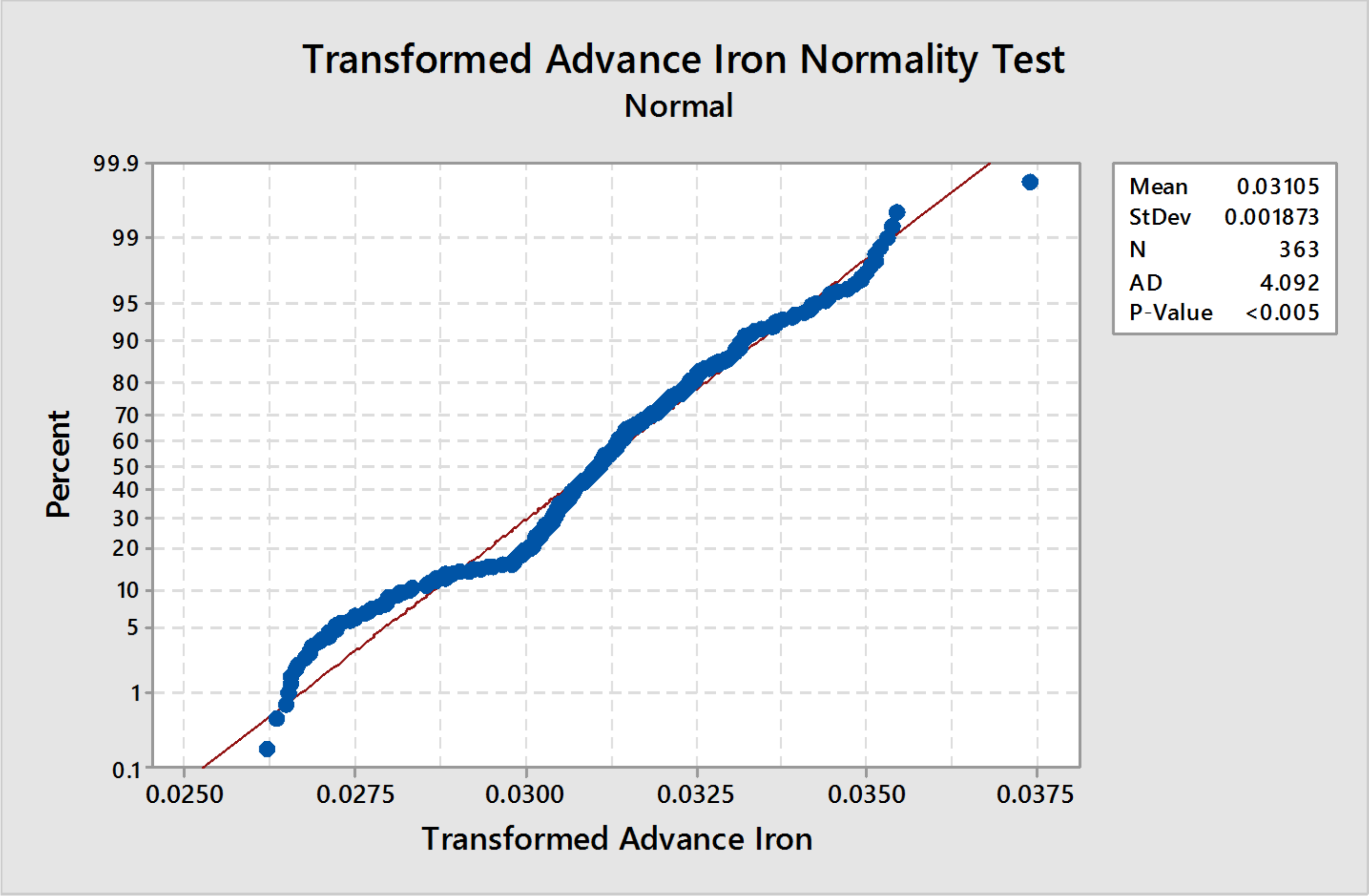


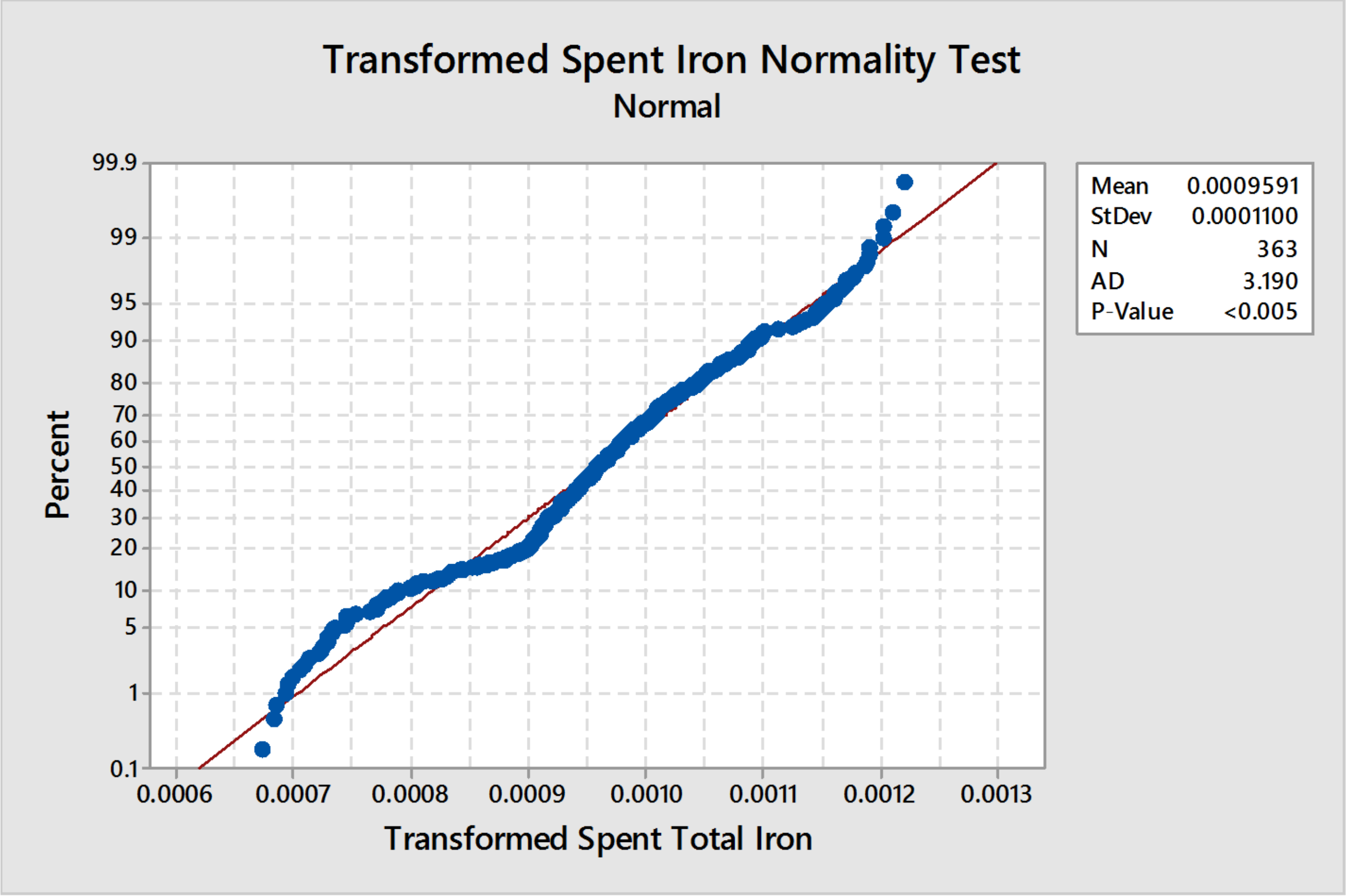


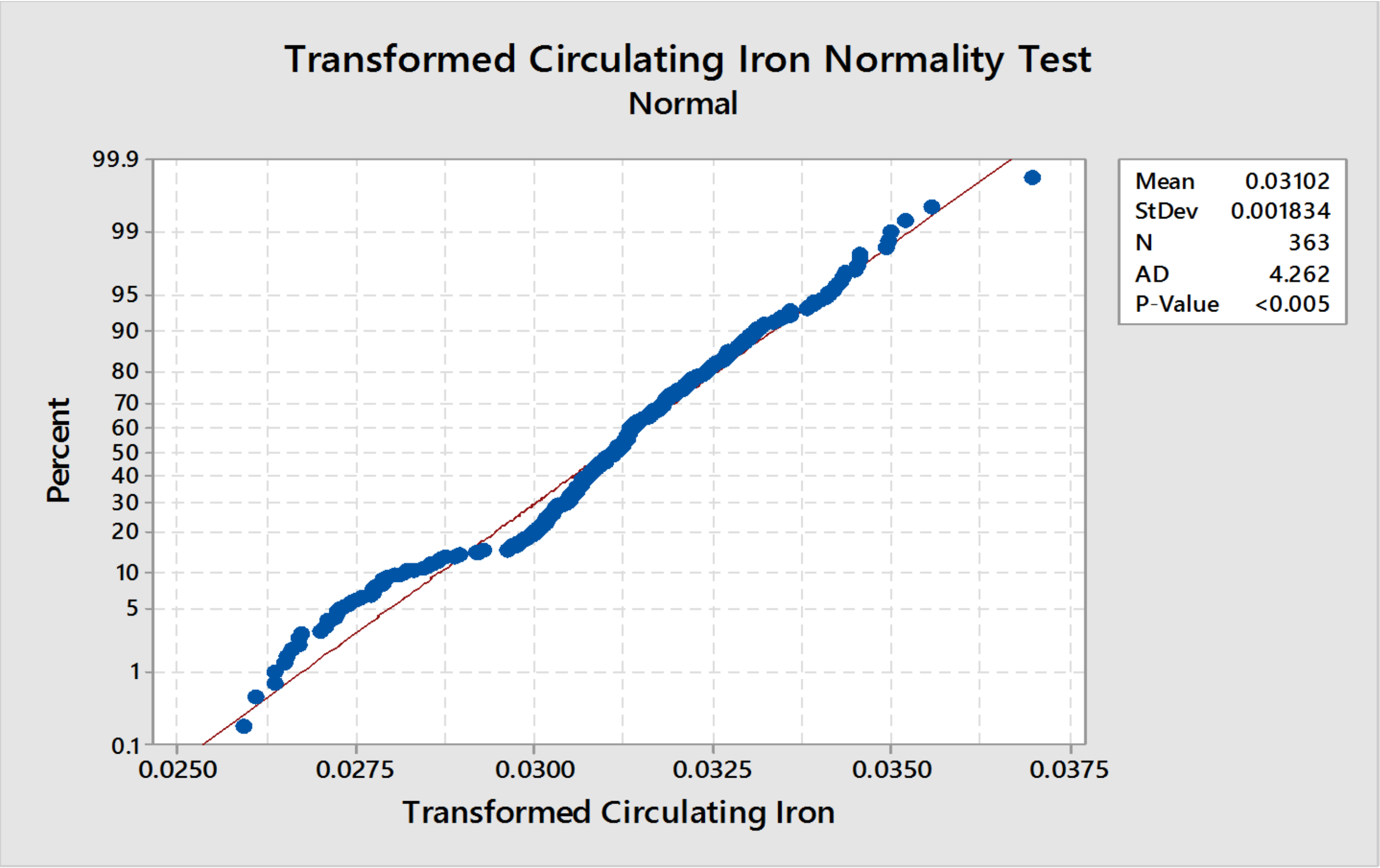


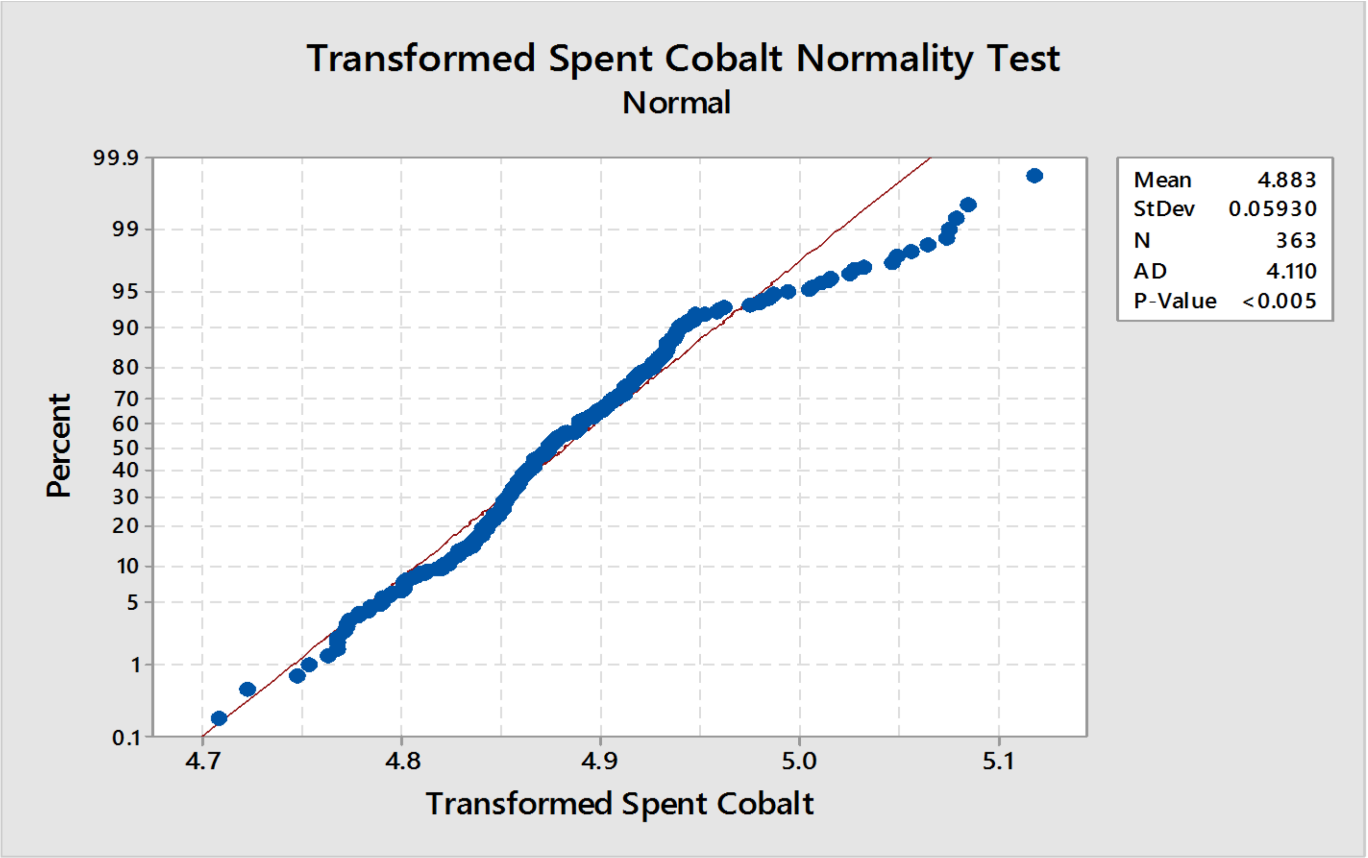

Transformed Spent Electrolyte Acid Tenor Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
-4
-3
-2
-1
0
1
2
3
4
Transformed Spent Acid Tenor
Mean 0.005435
StDev 1.012
N 2169
AD 0.417
P-Value 0.330

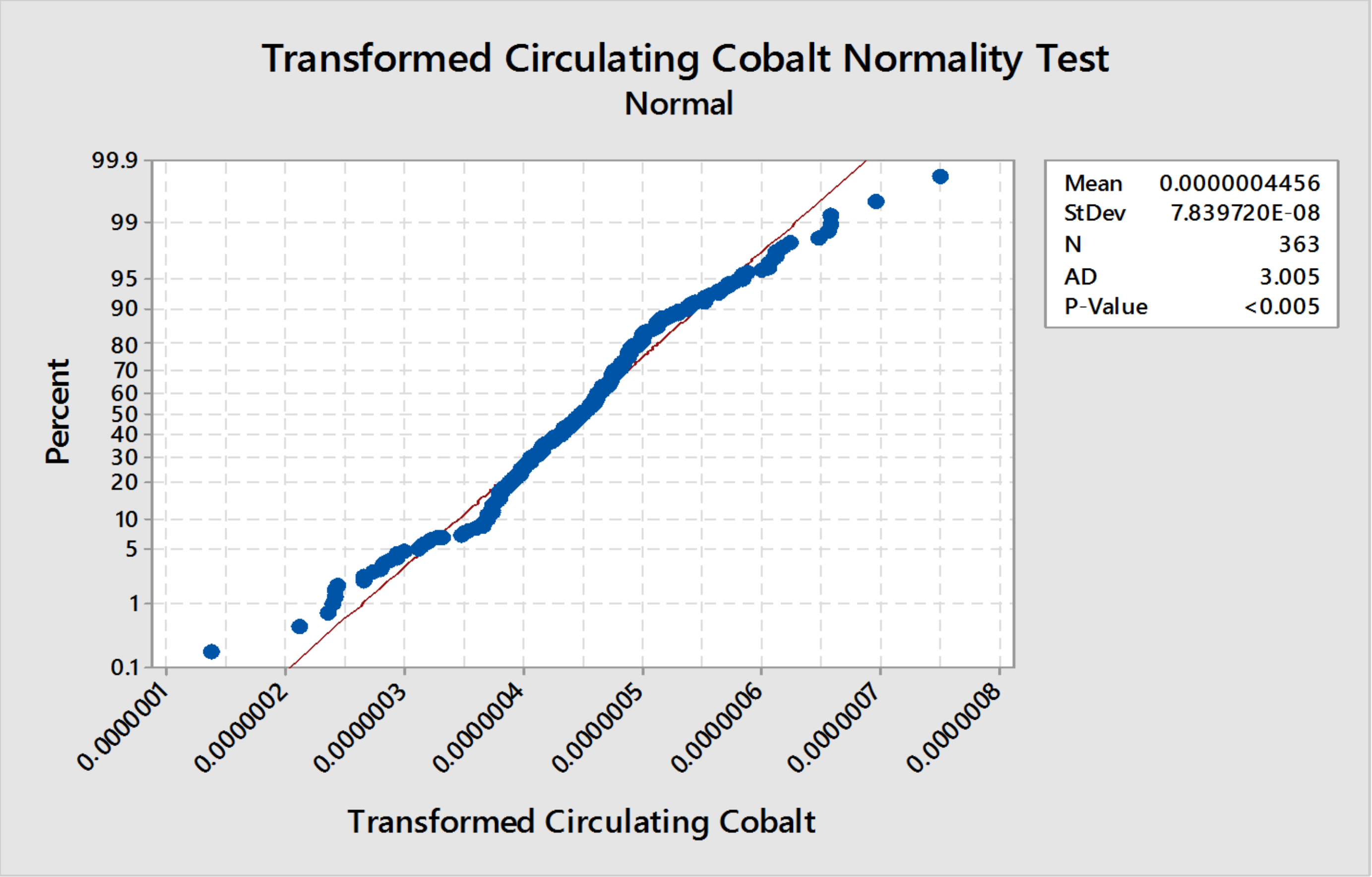

Transformed Circulating Electrolyte Acid Tenor Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
-4
-3
-2
-1
0
1
2
3
4
Transformed Circulating acid te
Mean 0.003146
StDev 1.002
N 2166
AD 0.294
P-Value 0.600

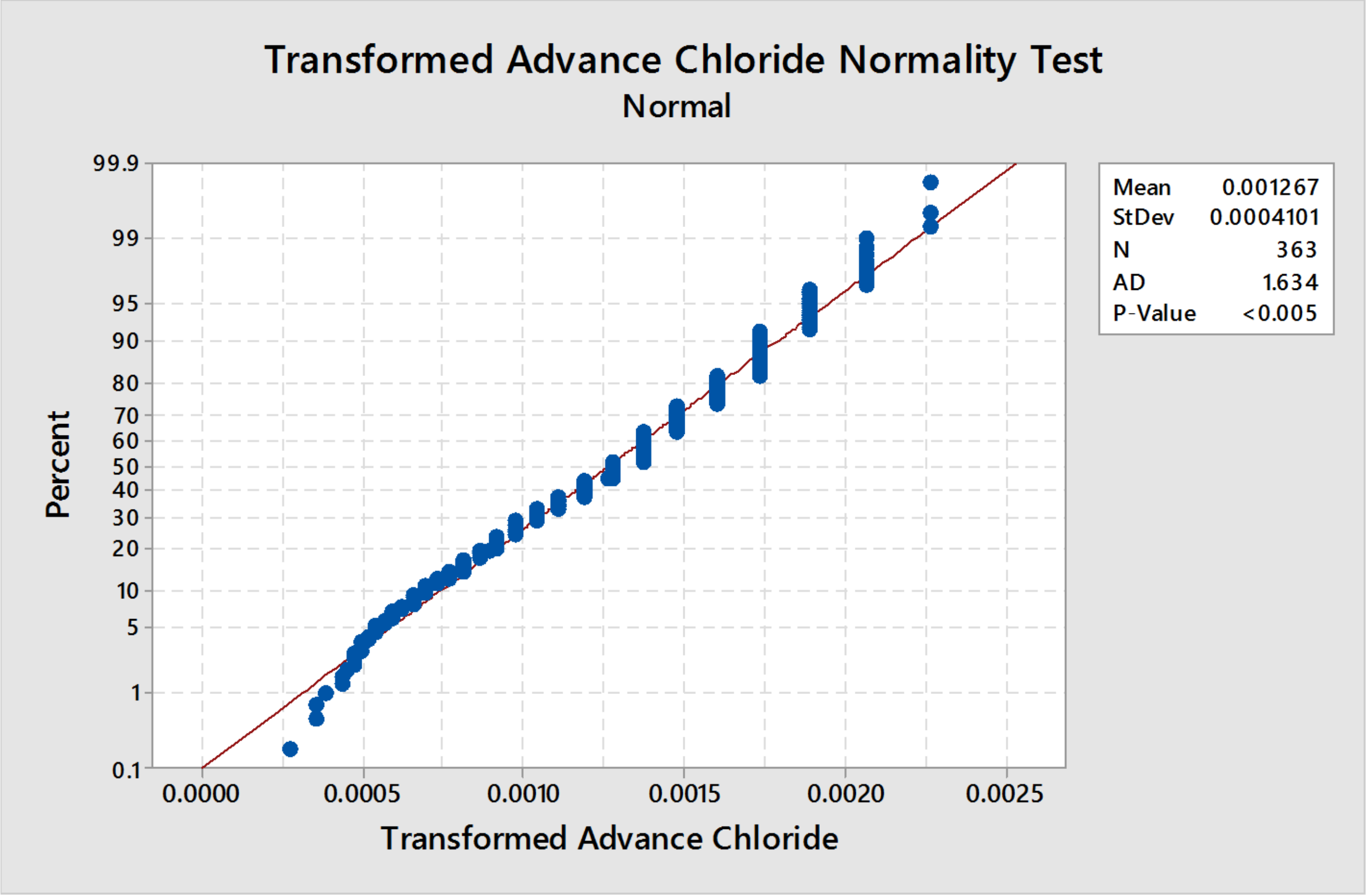

Transformed Advance Iron Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
0.0250
0.0275
0.0300
0.0325
0.0350
0.0375
Transformed Advance Iron
Mean 0.03105
StDev 0.001873
N 363
AD 4.092
P-Value <0.005

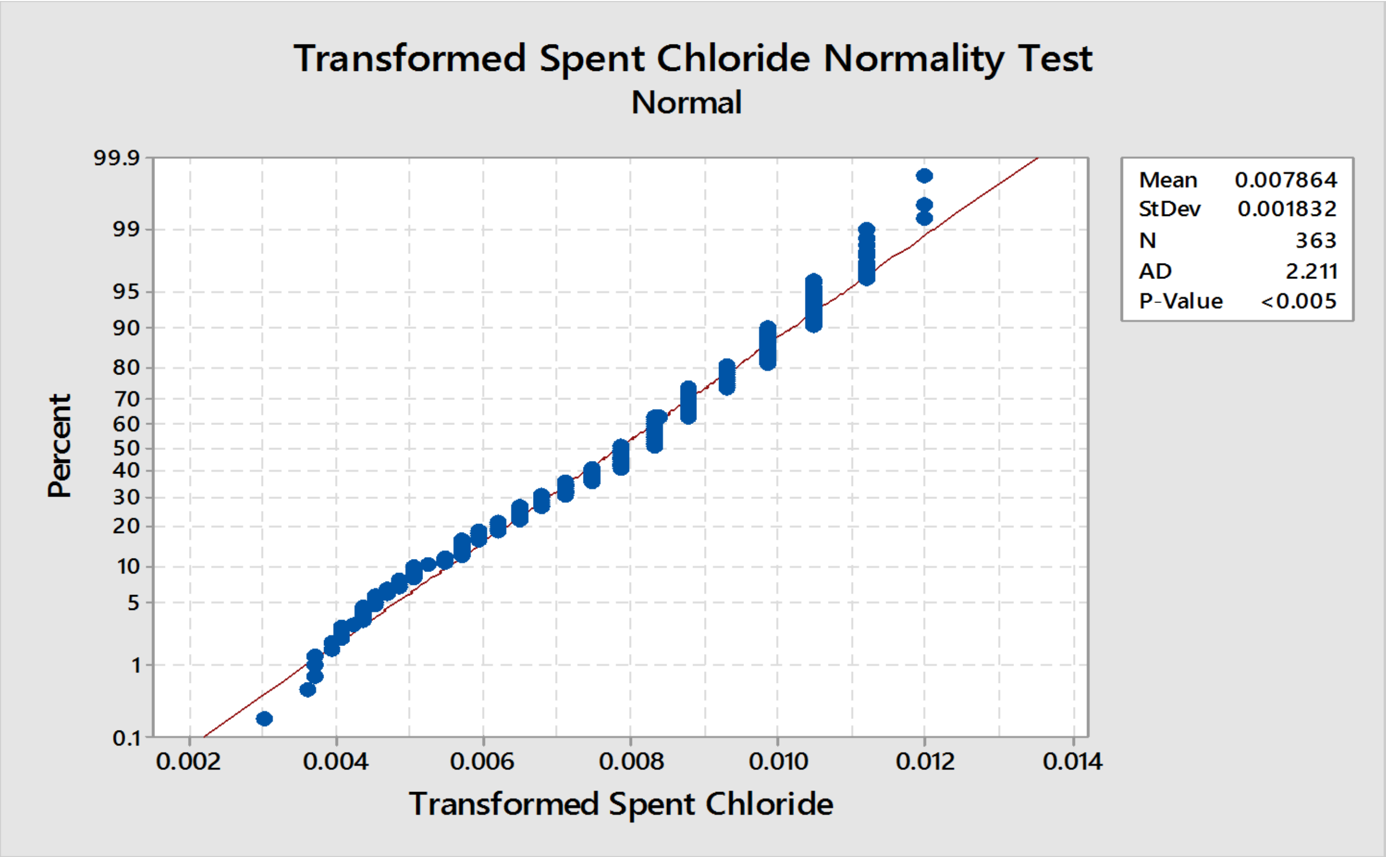

Transformed Spent Iron Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
0.0006
0.0007
0.0008
0.0009
0.0010
0.0011
0.0012
0.0013
Transformed Spent Total Iron
Mean 0.0009591
StDev 0.0001100
N 363
AD 3.190
P-Value <0.005

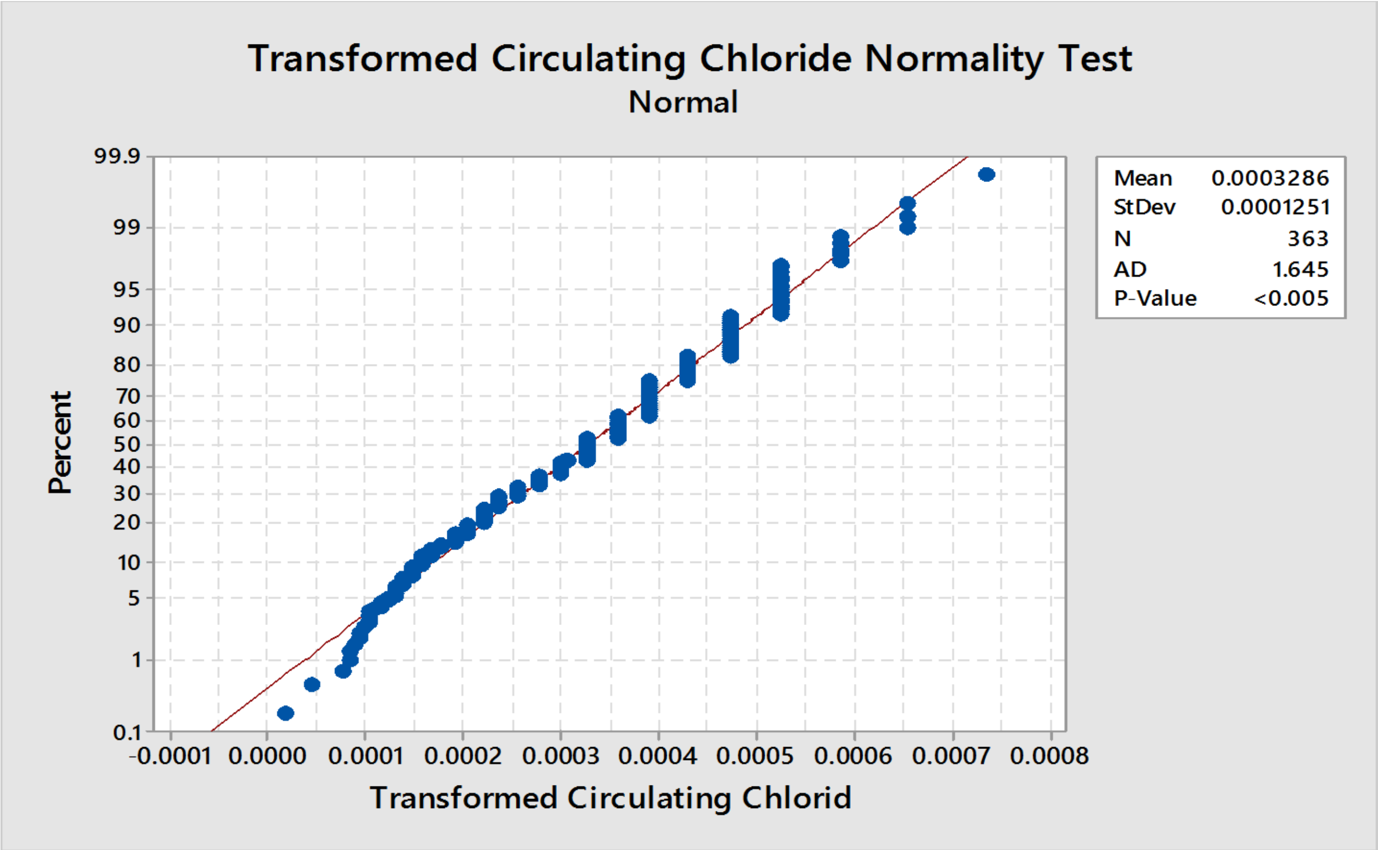

Transformed Circulating Iron Normality Test
Normal
Mean 0.03102
StDev 0.001834
N 363
AD 4.262
P-Value <0.005
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
0.0250
0.0275
0.0300
0.0325
0.0350
0.0375
Transformed Circulating Iron

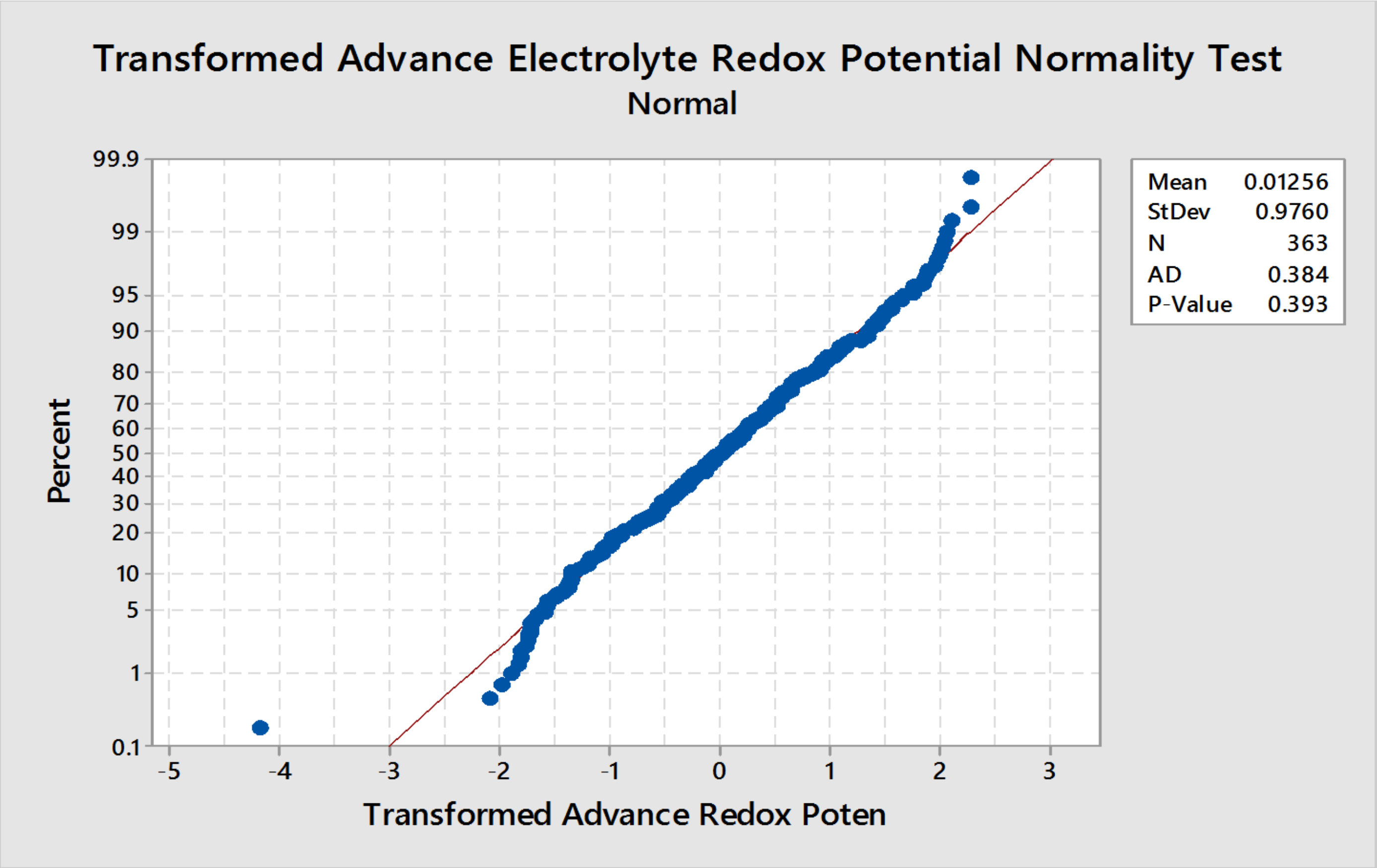

Transformed Spent Cobalt Normality Test
Normal
Mean 4.883
StDev 0.05930
N 363
AD 4.110
P-Value <0.005
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
4.7
4.8
4.9
5.0
5.1
Transformed Spent Cobalt

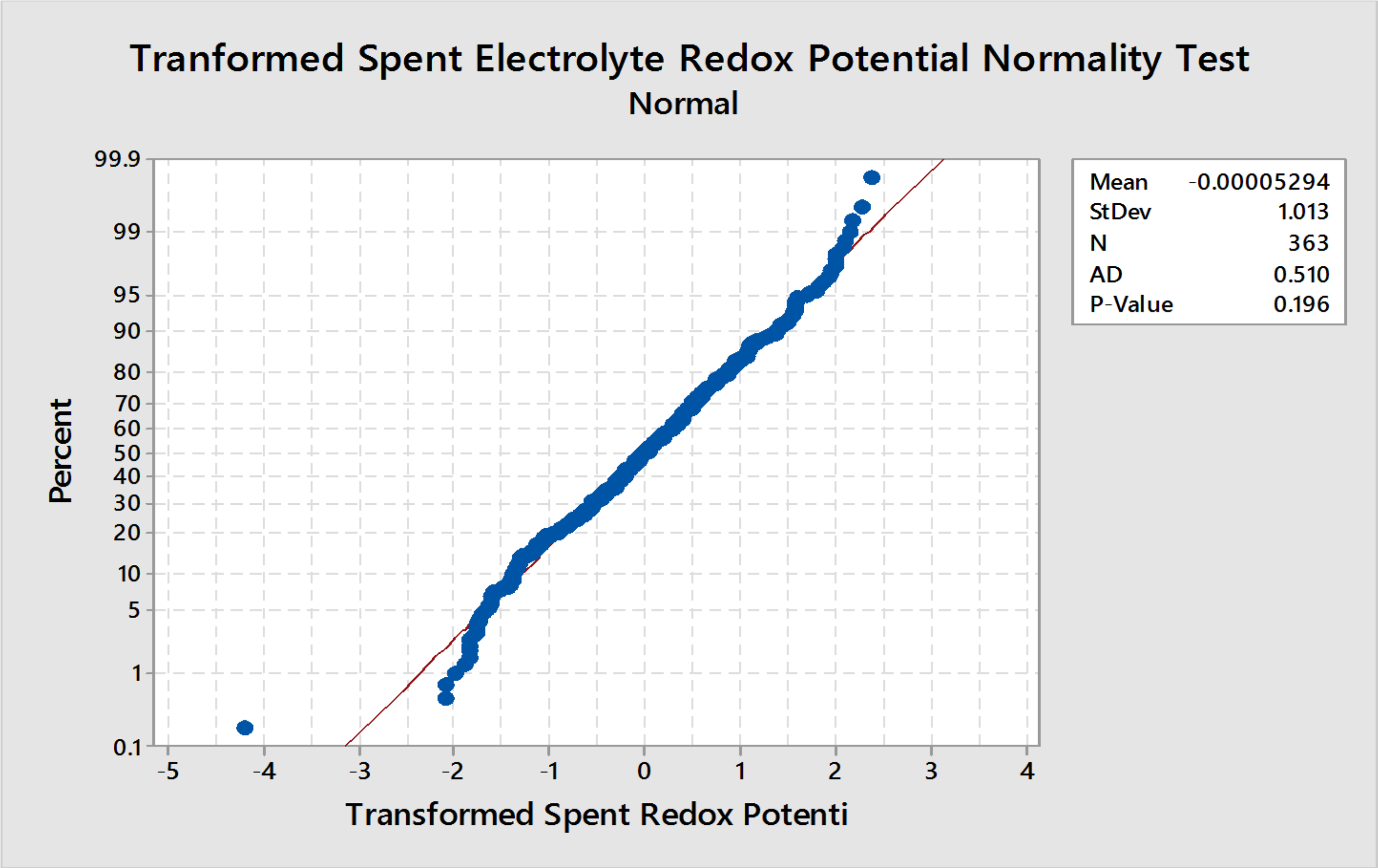

Transformed Circulating Cobalt Normality Test
Normal
Mean 0.0000004456
StDev 7.839720E-08
N 363
AD 3.005
P-Value <0.005
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
0.0000001
0.0000002
0.0000003
0.0000004
0.0000005
0.0000006
0.0000007
0.0000008
Transformed Circulating Cobalt

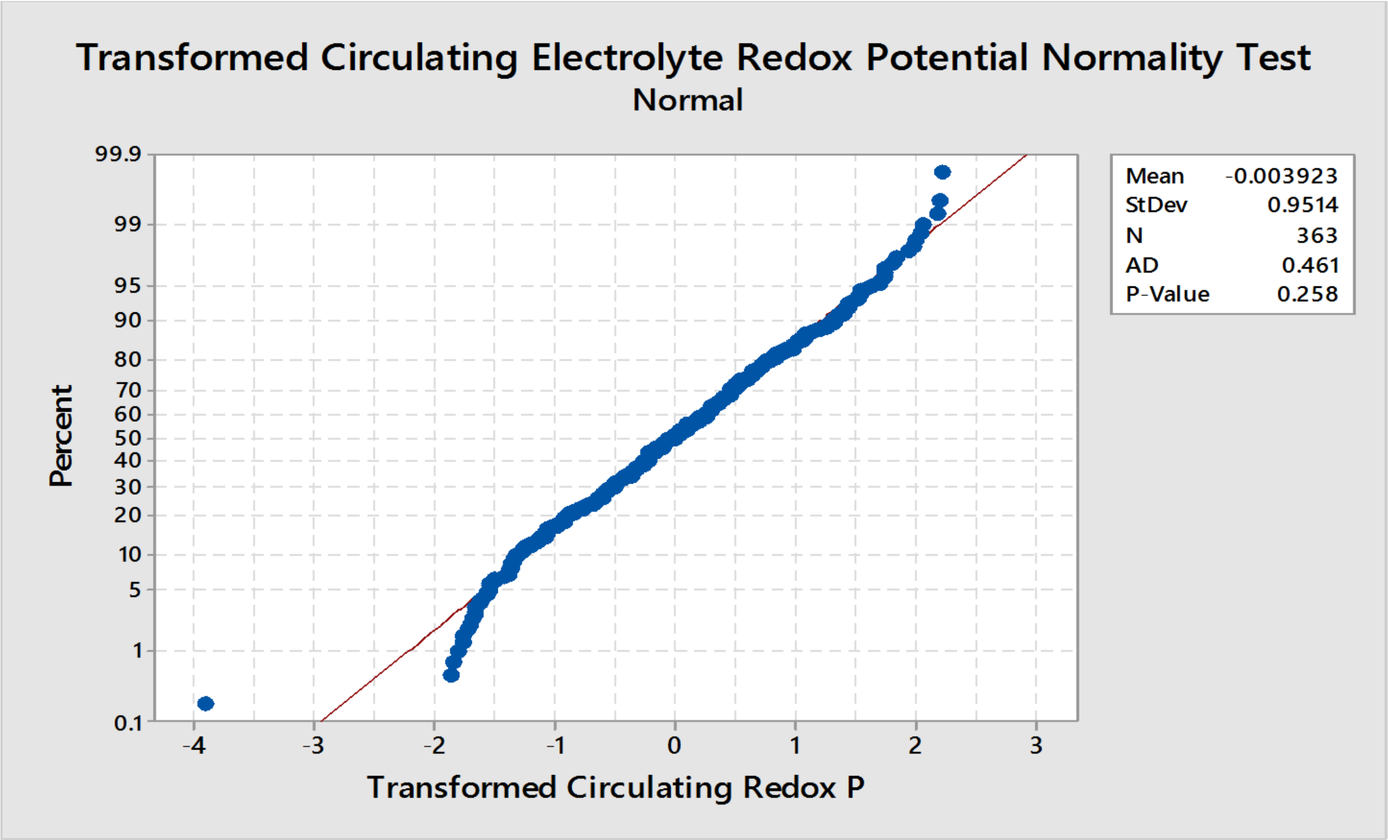

Transformed Advance Chloride Normality Test
Normal
Mean 0.001267
StDev 0.0004101
N 363
AD 1.634
P-Value <0.005
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
Transformed Advance Chloride

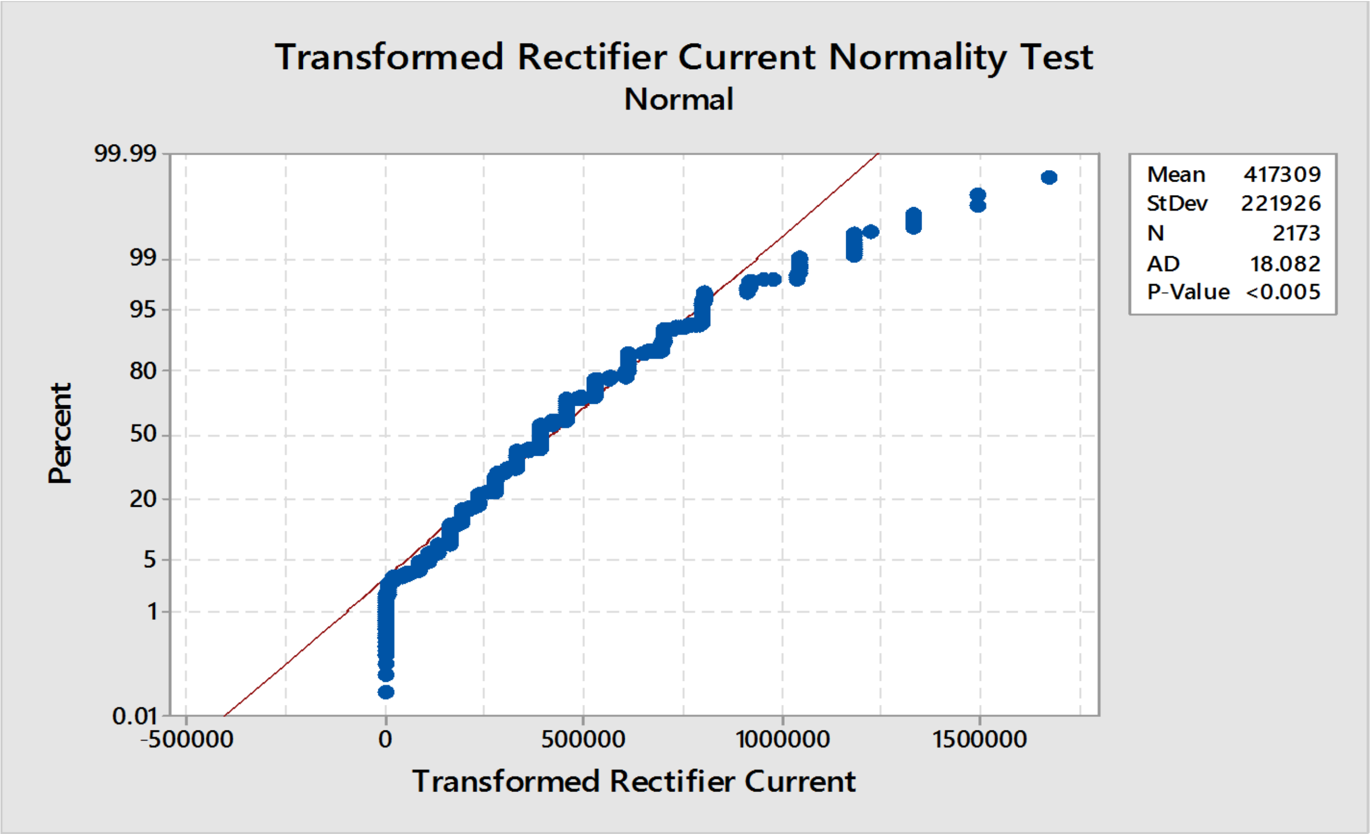

Transformed Spent Chloride Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
0.002
0.004
0.006
0.008
0.010
0.012
0.014
Transformed Spent Chloride
Mean 0.007864
StDev 0.001832
N 363
AD 2.211
P-Value <0.005

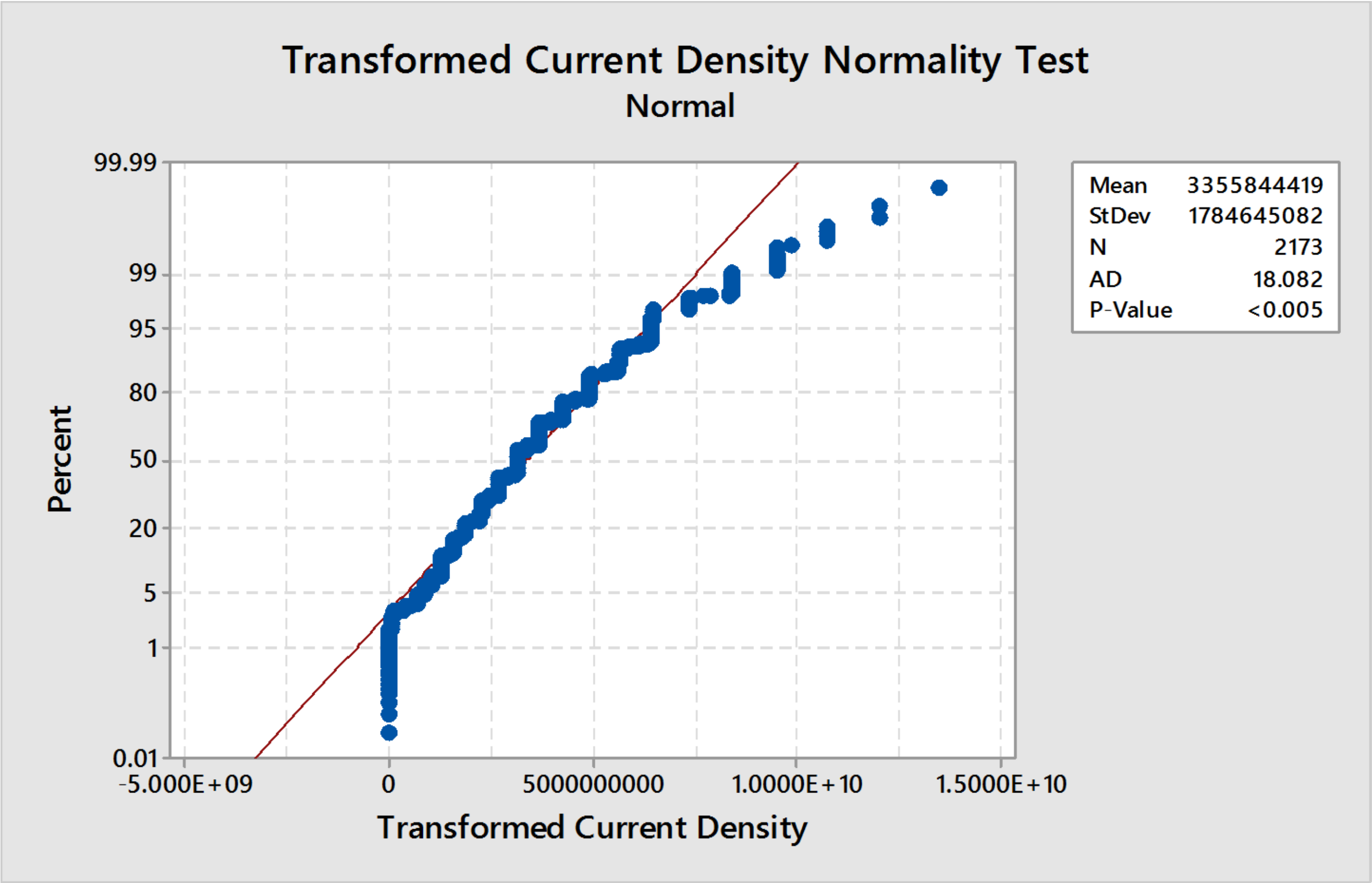

Transformed Circulating Chloride Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
-0.0001
0.0000
0.0001
0.0002
0.0003
0.0004
0.0005
0.0006
0.0007
0.0008
Transformed Circulating Chlorid
Mean 0.0003286
StDev 0.0001251
N 363
AD 1.645
P-Value <0.005

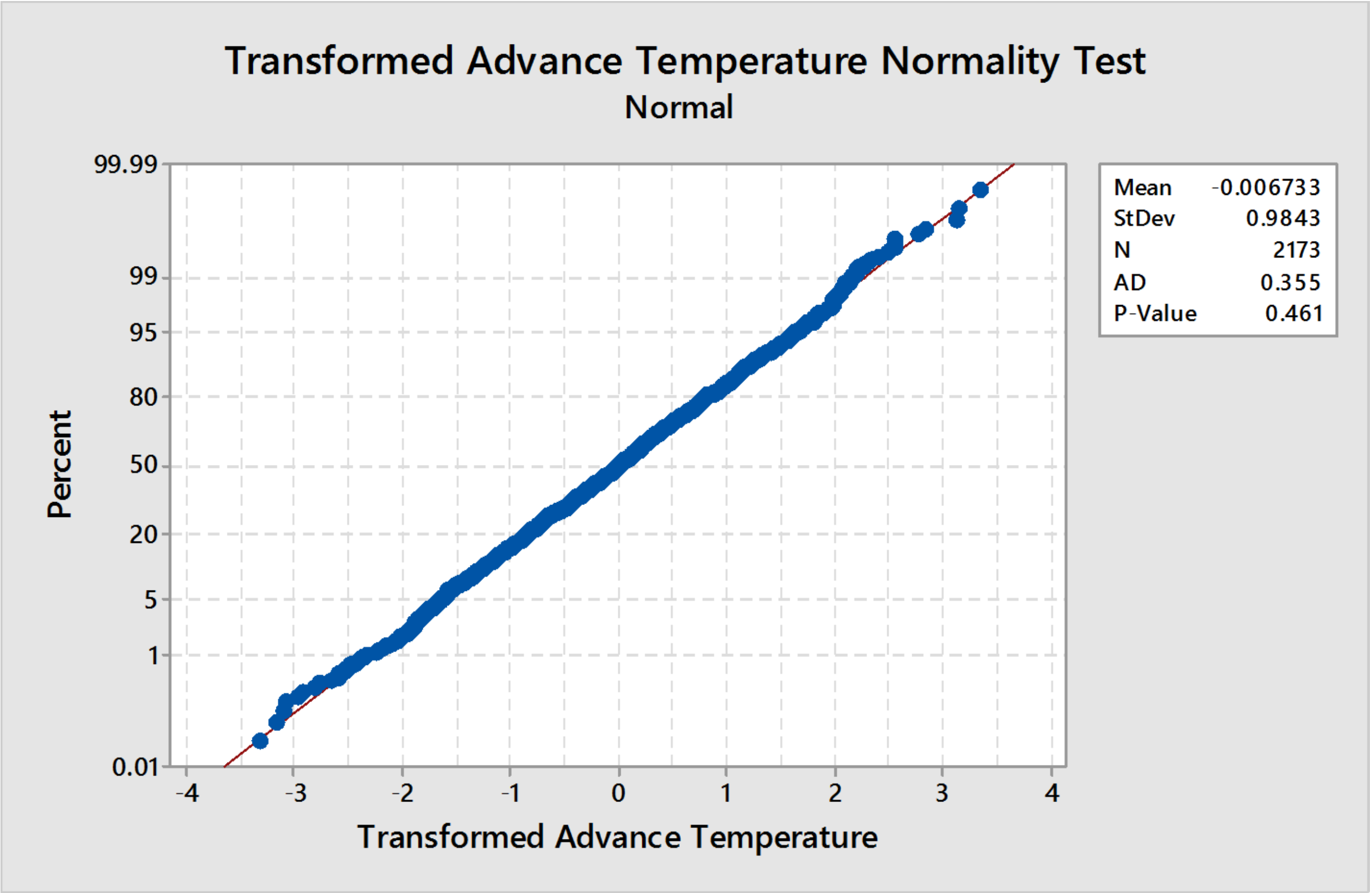

Transformed Advance Electrolyte Redox Potential Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
-5
-4
-3
-2
-1
0
1
2
3
Transformed Advance Redox Poten
Mean 0.01256
StDev 0.9760
N 363
AD 0.384
P-Value 0.393


Tranformed Spent Electrolyte Redox Potential Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
-5
-4
-3
-2
-1
0
1
2
3
4
Transformed Spent Redox Potenti
Mean -0.00005294
StDev 1.013
N 363
AD 0.510
P-Value 0.196


Transformed Circulating Electrolyte Redox Potential Normality Test
Normal
Percent
99.9
99
95
90
80
70
60
50
40
30
20
10
5
1
0.1
-4
-3
-2
-1
0
1
2
3
Transformed Circulating Redox P
Mean -0.003923
StDev 0.9514
N 363
AD 0.461
P-Value 0.258


Transformed Rectifier Current Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
-500000
0
500000
1000000
1500000
Transformed Rectifier Current
Mean 417309
StDev 221926
N 2173
AD 18.082
P-Value <0.005


Transformed Current Density Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
-5.000E+09
0
5000000000
1.0000E+10
1.5000E+10
Transformed Current Density
Mean 3355844419
StDev 1784645082
N 2173
AD 18.082
P-Value <0.005


Transformed Advance Temperature Normality Test
Normal
Percent
99.99
99
95
80
50
20
5
1
0.01
-4
-3
-2
-1
0
1
2
3
4
Transformed Advance Temperature
Mean -0.006733
StDev 0.9843
N 2173
AD 0.355
P-Value 0.461

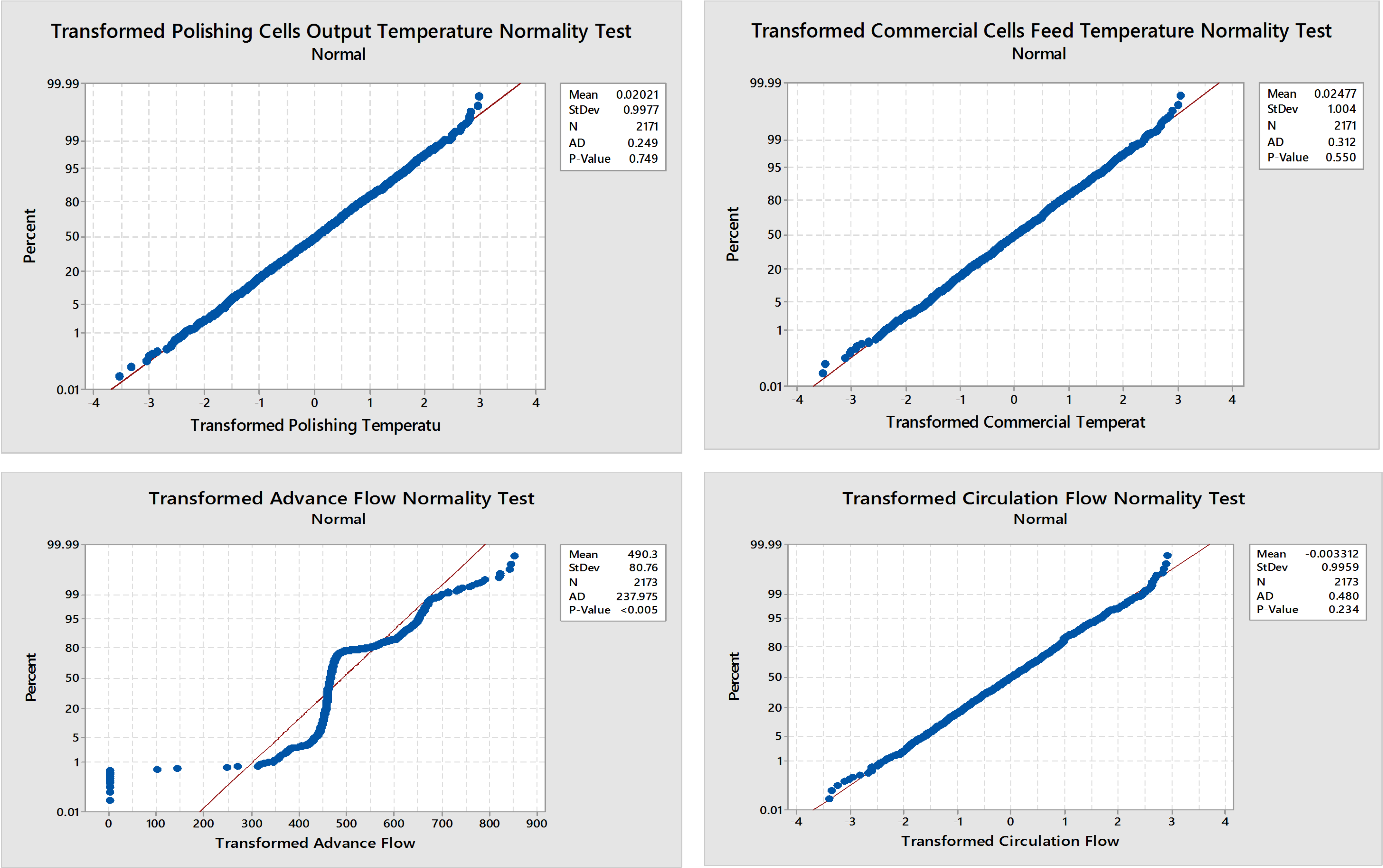
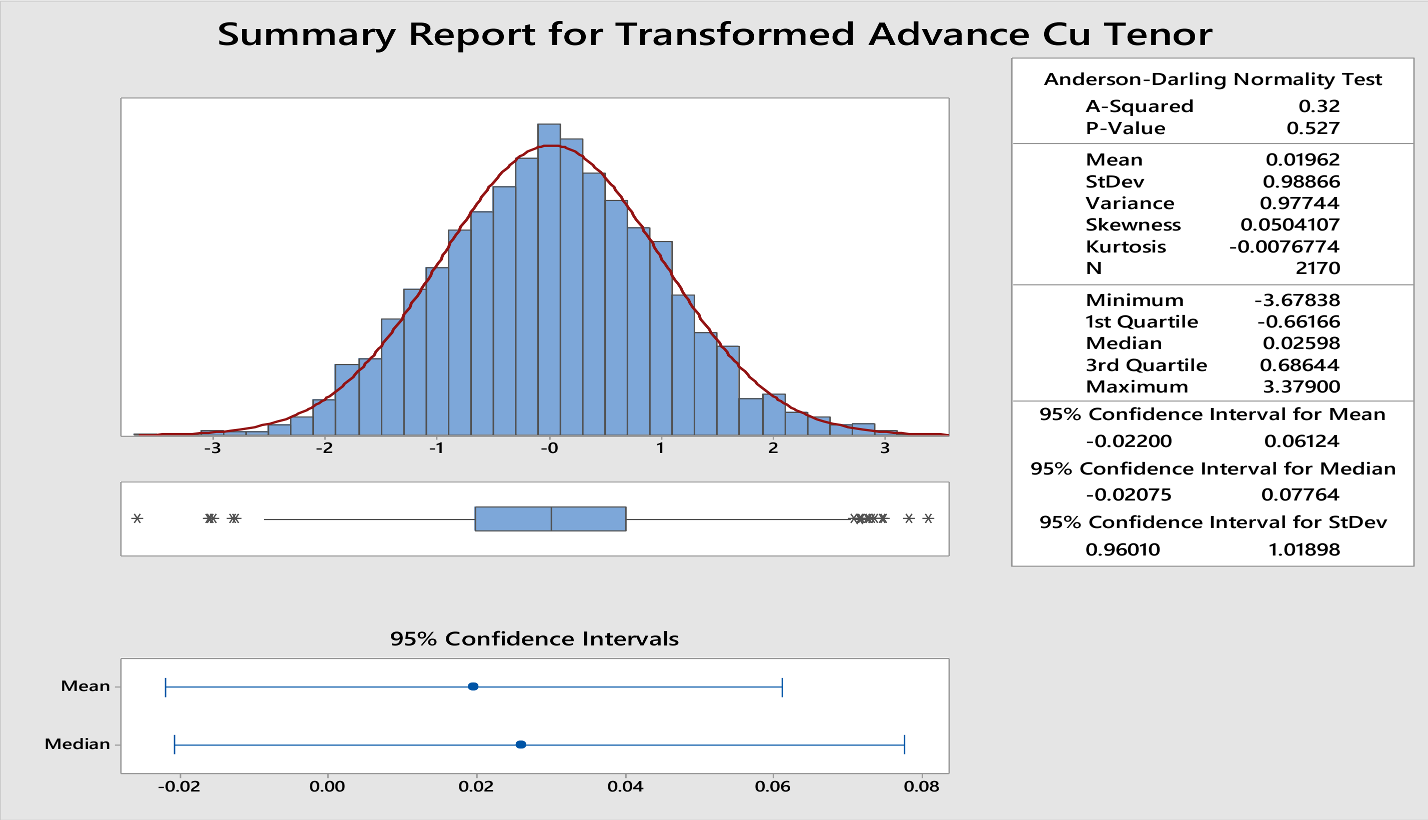


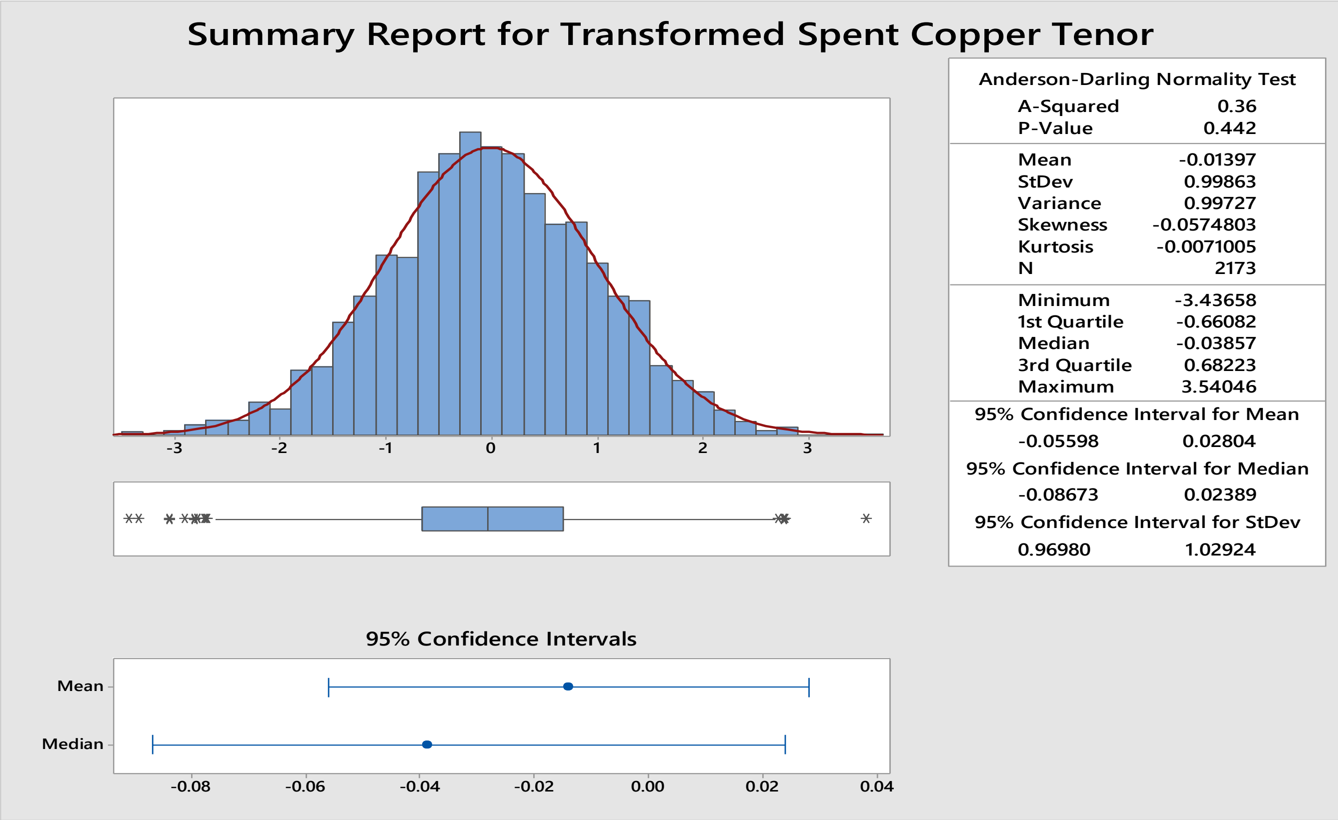
Figure 8.3: Minitab normality test output for transformed current efficiency factors data (created by the author)

Appendix E: Statistical summary report for current efficiency factors data created using Minitab statistical software



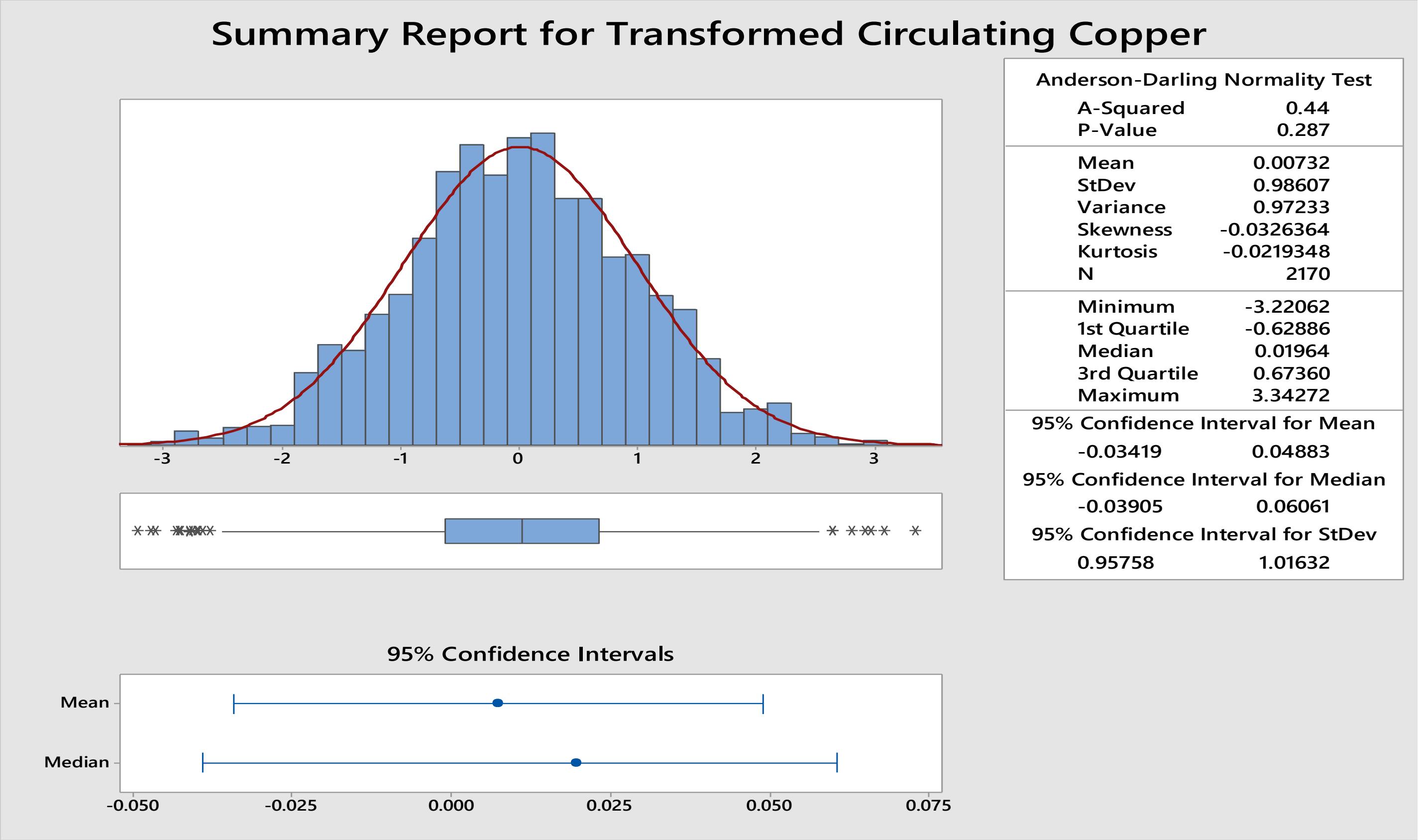
Summary Report for Transformed Advance Cu Tenor

```
Anderson-Darling Normality Test
  A-Squared            0.32
  P-Value             0.527

  Mean              0.01962
  StDev             0.98866
  Variance          0.97744
  Skewness        0.0504107
  Kurtosis       -0.0076774
  N                    2170

  Minimum          -3.67838
  1st Quartile     -0.66166
  Median            0.02598
  3rd Quartile      0.68644
  Maximum           3.37900

95% Confidence Interval for Mean
  -0.02200          0.06124
95% Confidence Interval for Median
  -0.02075          0.07764
95% Confidence Interval for StDev
  0.96010           1.01898
```



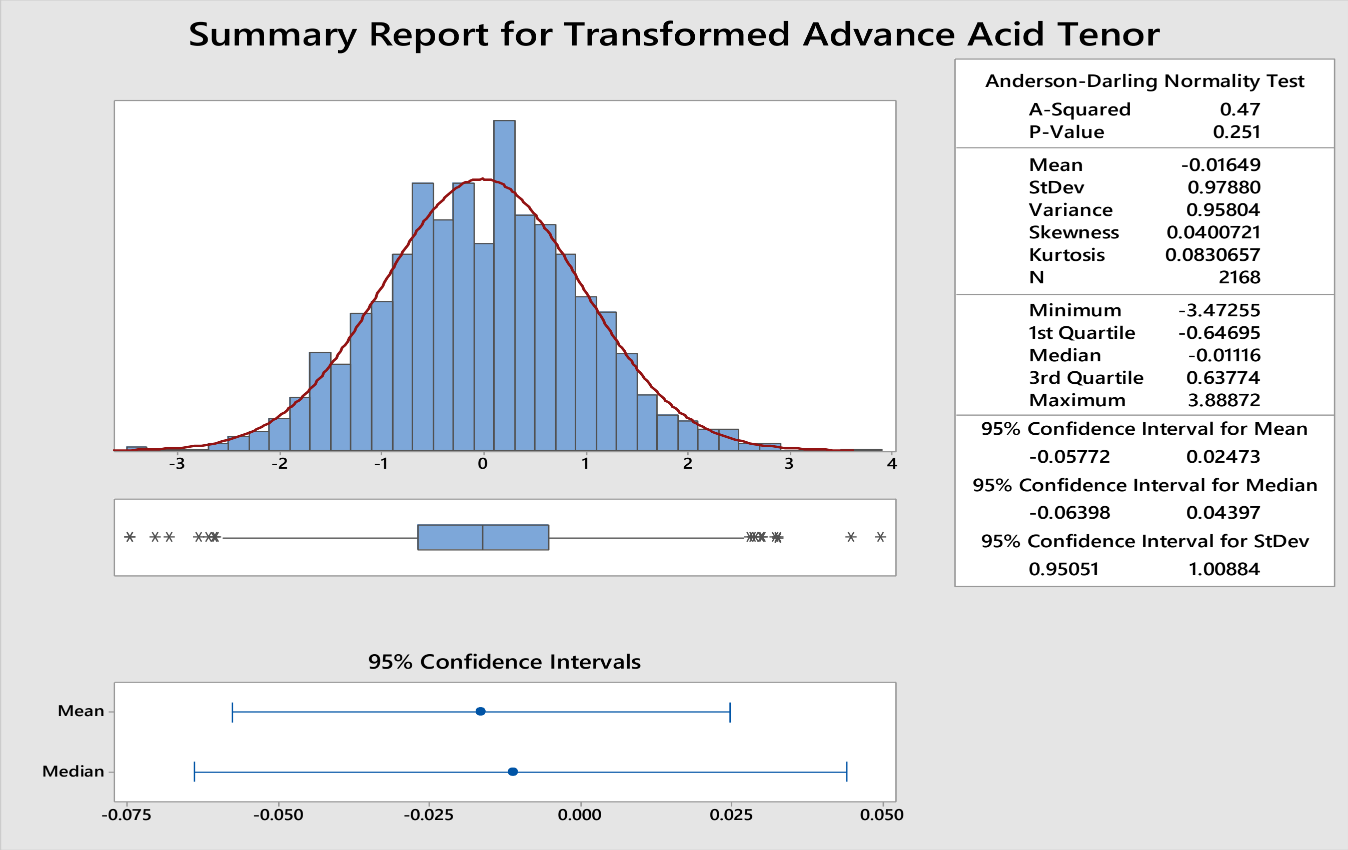
Summary Report for Transformed Spent Copper Tenor

```
Anderson-Darling Normality Test
  A-Squared            0.36
  P-Value             0.442

  Mean             -0.01397
  StDev             0.99863
  Variance          0.99727
  Skewness       -0.0574803
  Kurtosis       -0.0071005
  N                    2173

  Minimum          -3.43658
  1st Quartile     -0.66082
  Median           -0.03857
  3rd Quartile      0.68223
  Maximum           3.54046

95% Confidence Interval for Mean
  -0.05598          0.02804
95% Confidence Interval for Median
  -0.08673          0.02389
95% Confidence Interval for StDev
  0.96980           1.02924
```



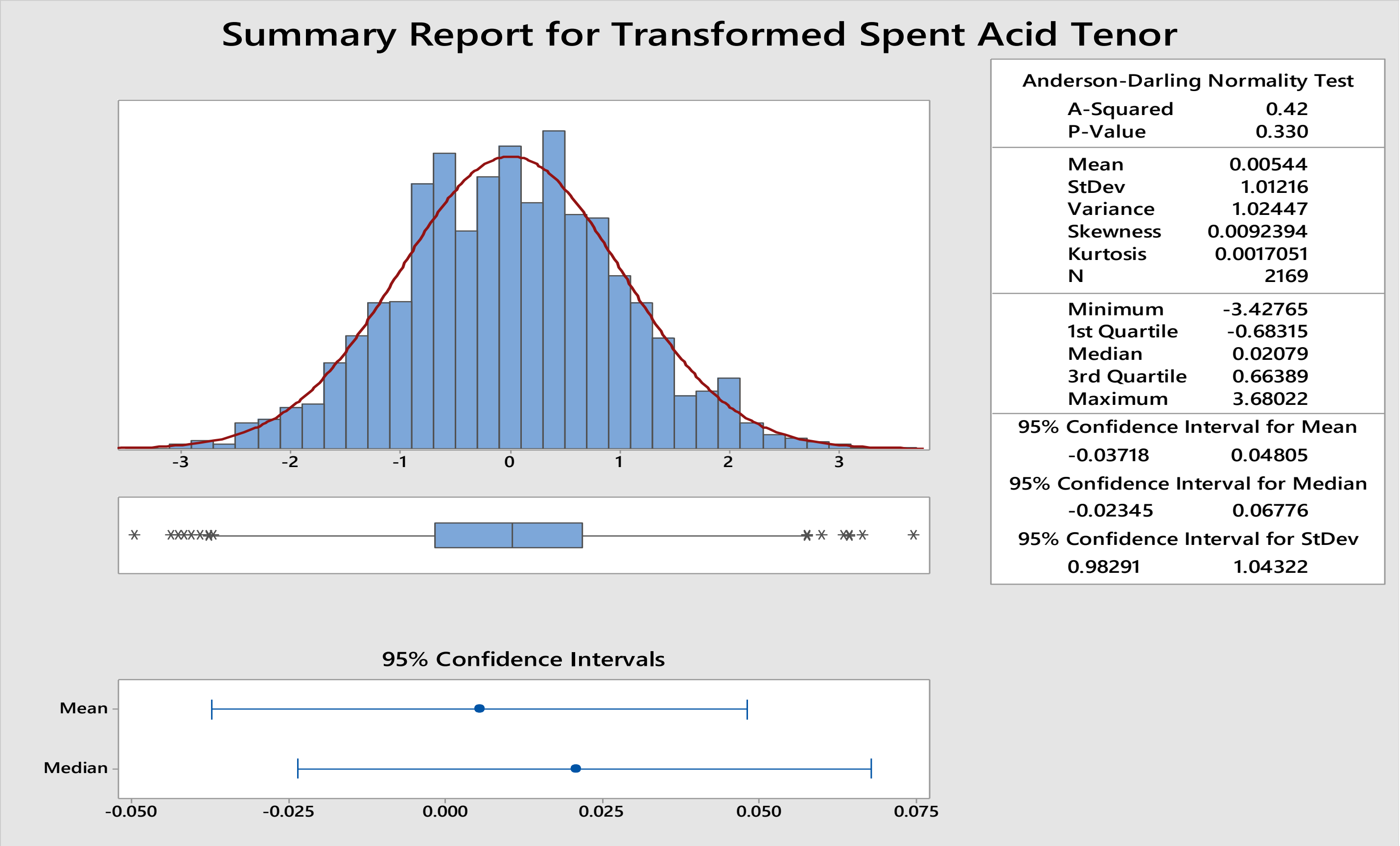
Summary Report for Transformed Circulating Copper

```
Anderson-Darling Normality Test
  A-Squared            0.44
  P-Value             0.287

  Mean              0.00732
  StDev             0.98607
  Variance          0.97233
  Skewness       -0.0326364
  Kurtosis       -0.0219348
  N                    2170

  Minimum          -3.22062
  1st Quartile     -0.62886
  Median            0.01964
  3rd Quartile      0.67360
  Maximum           3.34272

95% Confidence Interval for Mean
  -0.03419          0.04883
95% Confidence Interval for Median
  -0.03905          0.06061
95% Confidence Interval for StDev
  0.95758           1.01632
```

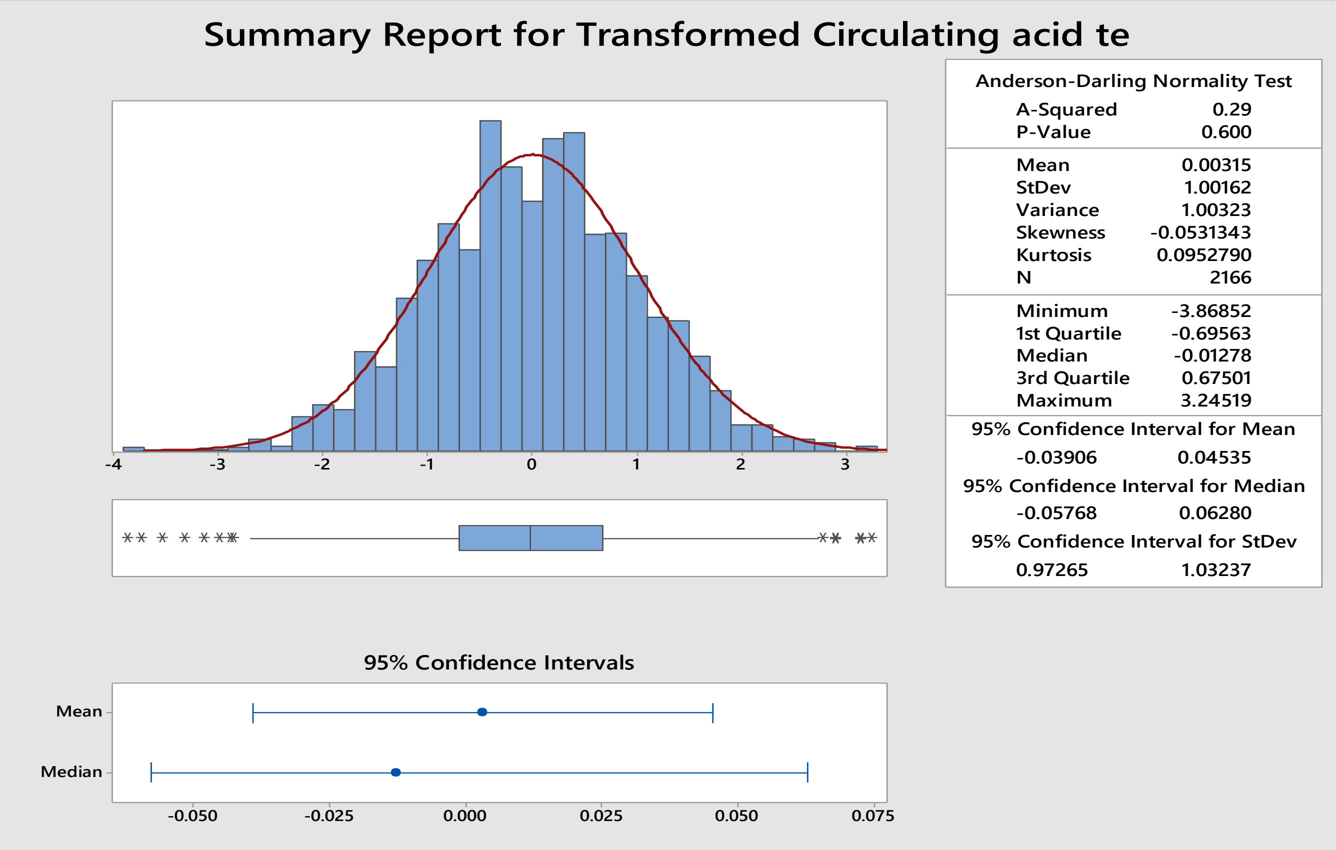


Summary Report for Transformed Advance Acid Tenor

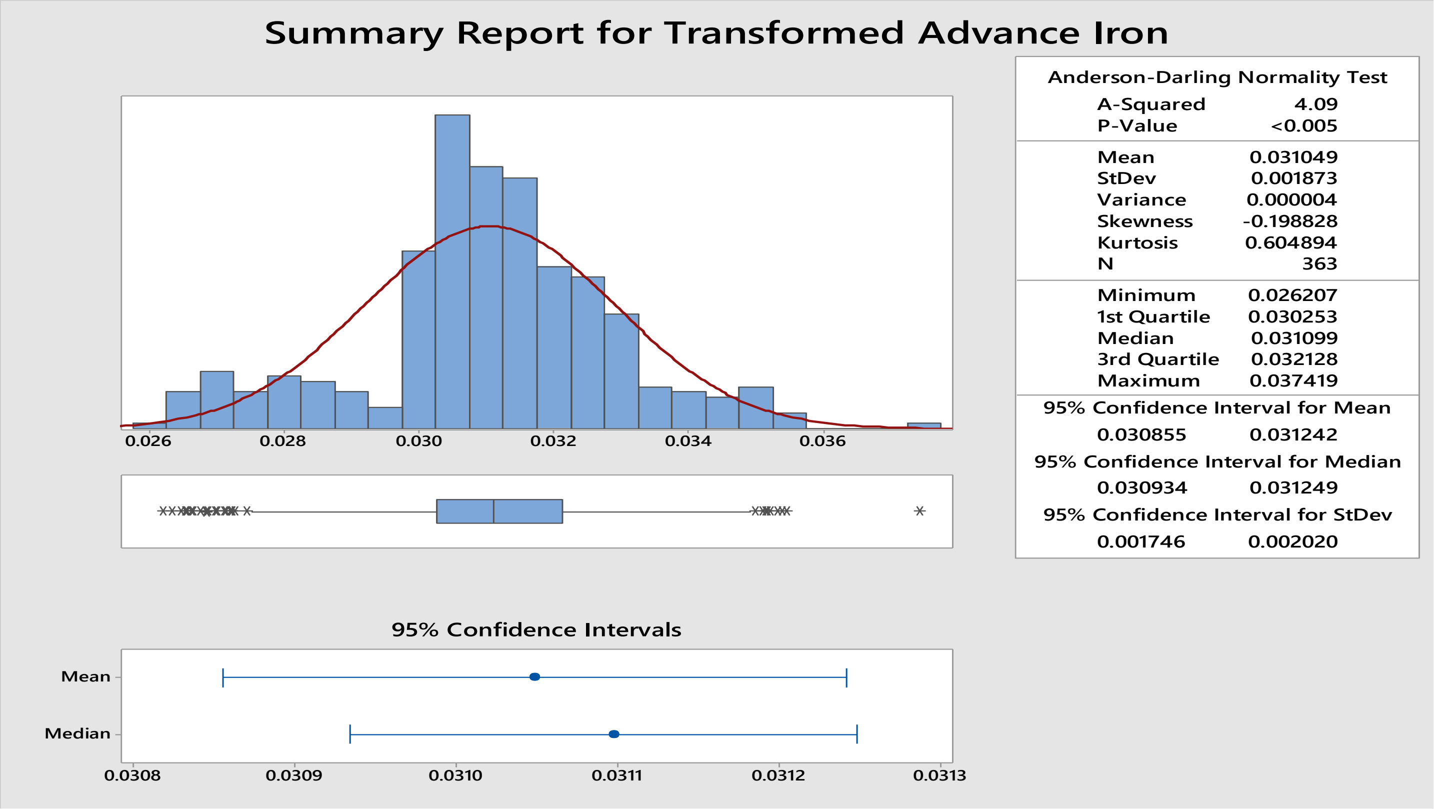
```
Anderson-Darling Normality Test
  A-Squared            0.47
  P-Value             0.251

  Mean             -0.01649
  StDev             0.97880
  Variance          0.95804
  Skewness        0.0400721
  Kurtosis        0.0830657
  N                    2168

  Minimum          -3.47255
  1st Quartile     -0.64695
  Median           -0.01116
  3rd Quartile      0.63774
  Maximum           3.88872

95% Confidence Interval for Mean
  -0.05772          0.02473
95% Confidence Interval for Median
  -0.06398          0.04397
95% Confidence Interval for StDev
  0.95051           1.00884
```


Summary Report for Transformed Spent Acid Tenor

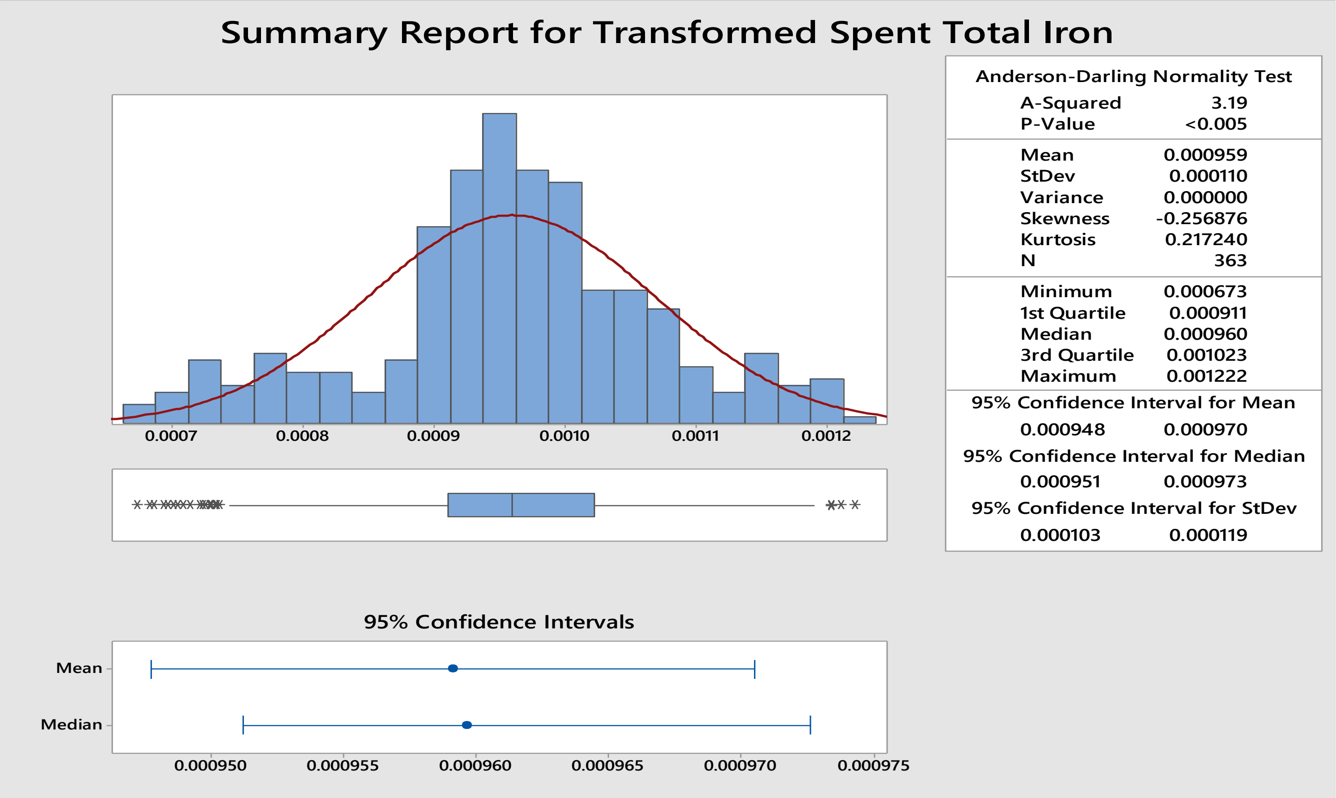
Anderson-Darling Normality Test	
A-Squared	0.42
P-Value	0.330
Mean	0.00544
StDev	1.01216
Variance	1.02447
Skewness	0.0092394
Kurtosis	0.0017051
N	2169
Minimum	-3.42765
1st Quartile	-0.68315
Median	0.02079
3rd Quartile	0.66389
Maximum	3.68022
95% Confidence Interval for Mean	
-0.03718	0.04805
95% Confidence Interval for Median	
-0.02345	0.06776
95% Confidence Interval for StDev	
0.98291	1.04322


Summary Report for Transformed Circulating acid te

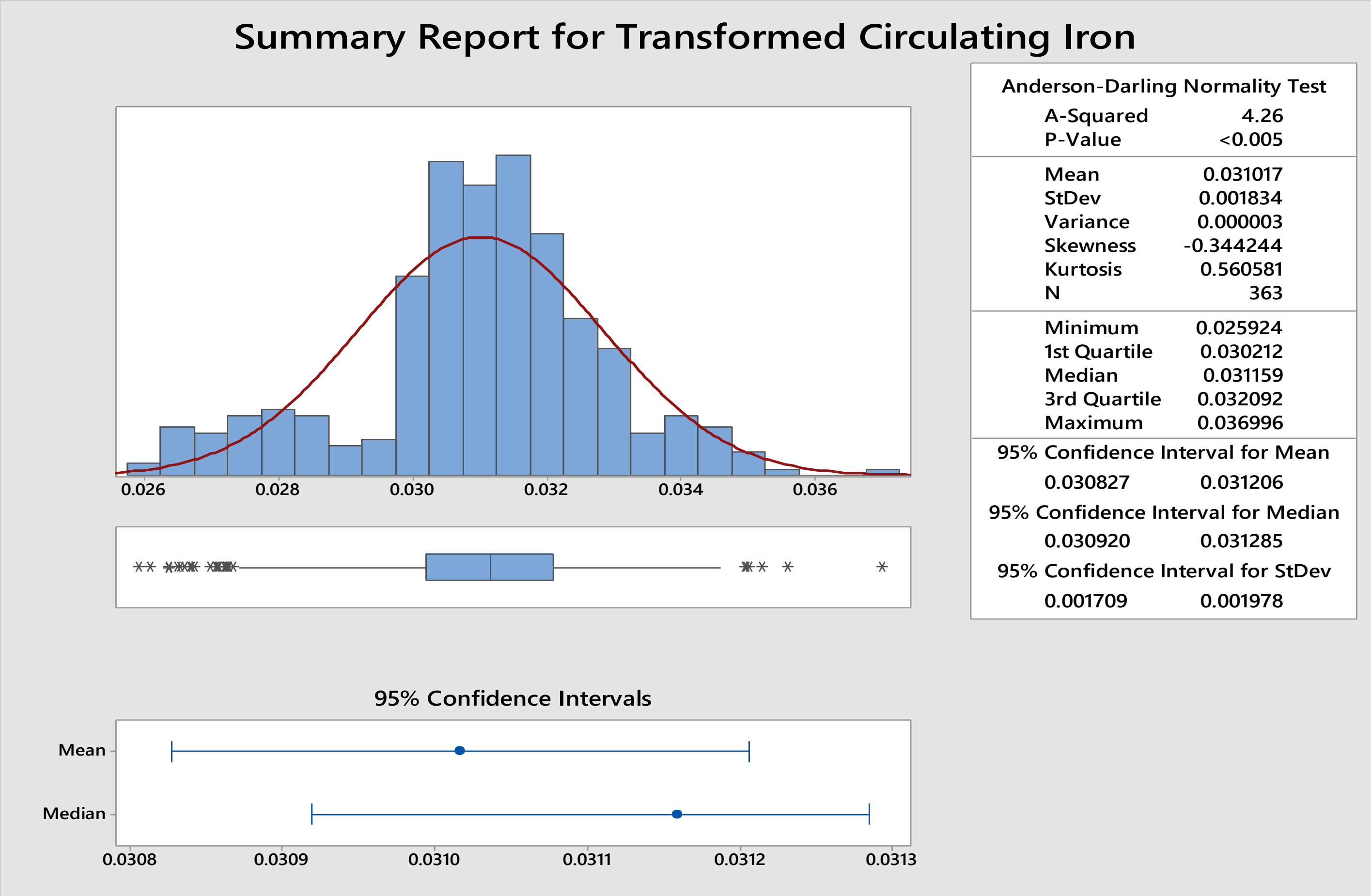
Anderson-Darling Normality Test	
A-Squared	0.29
P-Value	0.600
Mean	0.00315
StDev	1.00162
Variance	1.00323
Skewness	-0.0531343
Kurtosis	0.0952790
N	2166
Minimum	-3.86852
1st Quartile	-0.69563
Median	-0.01278
3rd Quartile	0.67501
Maximum	3.24519
95% Confidence Interval for Mean	
-0.03906	0.04535
95% Confidence Interval for Median	
-0.05768	0.06280
95% Confidence Interval for StDev	
0.97265	1.03237


Summary Report for Transformed Advance Iron

Anderson-Darling Normality Test	
A-Squared	4.09
P-Value	<0.005
Mean	0.031049
StDev	0.001873
Variance	0.000004
Skewness	-0.198828
Kurtosis	0.604894
N	363
Minimum	0.026207
1st Quartile	0.030253
Median	0.031099
3rd Quartile	0.032128
Maximum	0.037419
95% Confidence Interval for Mean	
0.030855	0.031242
95% Confidence Interval for Median	
0.030934	0.031249
95% Confidence Interval for StDev	
0.001746	0.002020


Summary Report for Transformed Spent Total Iron

Anderson-Darling Normality Test	
A-Squared	3.19
P-Value	<0.005
Mean	0.000959
StDev	0.000110
Variance	0.000000
Skewness	-0.256876
Kurtosis	0.217240
N	363
Minimum	0.000673
1st Quartile	0.000911
Median	0.000960
3rd Quartile	0.001023
Maximum	0.001222
95% Confidence Interval for Mean	
0.000948	0.000970
95% Confidence Interval for Median	
0.000951	0.000973
95% Confidence Interval for StDev	
0.000103	0.000119



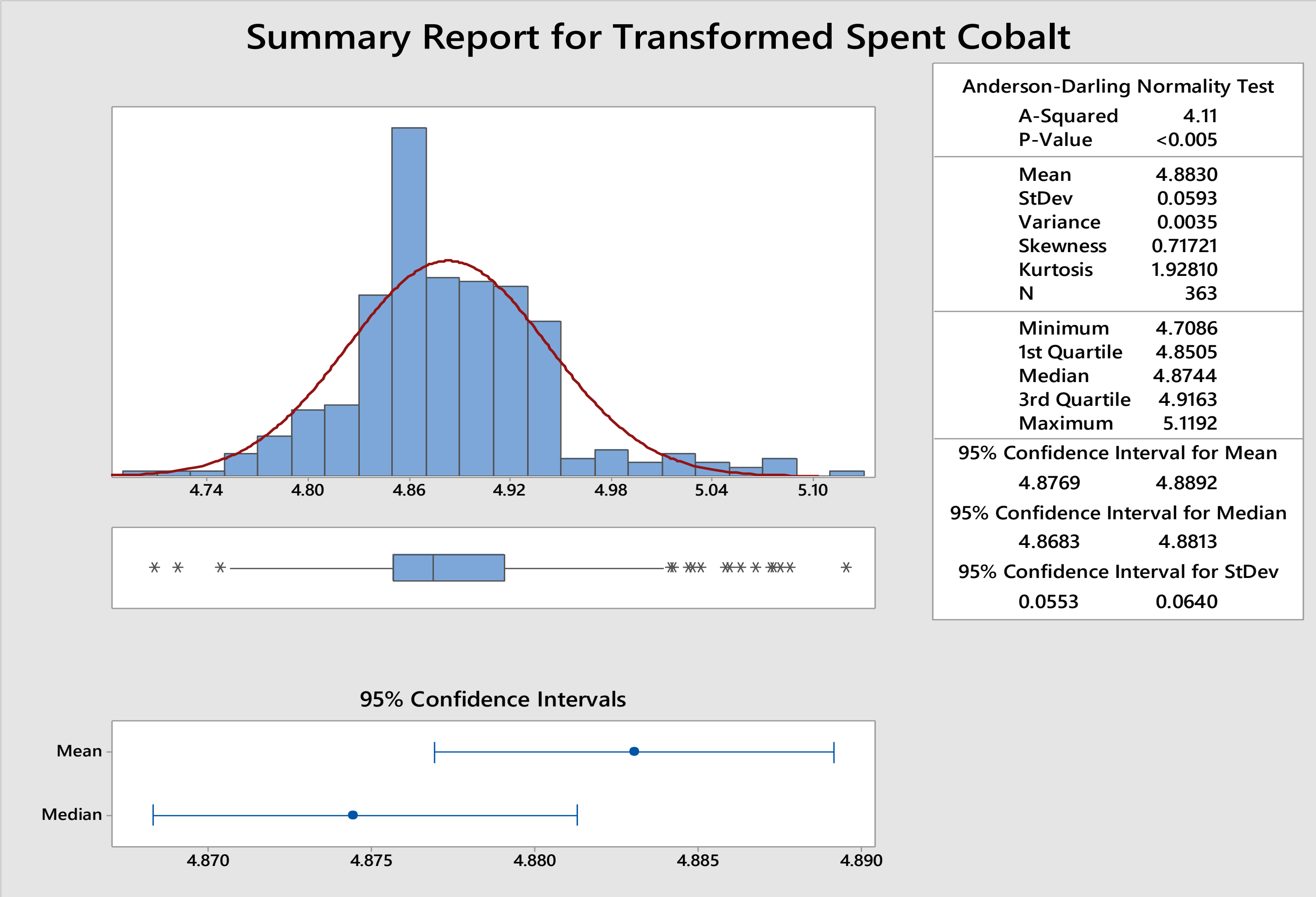
Summary Report for Transformed Circulating Iron

Anderson-Darling Normality Test
A-Squared 4.26
P-Value <0.005

Mean 0.031017
StDev 0.001834
Variance 0.000003
Skewness -0.344244
Kurtosis 0.560581
N 363

Minimum 0.025924
1st Quartile 0.030212
Median 0.031159
3rd Quartile 0.032092
Maximum 0.036996

95% Confidence Interval for Mean
0.030827 0.031206
95% Confidence Interval for Median
0.030920 0.031285
95% Confidence Interval for StDev
0.001709 0.001978



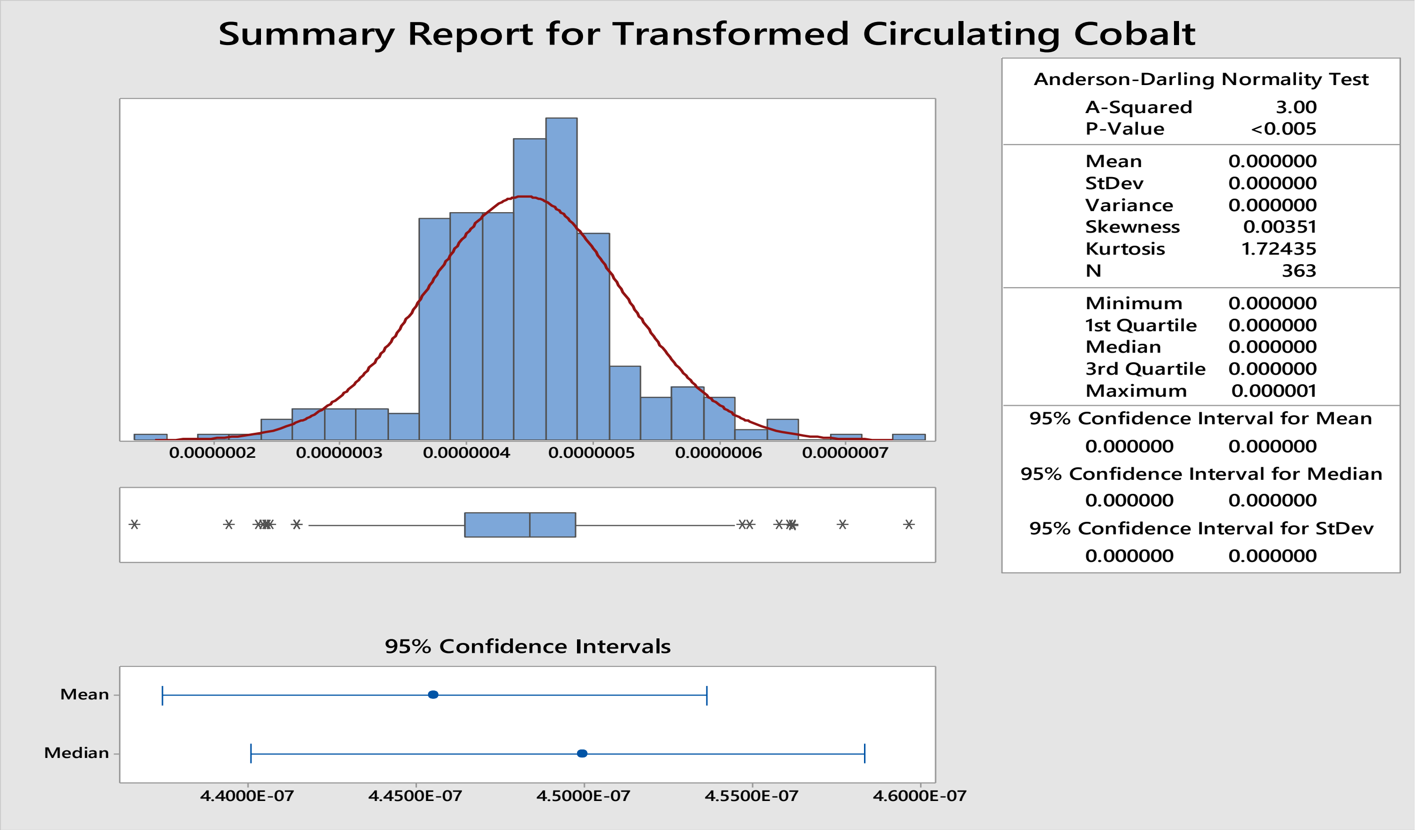
Summary Report for Transformed Spent Cobalt

Anderson-Darling Normality Test
A-Squared 4.11
P-Value <0.005

Mean 4.8830
StDev 0.0593
Variance 0.0035
Skewness 0.71721
Kurtosis 1.92810
N 363

Minimum 4.7086
1st Quartile 4.8505
Median 4.8744
3rd Quartile 4.9163
Maximum 5.1192

95% Confidence Interval for Mean
4.8769 4.8892
95% Confidence Interval for Median
4.8683 4.8813
95% Confidence Interval for StDev
0.0553 0.0640



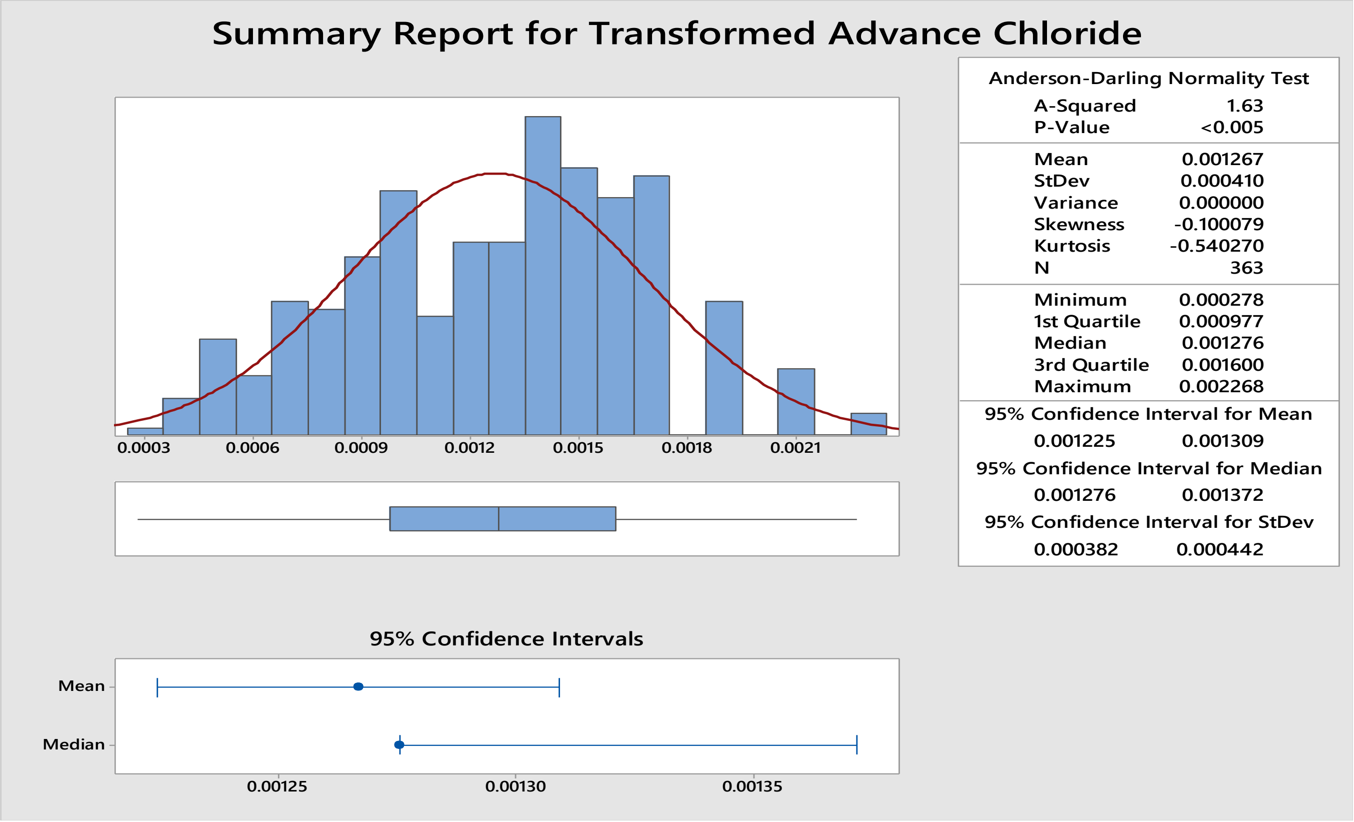
Summary Report for Transformed Circulating Cobalt

Anderson-Darling Normality Test
A-Squared 3.00
P-Value <0.005

Mean 0.000000
StDev 0.000000
Variance 0.000000
Skewness 0.00351
Kurtosis 1.72435
N 363

Minimum 0.000000
1st Quartile 0.000000
Median 0.000000
3rd Quartile 0.000000
Maximum 0.000001

95% Confidence Interval for Mean
0.000000 0.000000
95% Confidence Interval for Median
0.000000 0.000000
95% Confidence Interval for StDev
0.000000 0.000000



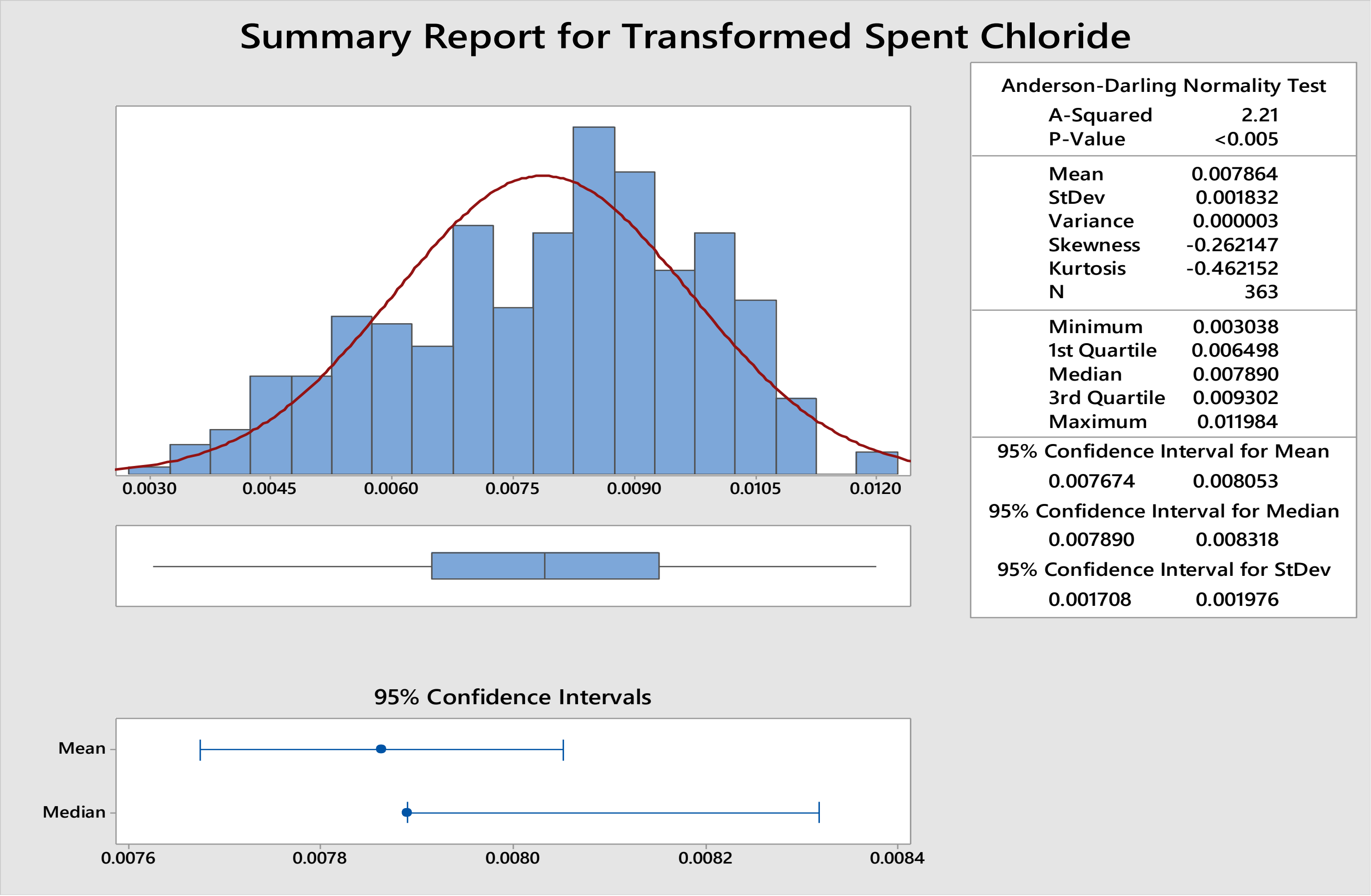
Summary Report for Transformed Advance Chloride

Anderson-Darling Normality Test
A-Squared 1.63
P-Value <0.005

Mean 0.001267
StDev 0.000410
Variance 0.000000
Skewness -0.100079
Kurtosis -0.540270
N 363

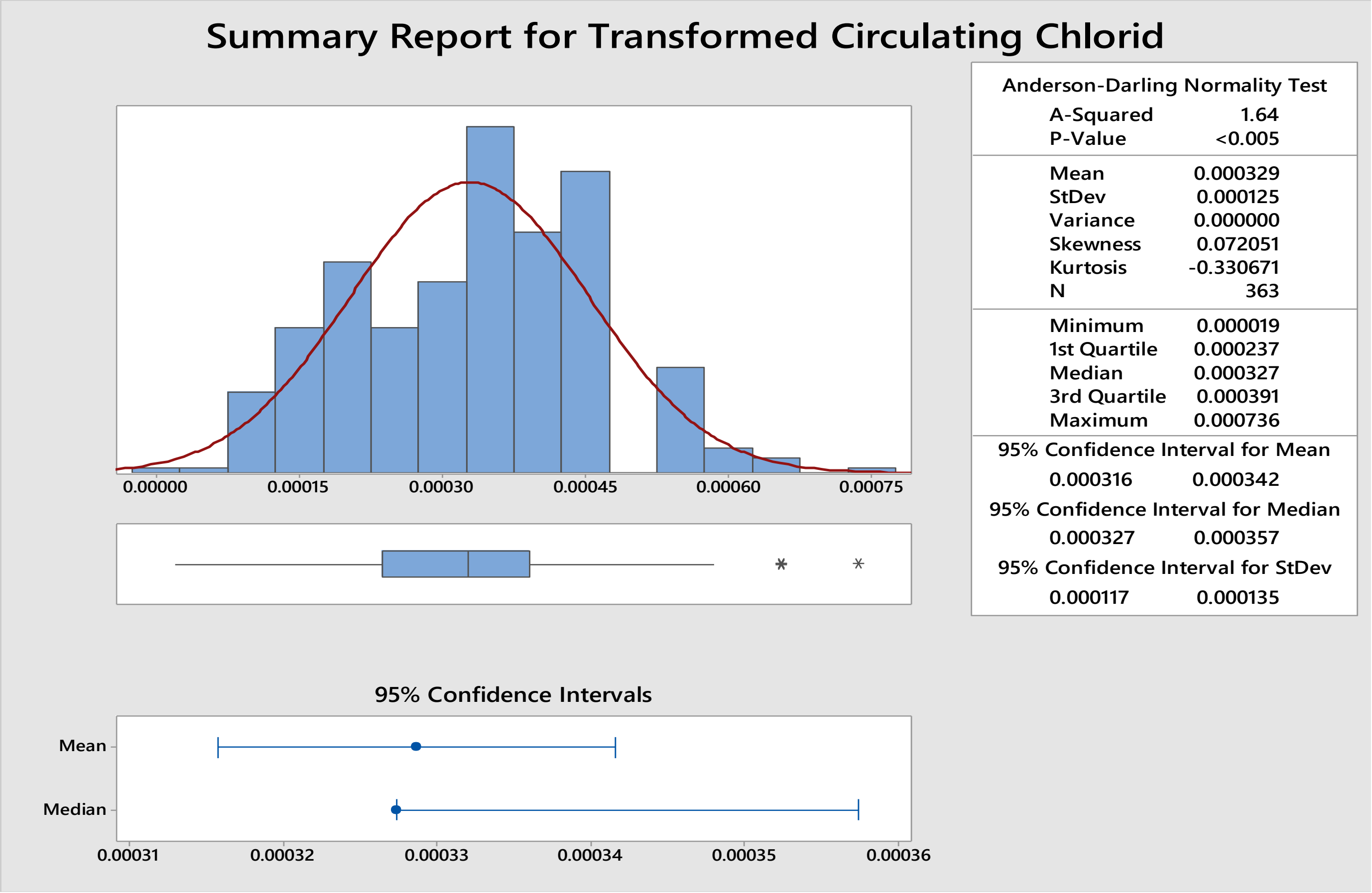
Minimum 0.000278
1st Quartile 0.000977
Median 0.001276
3rd Quartile 0.001600
Maximum 0.002268

95% Confidence Interval for Mean
0.001225 0.001309
95% Confidence Interval for Median
0.001276 0.001372
95% Confidence Interval for StDev
0.000382 0.000442



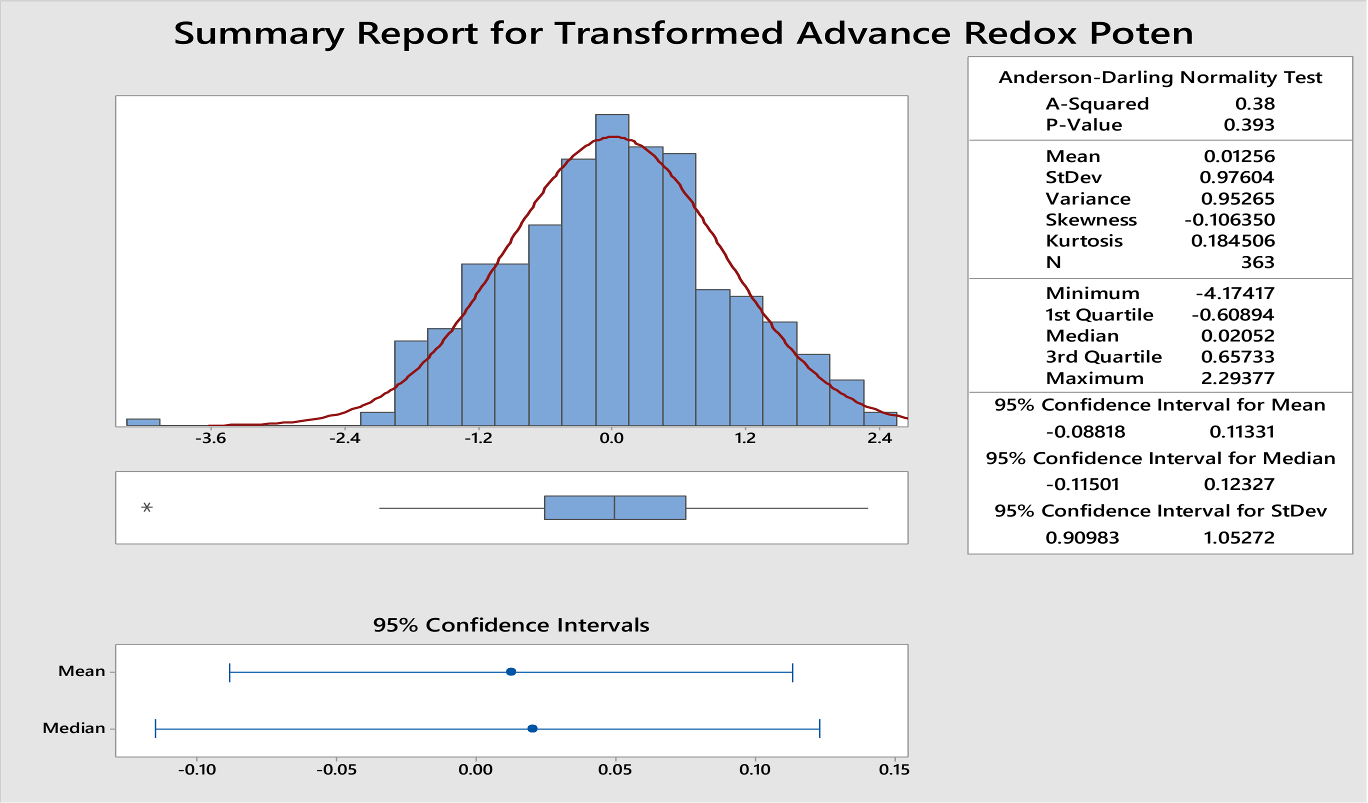
Summary Report for Transformed Spent Chloride

Anderson-Darling Normality Test	
A-Squared	2.21
P-Value	<0.005
Mean	0.007864
StDev	0.001832
Variance	0.000003
Skewness	-0.262147
Kurtosis	-0.462152
N	363
Minimum	0.003038
1st Quartile	0.006498
Median	0.007890
3rd Quartile	0.009302
Maximum	0.011984
95% Confidence Interval for Mean	
0.007674	0.008053
95% Confidence Interval for Median	
0.007890	0.008318
95% Confidence Interval for StDev	
0.001708	0.001976



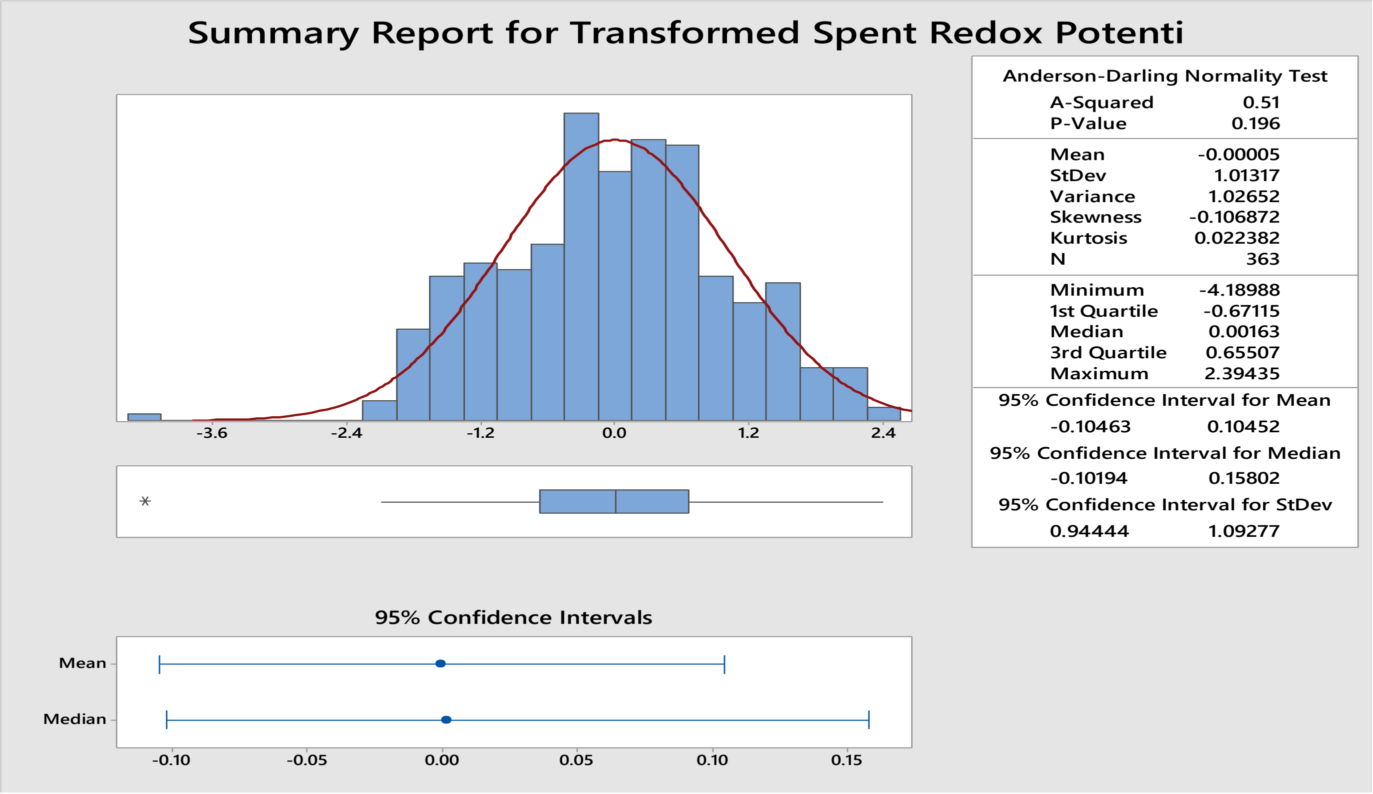
Summary Report for Transformed Circulating Chlorid

Anderson-Darling Normality Test	
A-Squared	1.64
P-Value	<0.005
Mean	0.000329
StDev	0.000125
Variance	0.000000
Skewness	0.072051
Kurtosis	-0.330671
N	363
Minimum	0.000019
1st Quartile	0.000237
Median	0.000327
3rd Quartile	0.000391
Maximum	0.000736
95% Confidence Interval for Mean	
0.000316	0.000342
95% Confidence Interval for Median	
0.000327	0.000357
95% Confidence Interval for StDev	
0.000117	0.000135



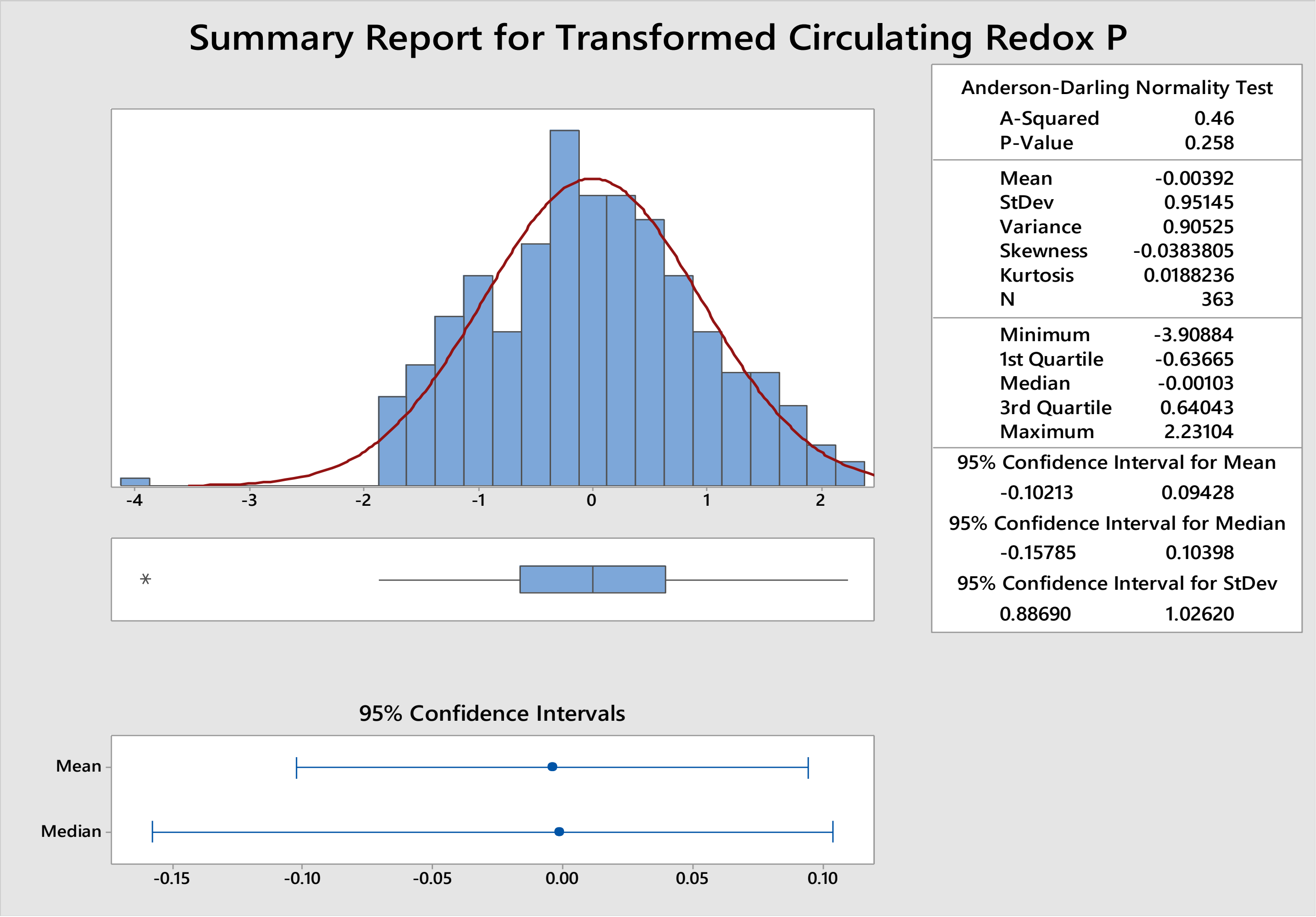
Summary Report for Transformed Advance Redox Poten

Anderson-Darling Normality Test	
A-Squared	0.38
P-Value	0.393
Mean	0.01256
StDev	0.97604
Variance	0.95265
Skewness	-0.106350
Kurtosis	0.184506
N	363
Minimum	-4.17417
1st Quartile	-0.60894
Median	0.02052
3rd Quartile	0.65733
Maximum	2.29377
95% Confidence Interval for Mean	
-0.08818	0.11331
95% Confidence Interval for Median	
-0.11501	0.12327
95% Confidence Interval for StDev	
0.90983	1.05272



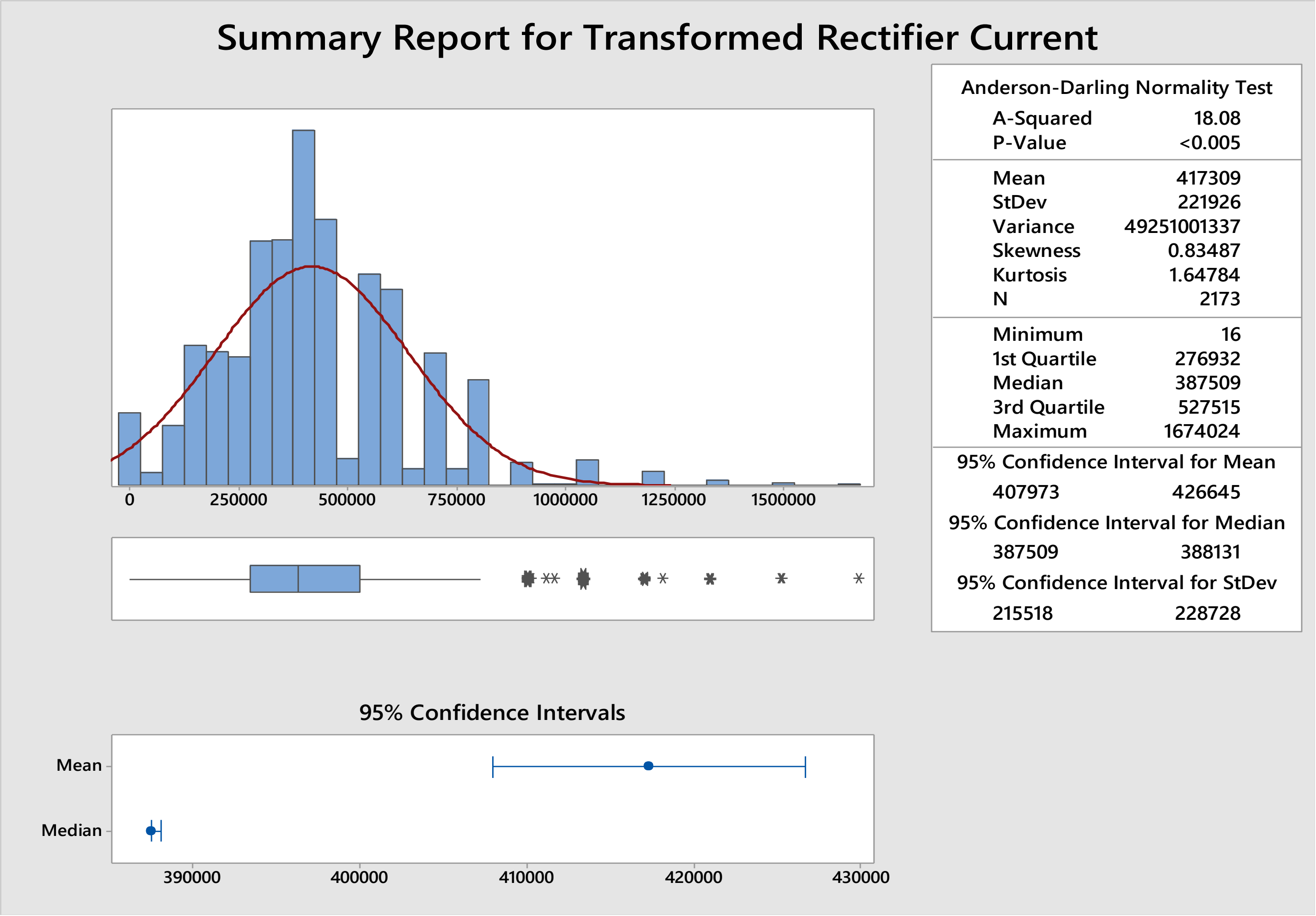
Summary Report for Transformed Spent Redox Potenti

Anderson-Darling Normality Test	
A-Squared	0.51
P-Value	0.196
Mean	-0.00005
StDev	1.01317
Variance	1.02652
Skewness	-0.106872
Kurtosis	0.022382
N	363
Minimum	-4.18988
1st Quartile	-0.67115
Median	0.00163
3rd Quartile	0.65507
Maximum	2.39435
95% Confidence Interval for Mean	
-0.10463	0.10452
95% Confidence Interval for Median	
-0.10194	0.15802
95% Confidence Interval for StDev	
0.94444	1.09277



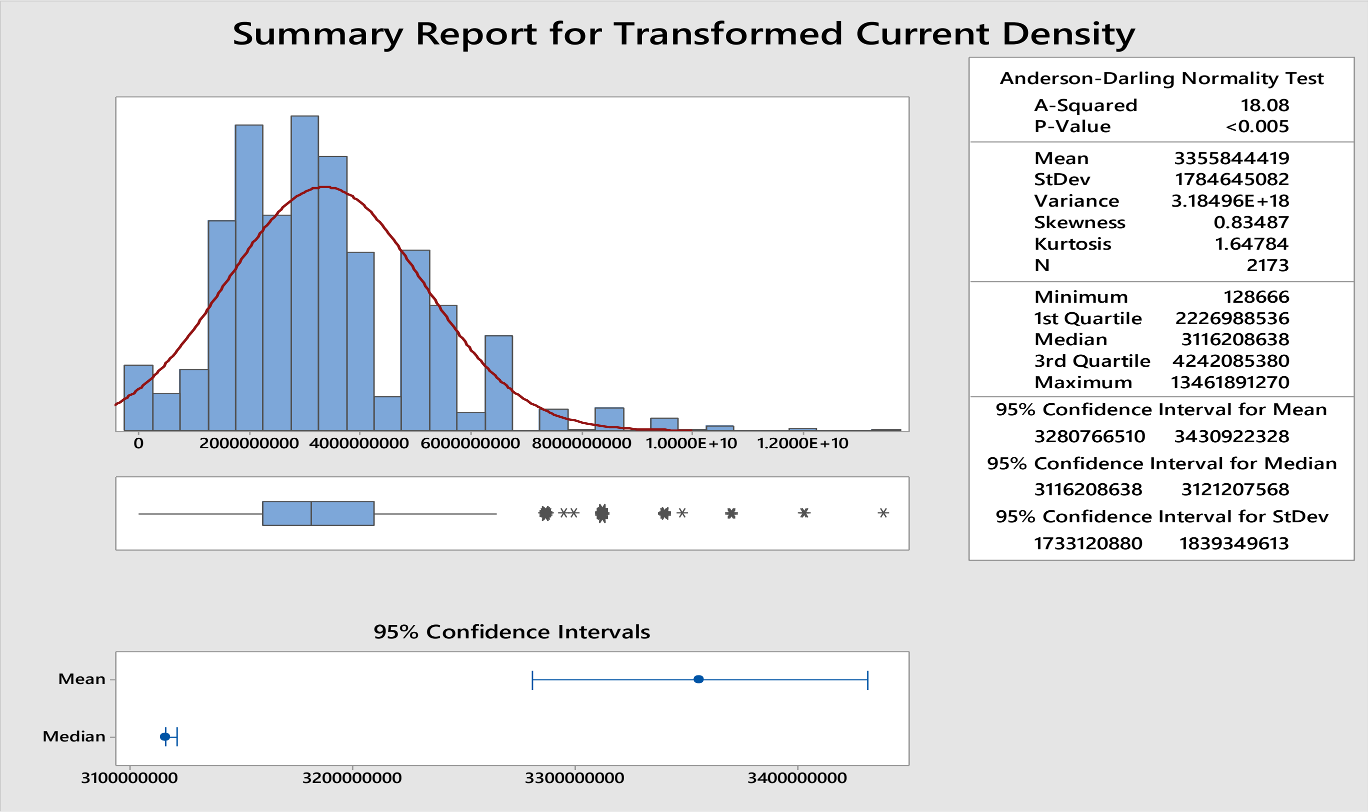
Summary Report for Transformed Circulating Redox P

Anderson-Darling Normality Test	
A-Squared	0.46
P-Value	0.258
Mean	-0.00392
StDev	0.95145
Variance	0.90525
Skewness	-0.0383805
Kurtosis	0.0188236
N	363
Minimum	-3.90884
1st Quartile	-0.63665
Median	-0.00103
3rd Quartile	0.64043
Maximum	2.23104
95% Confidence Interval for Mean	
-0.10213	0.09428
95% Confidence Interval for Median	
-0.15785	0.10398
95% Confidence Interval for StDev	
0.88690	1.02620



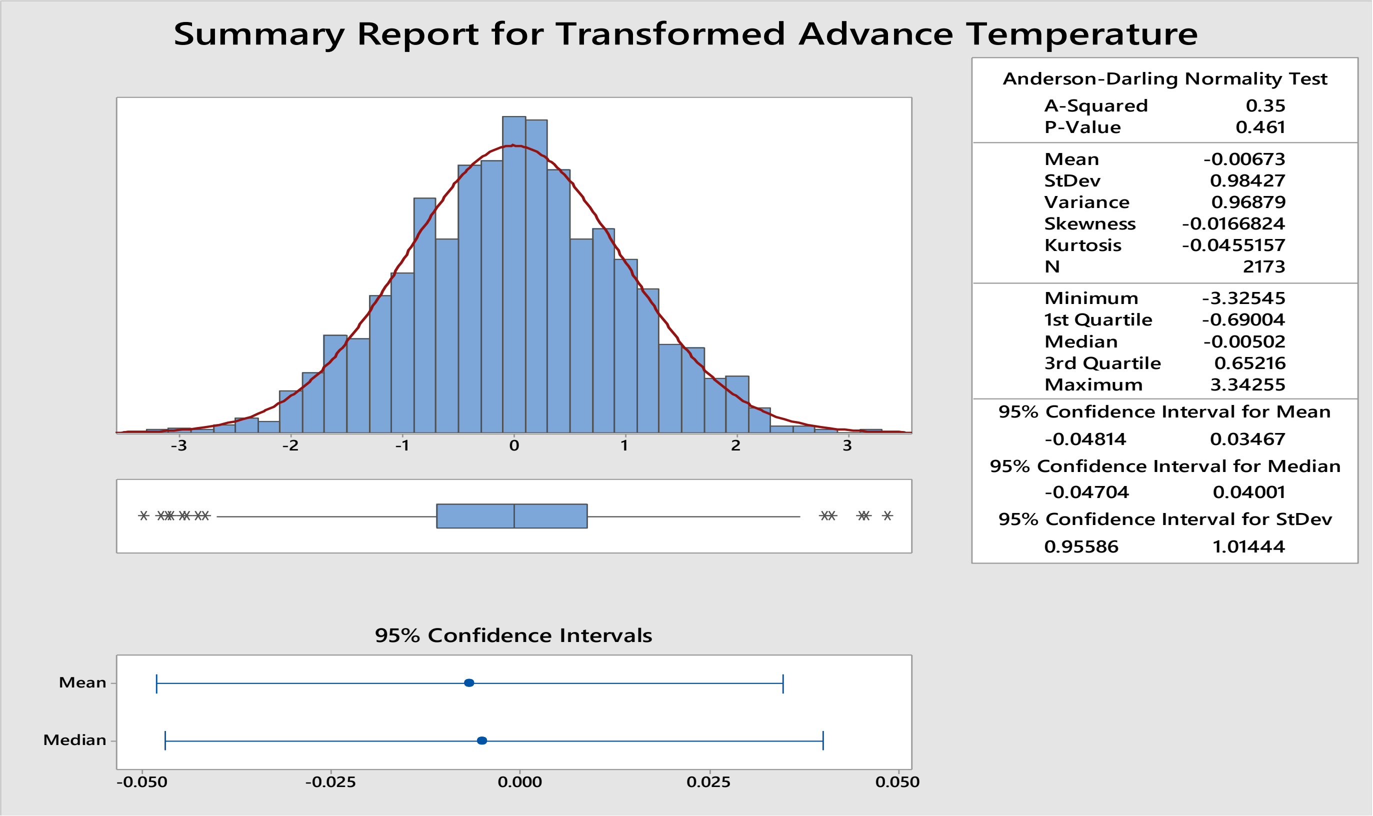
Summary Report for Transformed Rectifier Current

Anderson-Darling Normality Test	
A-Squared	18.08
P-Value	<0.005
Mean	417309
StDev	221926
Variance	49251001337
Skewness	0.83487
Kurtosis	1.64784
N	2173
Minimum	16
1st Quartile	276932
Median	387509
3rd Quartile	527515
Maximum	1674024
95% Confidence Interval for Mean	
407973	426645
95% Confidence Interval for Median	
387509	388131
95% Confidence Interval for StDev	
215518	228728



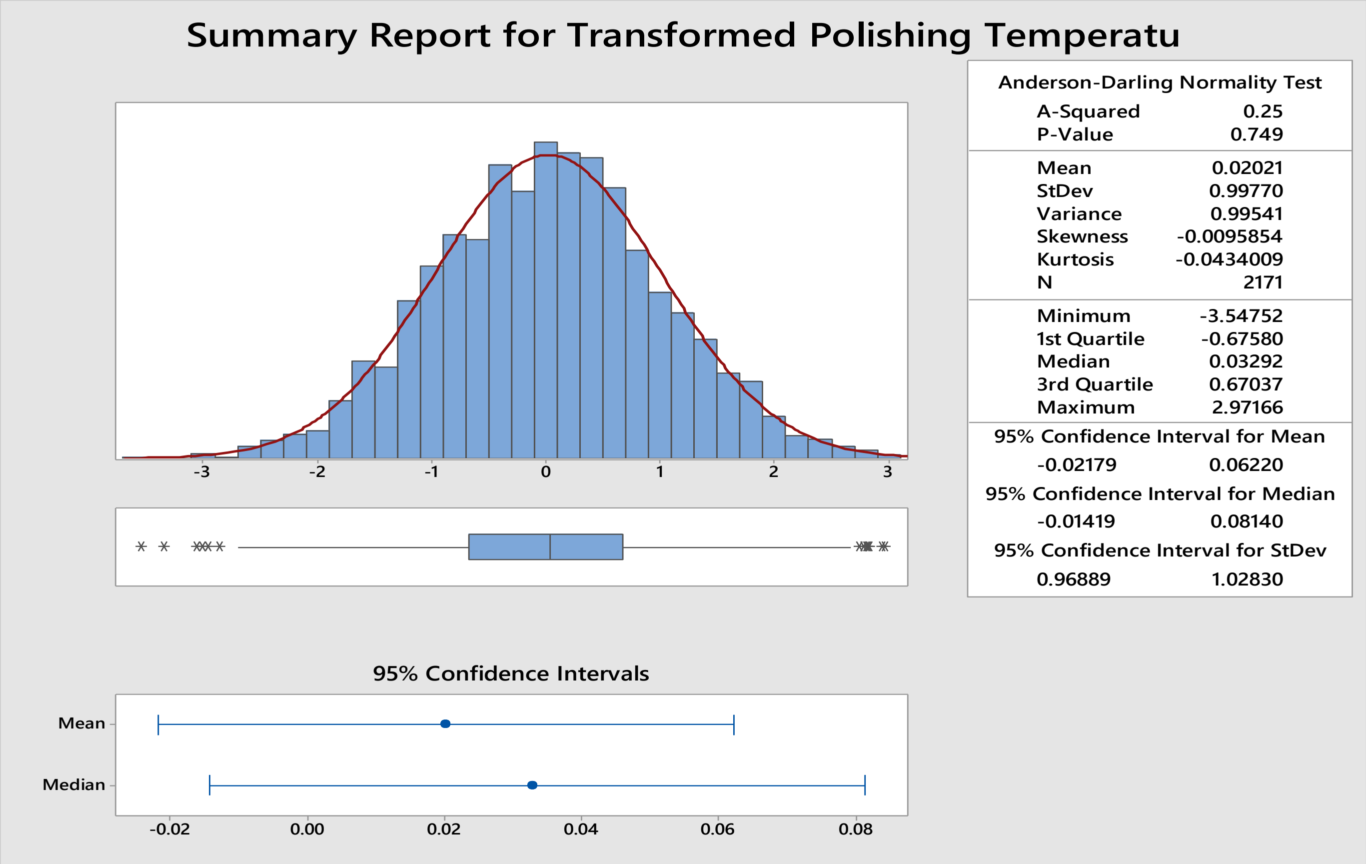
Summary Report for Transformed Current Density

Anderson-Darling Normality Test	
A-Squared	18.08
P-Value	<0.005
Mean	3355844419
StDev	1784645082
Variance	3.18496E+18
Skewness	0.83487
Kurtosis	1.64784
N	2173
Minimum	128666
1st Quartile	2226988536
Median	3116208638
3rd Quartile	4242085380
Maximum	13461891270
95% Confidence Interval for Mean	
3280766510	3430922328
95% Confidence Interval for Median	
3116208638	3121207568
95% Confidence Interval for StDev	
1733120880	1839349613



Summary Report for Transformed Advance Temperature

Anderson-Darling Normality Test	
A-Squared	0.35
P-Value	0.461
Mean	-0.00673
StDev	0.98427
Variance	0.96879
Skewness	-0.0166824
Kurtosis	-0.0455157
N	2173
Minimum	-3.32545
1st Quartile	-0.69004
Median	-0.00502
3rd Quartile	0.65216
Maximum	3.34255
95% Confidence Interval for Mean	
-0.04814	0.03467
95% Confidence Interval for Median	
-0.04704	0.04001
95% Confidence Interval for StDev	
0.95586	1.01444

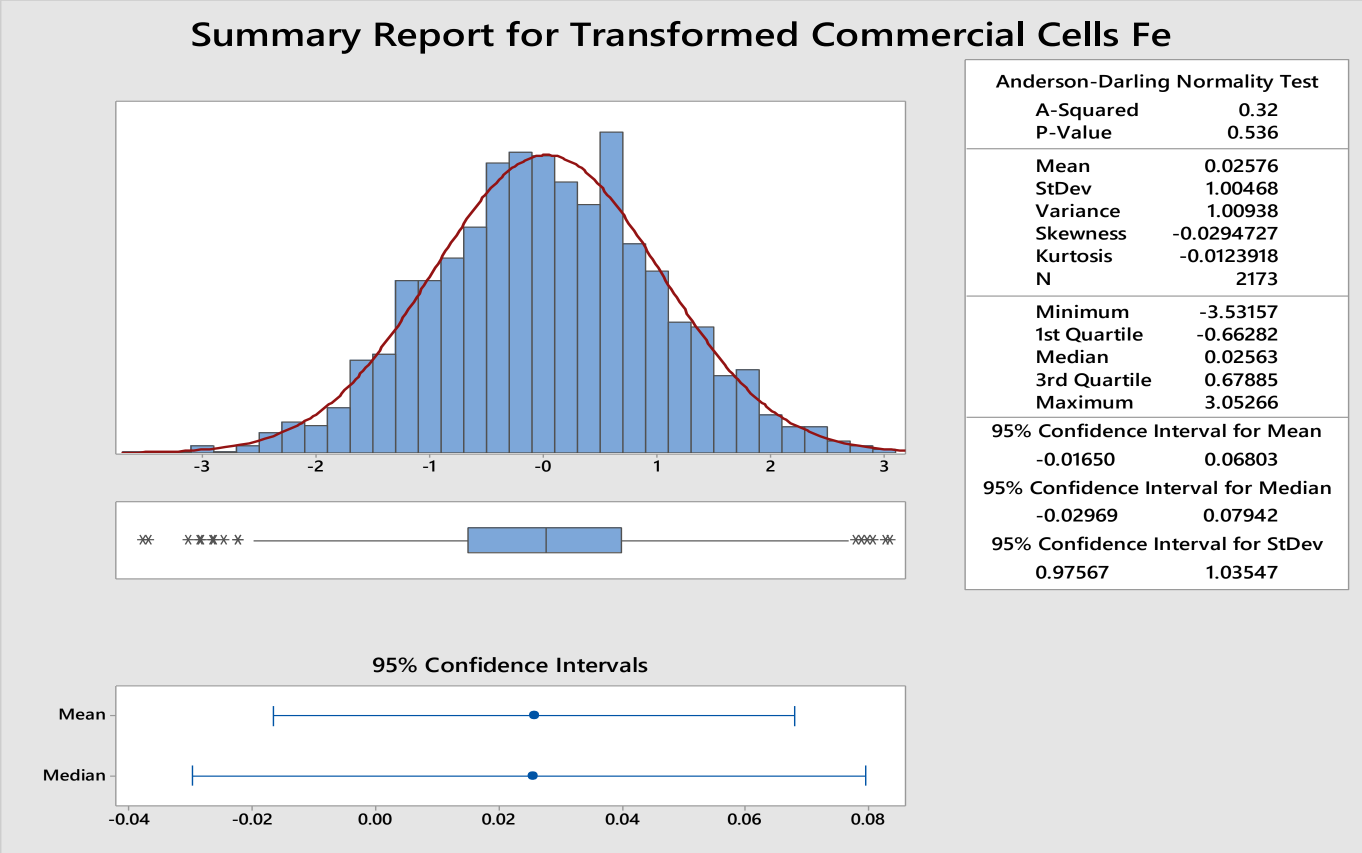


Summary Report for Transformed Polishing Temperatu

Anderson-Darling Normality Test

A-Squared	0.25
P-Value	0.749
Mean	0.02021
StDev	0.99770
Variance	0.99541
Skewness	-0.0095854
Kurtosis	-0.0434009
N	2171
Minimum	-3.54752
1st Quartile	-0.67580
Median	0.03292
3rd Quartile	0.67037
Maximum	2.97166

95% Confidence Interval for Mean	
-0.02179	0.06220
95% Confidence Interval for Median	
-0.01419	0.08140
95% Confidence Interval for StDev	
0.96889	1.02830

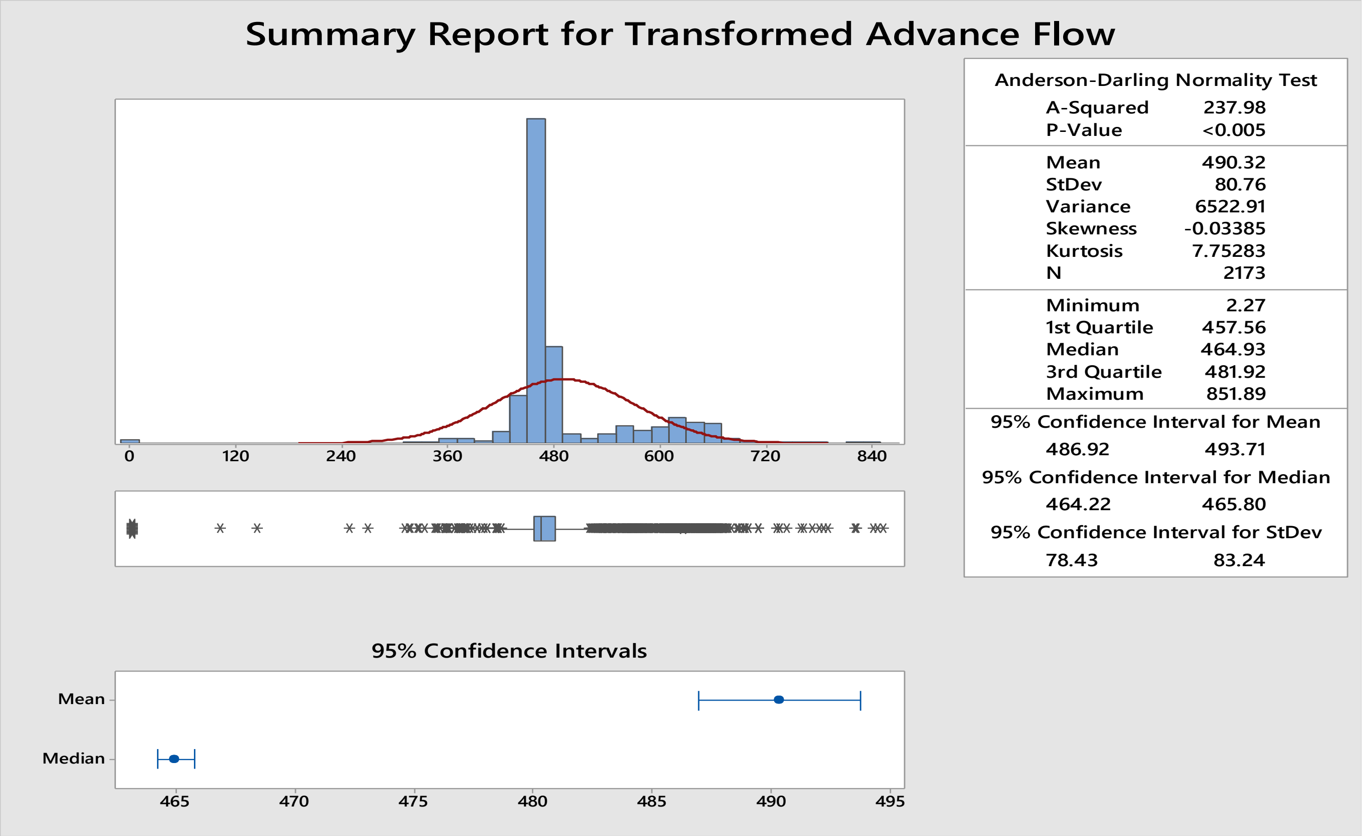


Summary Report for Transformed Commercial Cells Fe

Anderson-Darling Normality Test

A-Squared	0.32
P-Value	0.536
Mean	0.02576
StDev	1.00468
Variance	1.00938
Skewness	-0.0294727
Kurtosis	-0.0123918
N	2173
Minimum	-3.53157
1st Quartile	-0.66282
Median	0.02563
3rd Quartile	0.67885
Maximum	3.05266

95% Confidence Interval for Mean	
-0.01650	0.06803
95% Confidence Interval for Median	
-0.02969	0.07942
95% Confidence Interval for StDev	
0.97567	1.03547

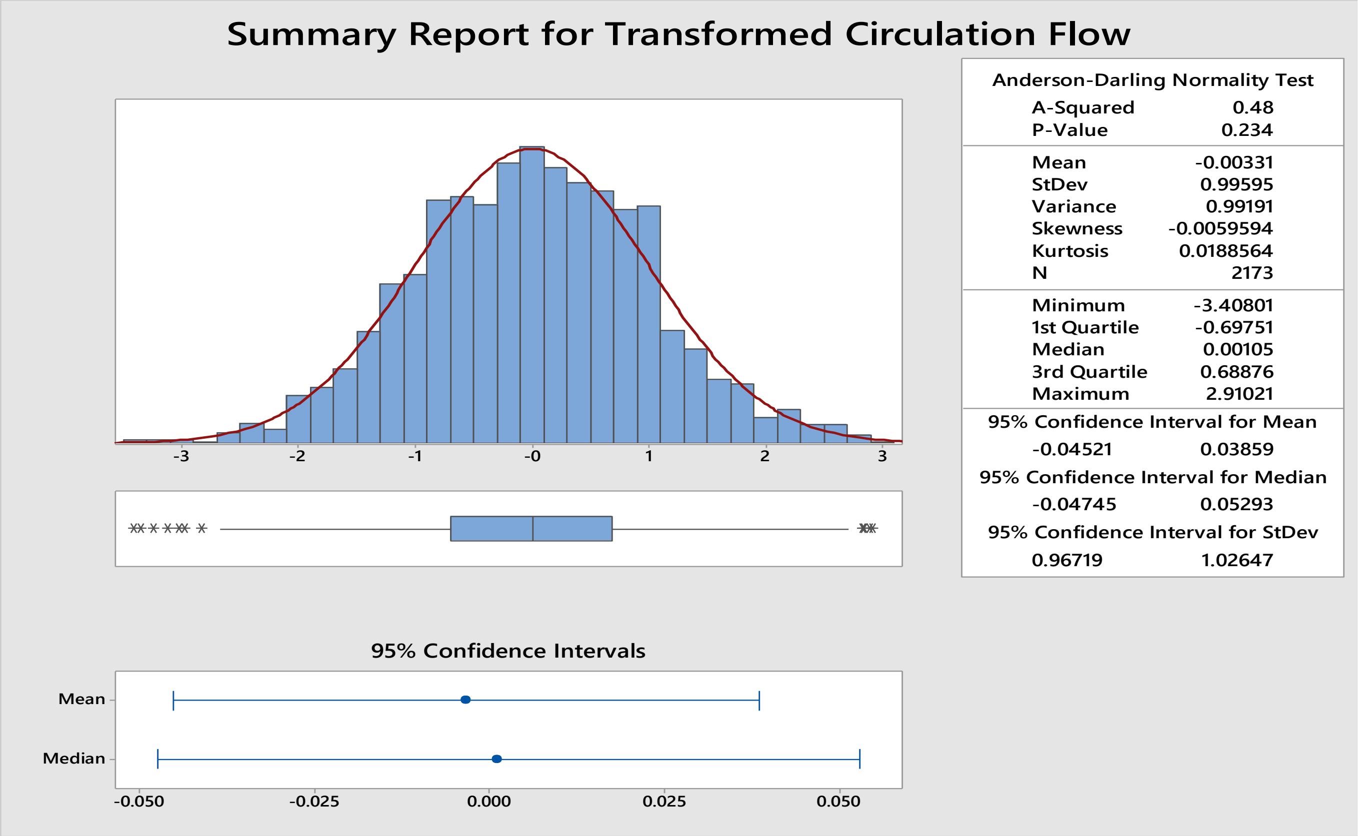


Summary Report for Transformed Advance Flow

Anderson-Darling Normality Test

A-Squared	237.98
P-Value	<0.005
Mean	490.32
StDev	80.76
Variance	6522.91
Skewness	-0.03385
Kurtosis	7.75283
N	2173
Minimum	2.27
1st Quartile	457.56
Median	464.93
3rd Quartile	481.92
Maximum	851.89

95% Confidence Interval for Mean	
486.92	493.71
95% Confidence Interval for Median	
464.22	465.80
95% Confidence Interval for StDev	
78.43	83.24

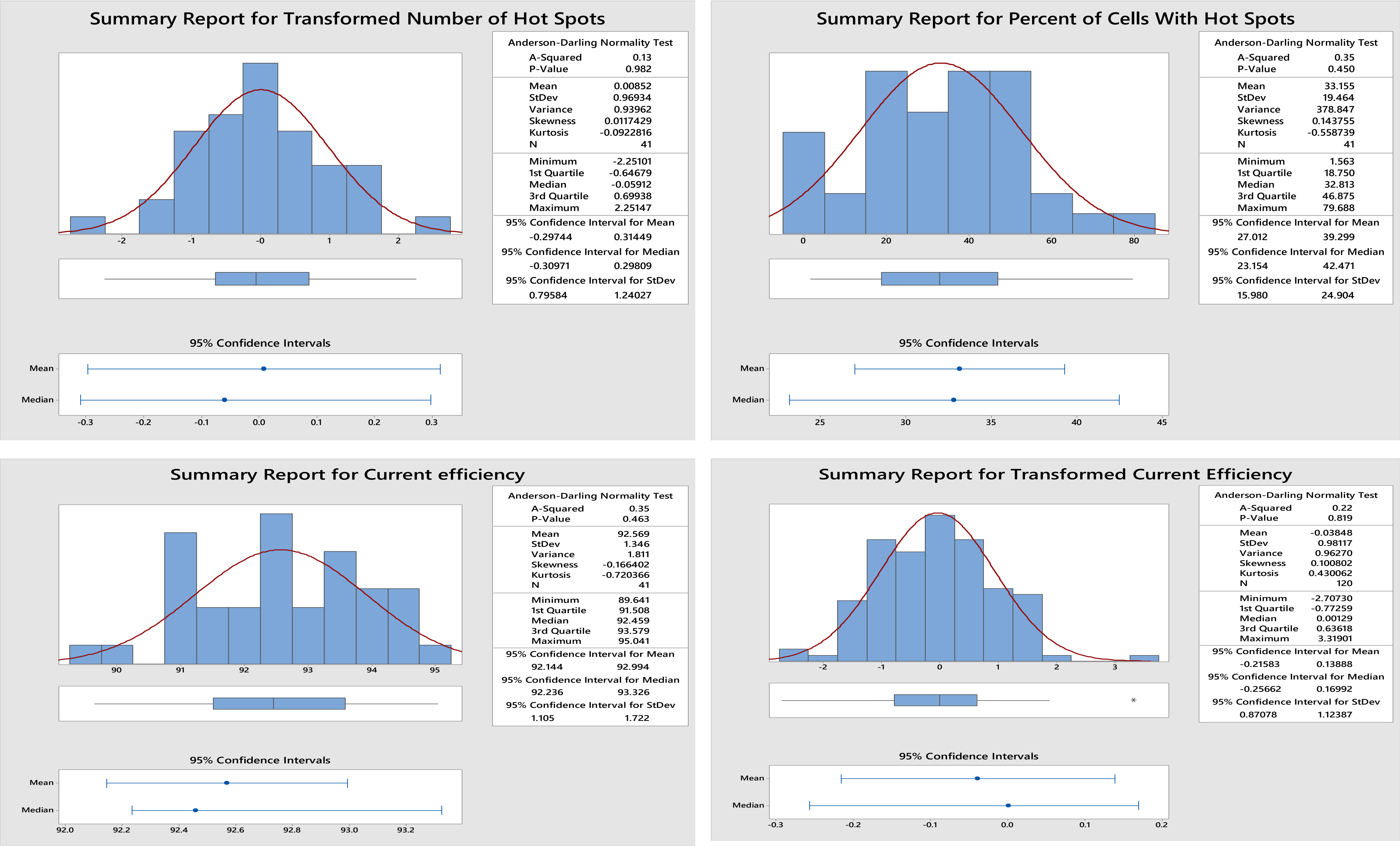


Summary Report for Transformed Circulation Flow

Anderson-Darling Normality Test

A-Squared	0.48
P-Value	0.234
Mean	-0.00331
StDev	0.99595
Variance	0.99191
Skewness	-0.0059594
Kurtosis	0.0188564
N	2173
Minimum	-3.40801
1st Quartile	-0.69751
Median	0.00105
3rd Quartile	0.68876
Maximum	2.91021

95% Confidence Interval for Mean	
-0.04521	0.03859
95% Confidence Interval for Median	
-0.04745	0.05293
95% Confidence Interval for StDev	
0.96719	1.02647



```
Anderson-Darling Normality Test
   A-Squared          0.13
   P-Value           0.982

   Mean            0.00852
   StDev           0.96934
   Variance        0.93962
   Skewness      0.0117429
   Kurtosis     -0.0922816
   N                    41

   Minimum        -2.25101
   1st Quartile   -0.64679
   Median         -0.05912
   3rd Quartile    0.69938
   Maximum         2.25147
95% Confidence Interval for Mean
   -0.29744        0.31449
95% Confidence Interval for Median
   -0.30971        0.29809
95% Confidence Interval for StDev
   0.79584         1.24027
```

```
Anderson-Darling Normality Test
   A-Squared          0.35
   P-Value           0.450

   Mean             33.155
   StDev            19.464
   Variance        378.847
   Skewness       0.143755
   Kurtosis      -0.558739
   N                    41

   Minimum           1.563
   1st Quartile     18.750
   Median           32.813
   3rd Quartile     46.875
   Maximum          79.688
95% Confidence Interval for Mean
   27.012           39.299
95% Confidence Interval for Median
   23.154           42.471
95% Confidence Interval for StDev
   15.980           24.904
```

```
Anderson-Darling Normality Test
   A-Squared          0.35
   P-Value           0.463

   Mean             92.569
   StDev             1.346
   Variance          1.811
   Skewness      -0.166402
   Kurtosis      -0.720366
   N                    41

   Minimum          89.641
   1st Quartile     91.508
   Median           92.459
   3rd Quartile     93.579
   Maximum          95.041
95% Confidence Interval for Mean
   92.144           92.994
95% Confidence Interval for Median
   92.236           93.326
95% Confidence Interval for StDev
   1.105             1.722
```

```
Anderson-Darling Normality Test
   A-Squared          0.22
   P-Value           0.819

   Mean           -0.03848
   StDev           0.98117
   Variance        0.96270
   Skewness       0.100802
   Kurtosis       0.430062
   N                   120

   Minimum        -2.70730
   1st Quartile   -0.77259
   Median          0.00129
   3rd Quartile    0.63618
   Maximum         3.31901
95% Confidence Interval for Mean
   -0.21583        0.13888
95% Confidence Interval for Median
   -0.25662        0.16992
95% Confidence Interval for StDev
   0.87078         1.12387
```

Figure 8.4: Minitab summary report for the current efficiency factors (created by the author)