



UNIVERSITY OF THE
WITWATERSRAND,
JOHANNESBURG

**Quantification of benefits of digitalisation of process data of a craft
distillery.**

Master of Science (MSc) in Chemical Engineering

RESEARCH DISSERTATION

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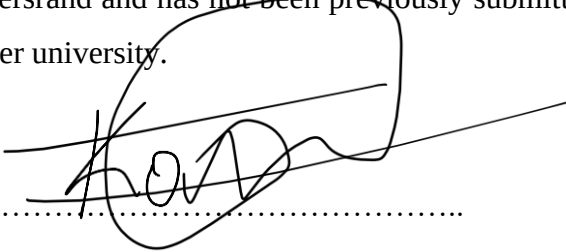
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31 December 2024

DECLARATION

I affirm that this dissertation is entirely my own work, completed without any external assistance. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand and has not been previously submitted for any other degree or examination at any other university.

A handwritten signature in black ink, appearing to be 'K. O. D.', is written over a solid horizontal line. Below the signature is a dotted horizontal line.

31st Day of December, Year 2024

ABSTRACT

Craft breweries and distilleries are frequently not digitalised, making them susceptible to regular production losses. Despite this, benefits of investing in digitalising process are often not easily measurable. The purpose of this research study is to develop a comprehensive framework to quantify the benefits of digitalising process data within the brewing process of a craft distillery. The study was based on historical data from Primal Spirit Distillery, located in Johannesburg, South Africa. The data underwent validation through the application of data visualisation techniques as well as a comprehensive statistical analysis. Mass balance calculations were conducted for the mash tun and fermentation processes, as well as an overall mass balance assessment to compare potential alcohol content with actual alcohol produced. Statistical tools, such as correlation analysis and the student t-test, were used to interpret the data and identify opportunities for digitalisation to enhance productivity. The study concluded with an economic analysis, assessing the financial implications and profitability of digitalising process data in the distillery. The conclusion of the research study highlighted the significant potential for improving productivity in craft distilleries and breweries through the digitalisation of process data. The developed framework proved effective in quantifying these benefits, encompassing steps such as historical data collection, visualisation, mass balance, statistical analysis, intervention planning, and economic feasibility assessment. The analysis revealed considerable sugar loss during mashing, with an average of 16.45%. Fermentation resulted in alcohol levels within the acceptable range in only 53.66% of instances, with an average alcohol deviation of 32.29%. The distillery, on average, operated at 67.71% of its potential alcohol production capacity. Correlation analysis and t-tests identified key variables requiring careful monitoring to reduce deviations and enhance productivity. While there are more economical alternatives, the optimal solution involves the use of affordable storage platform for process data, process control instrumentation devices, such as sensors and flow meters. The economic study indicates that a R 200,000 investment to digitalise the distillery's process data could boost productivity by 30%. The investment would be fully recovered in 4 months, with a 25.43% profit gain within 5 months. However, actual profitability may range between 10 to 20% due to potential unforeseen circumstances during production.

Keywords: Digitalisation, historical process data, craft distilleries, framework, data analysis, data validation, data accuracy, mass balance, statistical analysis, productivity, brewing process, alcohol deviation, sugar loss, economic analysis, return on investment, profitability.

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CHAPTER 1: INTRODUCTION

1.1. BACKGROUND

1.1.1. Digitalisation

Over recent years, the global industrial sector has been actively evolving its technological practices with the aim of reducing human intervention in specific domains of product manufacturing (Grau and Wang, 2020). These advancements, driven by the digital revolution, have sparked concerns about the future of employability, although they have predominantly resulted in the creation of additional job opportunities (Grau and Wang, 2020). The digital revolution, as described in this research report, represents a general acceleration in technological change within the economy, attributed to significant improvements in data storage, processing, and communication capabilities using electronic devices (Fernández-Macías, 2018). This revolution encompasses the integration of machines, control and instrumentation devices, storage systems, and software, often interconnected through local networks (Nimbalkar et al., 2020).

The digitalisation revolution is a pivotal component of the fourth industrial revolution, demanding the adoption of smart manufacturing concepts and forecasting the widespread utilisation of internet technologies in factories, thereby replacing traditional industrial components (Gunal and Karatas, 2019; Sima et al., 2020). In essence, digitalisation has opened possibilities for enhanced productivity and waste reduction (Fernández-Macías, 2018; Nimbalkar et al., 2020).

Certain industries, such as craft breweries and distilleries, have been slow to embrace digitalisation, making them susceptible to production, water, and energy losses regularly (Violino et al., 2020). However, quantifying the benefits of spending money for digitalising process unit equipment remains a challenging task. The objective of this project is to quantify the benefits of digitalisation by conducting a thorough analysis and interpretation of process data obtained from Primal Spirit Distillery, a local craft distillery located in Johannesburg, South Africa. The research aims to develop a comprehensive framework for quantifying the benefits of digitalisation. To achieve this, observations and calculations will be employed to demonstrate the potential benefits of adopting a digital approach, as opposed to relying on analogue devices or lacking appropriate measuring instrumentation.

A typical distillery process flow begins with the brewing process, followed by distillation to produce spirits. This research focuses on the brewing process within the distillery, as there is a lack of data available for the distillation section.

1.1.2. Overview of Brewing and Distilling Process

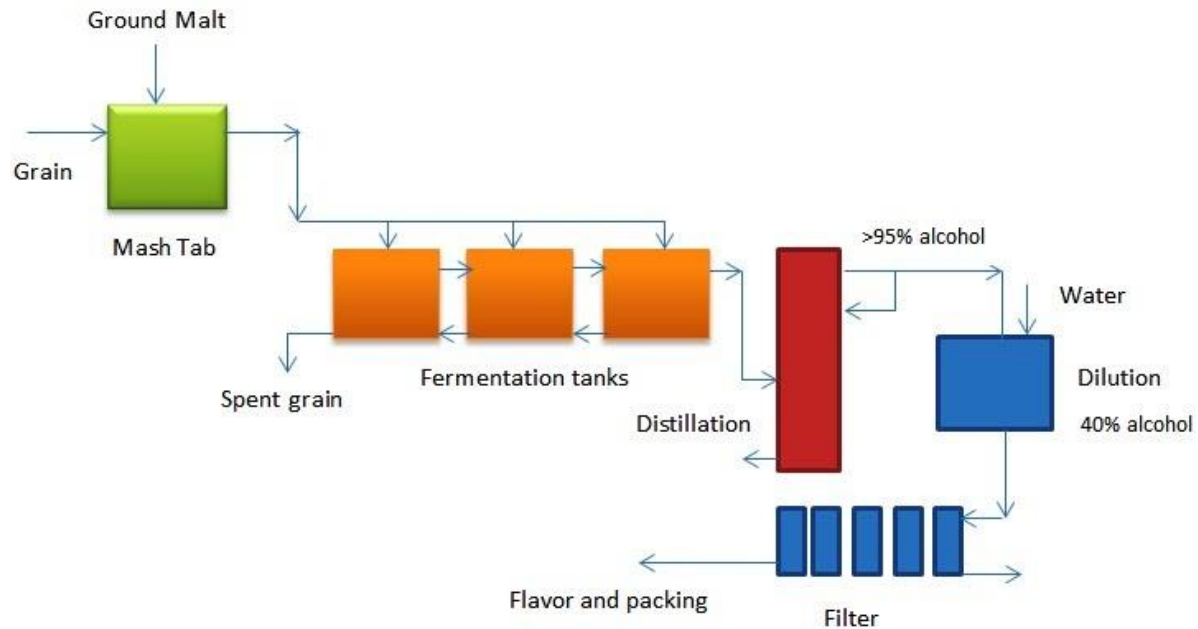


Figure 1: Overview of the Brewing and Distilling process (Vodka Production Process, 2015)

The brewing process side of a distillery involves a series of processes starting with the selection of raw materials, namely water, malted barley, hops, and yeast (Willaert, 2007). During malting, barley, and yeast naturally produce enzymes that play a crucial role in the brewing process (South African Breweries, 2017). Additional minor chemical changes occur during processes such as maturation, heat exchange, separation, and clarification (Nimbalkar et al., 2020; South African Breweries, 2017). Barley can produce all the necessary enzymes to break down starch, β -glucan, pentosans, lipids, and protein, which are essential compounds for brewing (Willaert, 2007).

The brewing process initiates with milling and mashing. Milling is the process of crushing malted barley and other grains to expose the starch inside. Furthermore, it is utilised to break down grains into smaller particles to increase their surface area and facilitate sugar extraction, also known as fermentable sugar, during mashing (Willaert, 2007). The obtained grist is mixed with hot water in a mash tun to create mash, which is then heated to a temperature range of 71

to 82 °C before being transferred into a lauter tun for wort separation, resulting in a sugar solution free from solid particles (Nimbalkar et al., 2020; Willaert, 2007). Wort contains vital nutrients that favour anaerobic yeast growth (Willaert, 2007).

Fermentation is a chemical reaction between yeast and extracted carbohydrates, converting carbohydrates into ethanol and other flavouring metabolic by-products such as carbon dioxide, releasing energy, hence, classified as an exothermic reaction (South African Breweries, 2017).

Post-fermentation, liquid mixtures undergo a purification process known as distillation to produce spirits or liquors. Distillation is a separation technology that separates liquid mixtures based on differences in their boiling points (Bone and Nixon, 2000). It involves heating the mixture to the boiling point of individual components, followed by condensation of vapours on a cold surface (Bone and Nixon, 2000). Distillation can be binary, separating a mixture into its two components such as water and ethanol, or multicomponent, separating a mixture containing ethanol, water, and several other volatile components with higher boiling points than the main components (Spaho, 2017).

Two types of distillation are distinguished: simple distillation and fractional distillation. Simple distillation begins with the vaporisation of more volatile components first such as methanol and acetone, to constitute the heads. Secondly, it is followed by less volatile ones such as ethanol with a few contaminants, to constitute the middle fraction. Lastly, the least volatile components such as amyl, butyl, and propyl alcohol will evaporate, hence, making the tails (Bone and Nixon). This type of distillation produces beverages like whiskey, rum, and brandy without clear-cut separation (Bone and Nixon, 2000). In contrast, fractional distillation involves stages at each plate of the distillation column, leading to clear-cut separation of various components in the mixture. The final products of fractional distillation are nearly pure constituents, drawn in sequence from the top of the column based on their boiling points (Bone and Nixon, 2000). Gin and vodka with 100% alcohol content are produced using fractional distillation before being diluted with water to 40% (Bone and Nixon, 2000).

1.2. Problem Statement

Craft breweries and distilleries are often not digitalised, hence, are prone to production losses regularly. However, the benefits of spending money needed to digitalise process data or unit equipment are often not quantifiable.

1.3. Research Aim and Objectives

1.3.1. Aim

The research aim is to develop a comprehensive framework capable of quantifying the benefits of digitalisation of process data and unit operation equipment within the brewing process of the distilling process plant of a local craft distillery in Johannesburg, South Africa.

1.3.2. The Objectives linked to the aim are:

- Utilise historical data for process flow analysis, specifically to calculate the amount of sugar supplied, lost, and retained in the system for alcohol production.
- Conduct statistical studies to extract relevant information from process data to enhance the significance of digitalisation efforts.
- Conduct an economic study capable of assessing the financial benefit and the profitability associated with the digitalisation of process data within the distillery.

CHAPTER 2: LITERATURE REVIEW

2.1. Digitalisation

2.1.1. Definition of the concept.

In a research report published in 2018, digitalisation is defined as the utilisation of sensors and other devices to convert physical process events into digital information (Fernández-Macías, 2018). Sensors serve as devices capable of converting analogue signals into digital data (Fernández-Macías, 2018). Digitalisation offers numerous advantages for the manufacturing industry as a whole and, specifically, for craft breweries. It enables time-to-time market responsiveness, as an intelligent and strategic implementation of industrial digitalisation in a brewery (Siemens, 2018). It can also enhance productivity to meet rapid market demands and establish a competitive edge (Siemens, 2018).

Significantly, digitalisation's primary contributions in the industry lie in the substantial cost reduction related to processing, storing, and communicating digital information, as well as the enhanced efficiency compared to using analogue equipment (Fernández-Macías, 2018). Digitisation has also brought about competitive advantages such as real-time cost of production calculation and analysis, real-time monitoring, improved financial indicators, and more informed managerial decision-making (Nimbalkar et al., 2020).

2.1.2. Digitalisation adoption challenges for manufacturing facilities in general.

For small and large facilities, the primary obstacle hindering the adoption of Industry 4.0 is the absence of a well-defined digital strategy within value-creating processes, such as production and logistics, coupled with insufficient leadership support (Nagy et al., 2018). The uncertainty surrounding the economic returns of digital investments and their associated costs instils fear in many companies, further complicating its adoption (Nagy et al., 2018).

Additionally, numerous firms lack the necessary infrastructure and protocols for the secure storage and management of data, adding another layer of complexity to implementation efforts such as pre-planned intervention protocols to minimise downtime and production losses (Nagy et al., 2018).

2.1.3. Digitalisation adoption challenges in small breweries and distilleries.

The primary drawback associated with the complete digitalisation of a craft manufacturing facility lies in the financial implications of its implementation, necessitating sometimes, a substantial upfront investment (Conduah, Kusakana, & Hohne, 2020). The secondary one is the lack of expertise in embracing digitalisation (Rose Gould, 2018).

2.1.4. Digitalisation in larger vs smaller breweries and distilleries.

The influence of digitalisation on distilleries varies between larger and smaller establishments. Larger distilleries, with their superior resources and infrastructure, are better equipped to adopt advanced digital technologies (Rose Gould, 2018). This includes the implementation of sophisticated data analytics platforms, automated production processes, and integrated supply chain management systems (Rose Gould, 2018). Conversely, smaller distilleries encounter hurdles in embracing digitalisation due to constraints such as limited financial resources and expertise (Rose Gould, 2018).

Despite these challenges, smaller distilleries are progressively leveraging digital tools like inventory management software to monitor energy consumption, reduce water waste, reduction of raw material consumption for packaging (Violinno et al., 2020; Rose Gould, 2018). Although the digitalisation process may be slower for smaller distilleries, the potential benefits are substantial, including enhanced marketing capabilities, improved inventory management, and heightened operational efficiency (Nimbalkar et al., 2020; Rose Gould, 2018).

Major breweries were early adopters of sensor technology and digitisation, a trend that initially lagged among smaller craft breweries (Violinno et al., 2020). Internet of Beer (IoB) technologies are becoming increasingly accessible to medium and small-scale brewing companies (Violinno et al., 2020). This trend is marked by a rapid uptick in the adoption of IoB systems aimed at enhancing efficiency, productivity, quality, and safety through real-time monitoring and data-driven decision support systems (Violinno et al., 2020). The cost of accessing IoB devices and software is expected to significantly decrease, while their variety in the market is set to increase, paving the way for widespread implementation across all production levels in the future (Violinno et al., 2020).

2.1.5. Digitalisation benefits for craft breweries and distilleries.

One of the key benefits of integrating solutions into production processes is the immediate access to comprehensive data. This data availability enables the development of pre-planned intervention protocols, streamlining decision-making processes and minimising unplanned downtime (Nagy et al., 2018).

Digitalisation offers numerous advantages for the manufacturing industry as a whole and, specifically, for craft breweries. It enables overcoming difficulties such as time-to-time market responsiveness, as an intelligent and strategic implementation of industrial digitalisation in a brewery (Siemens, 2018). It can also enhance productivity to meet rapid market demands and establish a competitive edge (Siemens, 2018).

Digitalisation plays a crucial role in the industry by significantly reducing costs associated with processing, storing, and transmitting digital information, while also improving efficiency over traditional analogue methods (Fernández-Macías, 2018). Moreover, digitisation offers competitive advantages, including real-time calculation and analysis of production costs, continuous monitoring, enhanced financial metrics, and more informed managerial decision-making (Nimbalkar et al., 2020).

Craft breweries and distilleries often encounter issues of quality consistency (Tamo and Hilario-Tacuri, 2020). Digitalisation is progressively remedying this problem. To address these challenges, proactive efforts are being made to implement technological advancements across all brewing stages to standardise production, improve product quality and homogeneity, as well as reduce production time (Tamo and Hilario-Tacuri, 2020; Deutsche Beverage Case study, 2018). For instance, Mike Cuddy, owner of Ghostface Brewing in Mooresville, North Carolina, claimed that digitalisation offers automation solutions that ensure consistent product quality, yielding the same product with every batch (Deutsche Beverage Case study, 2018). Notably, the Deutsche Beverage Case study (2018) demonstrated that through a combination of industry expertise and efficient technology solutions, Siemens and Deutsche Beverage technology successfully empowered a microbrewery to enhance quality and time-to-market through digitisation-driven flexibility and scalability.

2.1.6. A Few Important Concepts about Digitalisation

2.1.6.1. Smart Manufacturing (SM) & Internet of things (IoT)

The implementation of automation in craft breweries involves the integration of a localised network known as the “Internet of Things (IoT).” This IoT network enables seamless data storage, interconnectivity between various equipment, and real-time monitoring capabilities, all of which contribute to enhanced decision-making processes (Nimbalkar et al., 2020; Tamo and Hilario-Tacuri, 2020).

Smart manufacturing (SM) and the Internet of Things (IoT) represent growing technologies utilised and developed to enhance manufacturing processes (Nimbalkar et al., 2020). While defining them concisely is challenging due to their diverse advanced technologies and continuous improvements, SM and IoT can be described as the utilisation of transformed information gathered as data during manufacturing processes to make informed decisions, leading to increased productivity and efficiency, waste reduction, energy conservation, and reduced production lead time (Nimbalkar et al., 2020). These technologies encompass a wide array of tools, including process control and monitoring, instrumentation, advanced sensing, process optimisation, and practices that integrate information and communication technologies for real-time management of cost, resource utilisation, and productivity across manufacturing facilities (Nimbalkar et al., 2020). Moreover, the implementation of IoT and SM in breweries holds several advantages, including reduced manufacturing costs, heightened productivity, and improved efficiency in energy, water, and material usage (Nimbalkar et al., 2020).

Breweries can leverage IoT and SM practices to optimise their operations throughout the value chain, enhancing efficiency, productivity, and quality in their manufacturing facilities. These technologies enable real-time monitoring, facilitating data-driven decision-making and productivity improvement (Nimbalkar et al., 2020). In practice, SM and IoT find utility in various brewery processes, such as monitoring malt input to predict product yield, precisely measuring and controlling steam energy for malt mashing and boiling vessels, monitoring differential pressure across filters, identifying beer losses, and accurately measuring fermentation and its conversion efficiency (Nimbalkar et al., 2020).

For digitalisation to be effective in a microbrewery, seamless connectivity between equipment, sensors, and computers is essential (Siemens, 2018). Companies like Deutsche Beverage have implemented Siemens PROFIT communications protocol to enhance connectivity in their solutions. This protocol allows data transfer over Ethernet, enabling remote access to

automation equipment for diagnostic and maintenance information (Siemens, 2018). The remote access capability also reduces operational costs, as experts can access information, diagnose issues, and provide advice without physically visiting the brewery premises (Siemens, 2018).

Implementing a network system for information distribution using industrial ethernet is recommended for the manageability of food enterprises to optimise business processes, increase transparency and traceability, as proposed by Mustafina et al. (2020). Digital technologies provide competitive advantages, including real-time cost of production calculation and analysis, real-time production monitoring, increased production, and financial indicators, and crucially, support for managerial decision-making (Mustafina et al., 2020). Additionally, digitalisation of business processes enables optimisation of equipment systems' loading and operating modes to ensure parameterised values are adhered to (Mustafina et al., 2020).

2.1.6.2. Sensors and devices

The integration of IoT and smart manufacturing involves connecting equipment through a local network capable of seamless interaction with computers, controllers, sensors, and other devices (Nimbalkar et al., 2020). That connectivity is important for processes to be carried out effectively. For the brewing process, temperature monitoring and control play a role in adhering to predefined profiles specific to each brand being brewed (Willaert, 2007). To ensure optimal fermentation conditions and prevent undesired temperature ramps or overheating of vessels, thermostats are commonly utilised (Tamo and Hilario-Tacuri, 2020). Temperature ramps have a direct impact on the flavour of the beer, which is why they are carefully tailored for each beer type (Tamo and Hilario-Tacuri, 2020). Typically, thermostats are equipped with actuators, enabling the manipulation of heaters and fridges to precisely regulate temperatures during the brewing process (Tamo and Hilario-Tacuri, 2020).

2.1.6.3. Impact of Automation: Quality and Product Consistency

The brewing industry is currently offering a range of advantages and challenges. One significant challenge involves the rapid evolution of beer recipes and the standardisation of homemade brews (Tamo and Hilario-Tacuri, 2020). Craft breweries, in particular, experience lengthier beer production times compared to larger breweries and often encounter issues of quality inconsistency (Tamo and Hilario-Tacuri, 2020). To address these challenges, proactive

efforts are being made to implement technological advancements across all brewing stages to standardise production, improve product quality and homogeneity, as well as reduce production time (Tamo and Hilario-Tacuri, 2020; Deutsche Beverage Case study, 2018).

According to Mike Cuddy, owner of Ghostface Brewing in Mooresville, North Carolina, digitalisation offers automation solutions that ensure consistent product quality, yielding the same product with every batch (Deutsche Beverage Case study, 2018). Notably, the Deutsche Beverage Case study (2018) demonstrated that through a combination of industry expertise and efficient technology solutions, Siemens and Deutsche Beverage technology successfully empowered a microbrewery to enhance quality and time-to-market through digitisation-driven flexibility and scalability.

2.1.6.4. Time to market, Efficiency and Economic impact.

In response to the rapid development of craft beer recipes and the substantial growth in demand for craft beer production, researchers emphasise the necessity of digitalisation to achieve better quality, consistency, and increased production capacity to meet market demands (Tamo and Hilario-Tacuri, 2020; Siemens, 2018).

A case study conducted by Siemens Industry for Deutsche Beverage in 2018 revealed numerous advantages of digitalisation for craft breweries, including improved time-to-market and overall efficiency. Time-to-market is crucial for craft brewers, and digitalisation facilitates the ramping up of production to meet rapid market demand (Siemens, 2018). Moreover, digitalisation enables the optimisation of fermentation capacity through the implementation of an automated optimal fermentation profile, avoiding unnecessary delays in fermentation tanks (Siemens, 2018).

Additionally, digitalisation presents a significant advantage for microbreweries working with limited manpower, as it enhances production efficiency and competitiveness (Siemens, 2018). To foster competitiveness, Deutsche Beverage Technology offers microbreweries digital systems with features such as remote access, smart controls, and integrated process system communication technologies. The adoption of digital systems streamlines commissioning, reduces wiring costs, and minimises the need for individual push buttons and common points (Siemens, 2018).

In an analysis by Mustafina et al. (2020) conducted in a small non-alcoholic beer enterprise, the introduction of an automated process control system proved beneficial in developing an

effective investment strategy in the face of growing market competition. The economic investment assessment of introducing a new automated bottling line for beer in glass bottles with automatic pallet packaging, forecasted a 32% increase in labour productivity and a 57% increase in productivity by the cost method (Mustafina et al., 2020). These findings demonstrate the positive impact of digital technologies on productivity and overall business performance in the brewing industry.

2.1.6.5. Energy Need & Consumption

In recent times, researchers have focused on environmental degradation as a critical area of development (Bölük and Mert, 2014). Simultaneously, energy cost has emerged as a significant concern in various industries, including microbreweries (Nassary and Nasolwa, 2019). The energy sector's indispensability stems from the rising global demand in the industrial sector and production requirements (Nassary and Nasolwa, 2019). Studies predict an average annual increase of 1.2% in global industrial sector energy from 2012 to 2040 (Nassary and Nasolwa, 2019). Given the paramount importance of environmental and energy management aspects, there is a pressing need for innovative and sustainable solutions to reduce energy consumption and mitigate greenhouse effect (GHE) carbon emissions (Iwata and Okada, 2014).

To address these challenges, various initiatives and practical measures have been implemented to reduce energy consumption in industries, including microbreweries. One such initiative involves improving the power factor of the power supply system to optimise energy efficiency (Conduah, Kusakana, and Hohne, 2020). Additionally, the adoption of digital devices for monitoring energy consumption and efficient production planning has been explored to enhance energy management (Conduah, Kusakana, and Hohne, 2020). These strategies aim to prioritise energy efficiency and sustainable practices in the context of environmental conservation and economic viability.

2.1.6.6. Real-time monitoring & Energy Reduction

In 2020, a team of three scientists conducted an optimisation study at a microbrewery situated in Bloemfontein, South Africa, with the objective of analysing the energy consumption data pattern and identifying potential areas for reducing energy usage to lower monthly electricity bills (Conduah, Kusakana, and Hohne, 2020). To achieve this goal, they installed a digital real-time monitoring device known as the “Power Energy Logger 103 (PEL 103)” at the microbrewery’s distribution box (Conduah, Kusakana, and Hohne, 2020). The PEL 103 is a power quality analyser designed to measure and store crucial energy consumption data without

power interruption, facilitating precise analysis (Power Energy Logger, 2022). It provided load per unit time, enabling the identification of areas where consumers could potentially reduce electricity bills (Conduah, Kusakana, and Hohne, 2020; Power Energy Logger, 2022).

The PEL 103 was chosen for its ability to record and display real-time energy consumption data. The collected data is stored either on the device's internal memory or a removable memory card, which can be extracted using universal serial bus (USB), Bluetooth, or Ethernet connections and displayed on a computer in the form of graphs or tables with a time scale (Conduah, Kusakana, and Hohne, 2020; Power Energy Logger, 2022).

The real-time monitoring using the power quality analyser (PEL 103), proved beneficial in determining the energy consumption for each piece of equipment or system, as identified by Conduah and colleagues in 2020. The analysis revealed that energy was primarily consumed during peak billing periods under the time-of-use (ToU) tariff, with wort boiling being the most energy-intensive process during brewing (Conduah, Kusakana, and Hohne, 2020). Other energy-intensive steps accounting for significant energy usage during peak consumption were water heating, mashing, and refrigeration (Conduah, Kusakana, and Hohne, 2020). The real-time monitoring of energy consumption allowed the researchers to deduce the energy usage of each equipment in the microbrewery, and by comparing load consumption per equipment, they could determine the most energy-consuming systems. With this valuable information, production can be optimised for better energy efficiency (Conduah, Kusakana, and Hohne, 2020).

2.1.6.7. Time of use (ToU) & Efficiency

Energy optimisation necessitates access to digital information regarding energy consumption patterns. Conduah and colleagues (2020) conducted an analysis on the concept of Time of Use (ToU), a tariff structure implemented by the Mangaung municipality, wherein prices fluctuate based on the time of day and season (Conduah, Kusakana, and Hohne, 2020). During winter, higher energy demand is observed compared to summer, and off-peak rates are lower than standard rates (Conduah, Kusakana, and Hohne, 2020). To address this dynamic pricing, they proposed a control system to optimally schedule each brewing process based on energy consumption and ToU rates (Conduah, Kusakana, and Hohne, 2020).

2.1.6.8. Power Factor

Optimising energy consumption involves not only considering Time of Use (ToU) but also improving the power factor of the power supply system (Conduah, Kusakana, and Hohne, 2020). The power factor represents the ratio of power output to input and serves as an indicator of the energy efficiency of mechanical equipment or systems, such as pumps, motors, and fans (Thollander and Palm, 2012). Recent research highlights that energy reduction can be achieved by replacing old and inefficient small single equipment with more efficient alternatives, thereby enhancing energy management, and reducing energy losses (Thollander and Palm, 2012).

Practical strategies include replacing inefficient small single air conditioning units, utilising waste biogas, and upgrading lighting systems for improved boiler automation, refrigeration load rescheduling, and compressor sequencing to adopt more efficient practices (Thollander and Palm, 2012).

By analysing ToU data alongside equipment load and efficiency, the researchers concluded that precise scheduling and control of each brewing process are crucial to maintain beer quality, while simultaneously reducing both peak demands and total electricity costs (Conduah, Kusakana, and Hohne, 2020; Thollander and Palm, 2012).

2.2. Data Analysis

2.2.1. Overview and Definition of Concept

Data analysis is a crucial process involving specific calculations and assessments to extract relevant information from collected data (Ibrahim, 2015). Researchers heavily rely on data analysis to draw meaningful conclusions, making it an essential tool that enhances the effectiveness and reliability of research (Alem, 2020). The core stages of data analysis typically include data collection, analysis, interpretation, and evaluation (Egger and Carpi, 2008). However, it is essential to acknowledge that data analysis methods may vary based on the field of study (Ibrahim, 2015). Scientists must carefully select the most relevant data for their research and decide on appropriate processing and analysis techniques to generate a meaningful dataset, drawing upon their prior knowledge (Egger and Capri, 2008).

Ibrahim (2015) emphasises the importance of accurate data collection for conducting reliable data analysis. The initial step involves identifying the data sources, followed by effective extraction of pertinent information, which may involve cleaning, manipulation, and

reorganisation of the collected data (Ibrahim, 2015). Once the prerequisites are met, the actual data analysis can commence. The analysis entails studying the data to unveil underlying patterns and truths (Ibrahim, 2015). This process makes the data accessible for further operations aimed at drawing conclusions and subsequent manipulations. Adequate data organisation is crucial to facilitate the data analysis process. However, the complexity of data analysis may vary depending on the specific study (Ibrahim, 2015).

After conducting the analysis, researchers express their findings qualitatively or quantitatively, providing a meaningful basis for decision-making and conclusions (Alem, 2020). The next step involves evaluating and explaining the data. Scientists rely on their background knowledge, experience, and expertise while interpreting data to identify patterns and trends discovered during research (Egger and Capri, 2008). They also establish connections between their findings and pre-existing scientific theories. While this interpretation can be subjective due to the individualised nature of knowledge, it is subjected to scrutiny through the peer review process (Egger and Capri, 2008).

2.2.2. Types of Data Analysis

Data analysis encompasses both qualitative and quantitative methods, with the choice depending on the nature of the study. Qualitative data analysis employs various techniques and procedures to transform gathered qualitative data into explanations, understandings, or interpretations of the subjects under investigation, typically grounded in an interpretative philosophy (Alem, 2020). In essence, qualitative data analysis deals with non-numerical information, such as text documents, audio and video recordings, photographs, and interview transcripts (Alem, 2020).

On the other hand, quantitative data is expressed numerically, with values ranging from large to small (Alem, 2020). We can distinguish between situations that are likely to be true reflections of the behaviour of a language or variety and those that are just accidental occurrences using quantitative analysis (Alem, 2020). However, the picture of data obtained from quantitative analysis is comparatively less comprehensive than that from qualitative analysis (Alem, 2020). Thus, quantitative analysis sometimes serves as an idealisation of the facts and tends to overlook uncommon occurrences (Alem, 2020).

2.2.3. Representation and Analysis of Data

In accordance with Ibrahim's (2015) article on "The Art of Data Analysis," the steps involved in data analysis are closely tailored to the nature of the study. After the collection and categorisation of data, researchers may follow the sequence of graphical representation, measures of location, measures of variation, measures of relationship, and utilisation of statistical inference.

Graphical representation involves the creation of bar charts and histograms to visually depict the data (Ibrahim, 2015). Measure of location includes the computation of the sample data's mean, median, and mode. Measure of variation entails calculating parameters like range, standard deviation, and variance (Ibrahim, 2015). For investigating relationships between two variables, researchers may employ parameters of relationship measurement, such as regression and correlation (Ibrahim, 2015; Alem, 2020).

The process of drawing conclusions and making decisions about the population based on sample data is known as statistical inference (Ibrahim, 2015; Alem, 2020). To facilitate decision-making, researchers select the suitable statistic methods for estimation and testing of hypothesis (Ibrahim, 2015; Alem, 2020).

Here are a few expressions of measures of location, variation, variance, and relationship:

$$\text{Arithmetic mean} = \bar{x} = \frac{\sum x}{n} = \frac{x_1 + x_2 + \dots + x_n}{n} \quad (1)$$

With x: sample values and n: total number of values.

$$\text{Median} = \text{median} = \left(\frac{n+1}{2} \right) \text{th value of data} \quad (2)$$

$$\text{Standard Deviation: } SD = \sqrt{\frac{\sum (x - \bar{x})^2}{n}} \quad (3)$$

$$\text{Correlation: } r = \frac{\sum xy - n\bar{x}\bar{y}}{\sqrt{(\sum x^2 - n\bar{x}^2)(\sum y^2 - n\bar{y}^2)}} \quad (4)$$

For estimation of large sample, the following is used:

$$\bar{x} \pm 1.96 \frac{\sigma}{\sqrt{n}} \quad (5)$$

For estimation of small sample, the following is used:

$$\bar{x} \pm t \frac{s}{\sqrt{n}} \quad (6)$$

A proficient understanding of statistics and precise data analysis is imperative for effective decision-making and drawing accurate conclusions. Without a solid foundation in these disciplines, the obtained findings could potentially lead to erroneous interpretations and conclusions.

2.2.4. Sharing of Data

Utilising platforms such as public databases to record, access, and share collected data is highly recommended in scientific research (Egger and Capri, 2008). The establishment of open and accessible databases is considered a significant advancement in the science, promoting better research through data sharing (Mauthner and Parry, 2013). This concept of open access to research data was first introduced in the 1950s with the establishment of World Data Centres, aiming to mitigate data loss risks and maximize data accessibility (Shapley and Hart, 1982).

Recent advancements in technology, including sophisticated computers and information technology, have led to an exponential increase in data generation, making data sharing and preservation more feasible and efficient (Mauthner and Parry, 2013). The Organisation for Economic Cooperation and Development (OECD) has recognised the global importance of such databases, considering them a crucial component of the global science system's infrastructure (Mauthner and Parry, 2013). Consequently, these platforms offer researchers and the public the opportunity to access, download, and utilise data for their own research, analysis, and interpretation (Egger and Capri, 2008). By publishing data and their analysis methods, scientists further contribute to knowledge dissemination and encourage future research endeavours utilising their data (Egger and Capri, 2008).

2.2.5. Advantages and disadvantages of quantitative analysis

In an article published by Alem (2020), one can find few advantages and disadvantages of qualitative analysis. The advantages of quantitative analysis are as follows:

- Scientific rigour: Quantitative data analysis employs a range of statistical techniques grounded in probability and mathematics to derive meaningful insights from numerical data.

- Confidence in findings: By subjecting the data to statistical tests of significance, researchers can enhance the credibility of their interpretations and increase their confidence level in the results obtained.
- Precise measurement: Quantitative data analysis offers a robust framework for accurately describing and analysing numerical data, enabling researchers to obtain precise measurements.
- Effective presentation: Organising quantitative data into tables and charts facilitates clear and efficient presentation of research outcomes to others.

The disadvantages of quantitative analysis are as follows:

- Data quality: The accuracy of quantitative data heavily depends on the rigour and precision of data collection procedures and the appropriateness of the questions used. The saying 'Rubbish in, rubbish out' holds true, emphasising the importance of high-quality data inputs to ensure reliable analysis outcomes.
- Technician tendency: There is a potential risk in quantitative analysis where researchers may excessively focus on the intricacies of analytical methods, possibly neglecting the broader research questions and underlying issues that drive the investigation.
- Handling large data sets: While the ability to analyse large volumes of data can be advantageous in quantitative analysis, it also brings the risk of overwhelming the researcher if not managed carefully. Proper data management and processing become crucial in dealing with substantial data sets effectively.
- Subjectivity in analysis: Contrary to popular belief, quantitative data analysis is not inherently devoid of subjectivity. The choices made during the analytical process can significantly influence the conclusions drawn from the data. Researchers need to be cautious in maintaining objectivity during analysis, just as in qualitative data analysis.

2.2.6. Advantages and disadvantages of qualitative analysis

Alem (2020) also highlighted both advantages and disadvantages of the qualitative analysis.

The advantages are as follow:

- Generate hypotheses and descriptions: One of the primary advantages of qualitative research lies in its capacity to produce hypotheses and provide practical illustrations and in-depth descriptions of phenomena under study.

- Rich and detailed data: Qualitative research yields rich and detailed data, offering a comprehensive understanding of the research subject, often capturing nuances and complexities.
- Tolerance for ambiguity and contradictions: Qualitative research embraces ambiguity and contradictions that may arise during data analysis, allowing for a more holistic perspective.
- Potential for additional explanations: There is an opportunity for qualitative research to uncover unexpected insights or uncover additional explanations beyond what was initially anticipated.

The Disadvantages are as follow:

- Limited representativeness: A drawback of qualitative research is that the data may be less representative of a broader population due to the smaller sample size or localised focus.
- Researcher interconnectedness: The interpretations in qualitative research can be influenced by the "self" of the researcher, leading to potential biases or subjective interpretations.
- Contextual meaning disconnection: There is a risk of removing the meaning of data from its original context during analysis, potentially impacting the validity of findings.
- Oversimplified explanations: Qualitative research may face challenges in providing definitive and concise explanations, potentially leading to oversimplification of complex phenomena.
- Time-intensive analyses: Analysing qualitative data can be more time-consuming compared to quantitative data analysis due to the depth of interpretation and the volume of textual or visual data.

2.3. Statistical Tools for Data Analysis

2.3.1. Correlation

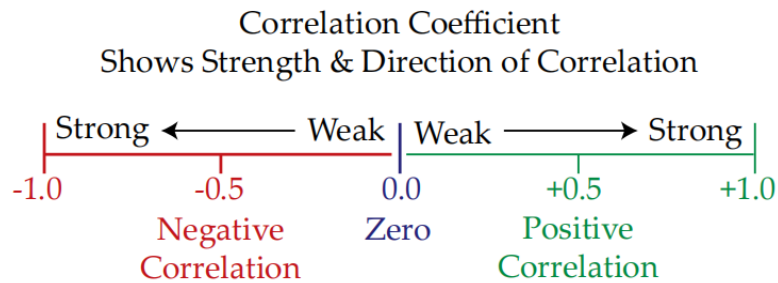


Figure 2: The spectrum of the correlation coefficient (Gogtay and Thatte, 2017).

Correlation is a statistical technique used to assess the relationship between variables, without implying causation (Gogtay and Thatte, 2017; Senthilnathan, 2019). It does not only measure the strength of the relationship but also its direction, which can be positive, negative, or null (Gogtay and Thatte, 2017). Correlation examines the closeness of two variables, and this association can be established between independent and dependent variables or even between independent variables themselves (Senthilnathan, 2019). The strength of the relationship revealed by correlation analysis can be depicted graphically and quantified using a correlation coefficient, which ranges from -1 to 1 (Senthilnathan, 2019; Gogtay and Thatte, 2017).

The correlation coefficient is a valuable metric to quantify the relationship between variables (Senthilnathan, 2019). A correlation coefficient of 1 indicates a perfect positive relationship, meaning that the variables are directly proportional to each other (Gogtay and Thatte, 2017). Conversely, a correlation coefficient of -1 signifies a perfect negative relationship, indicating that the variables are inversely proportional to each other (Gogtay and Thatte, 2017). Cohen (1992) has proposed the interpretation of correlation coefficient values, where an absolute value of 1 represents a strong correlation, 0.3 indicates a medium correlation, and 0.5 suggests a large correlation.

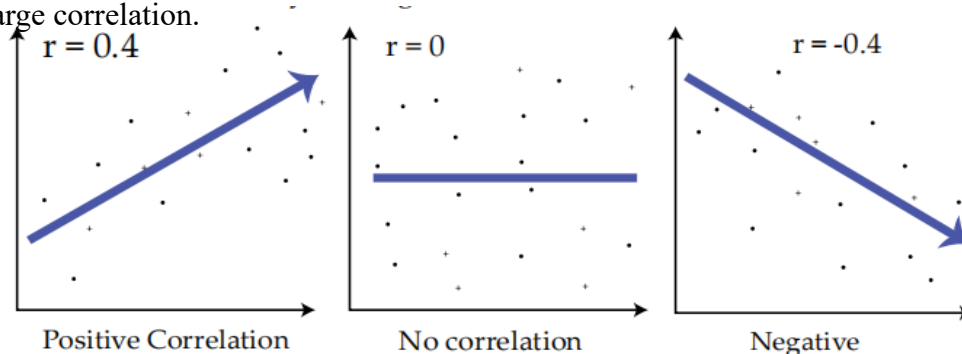


Figure 3: The spectrum of the correlation coefficient (Gogtay and Thatte, 2017).

The figure presented above illustrates the measurement of the linear relationship between variables through correlation analysis. The degree of correlation can be classified into three directions: positive, negative, or zero, indicating the absence of correlation, as depicted in the figure (Senthilnathan, 2019; Gogtay and Thatte, 2017).

The correlation coefficient is calculated as follow:

$$R = \frac{n(\sum XY) - (\sum X) \cdot (\sum Y)}{\sqrt{n(\sum X^2) - (\sum X)^2} \sqrt{n(\sum Y^2) - (\sum Y)^2}} \quad (7)$$

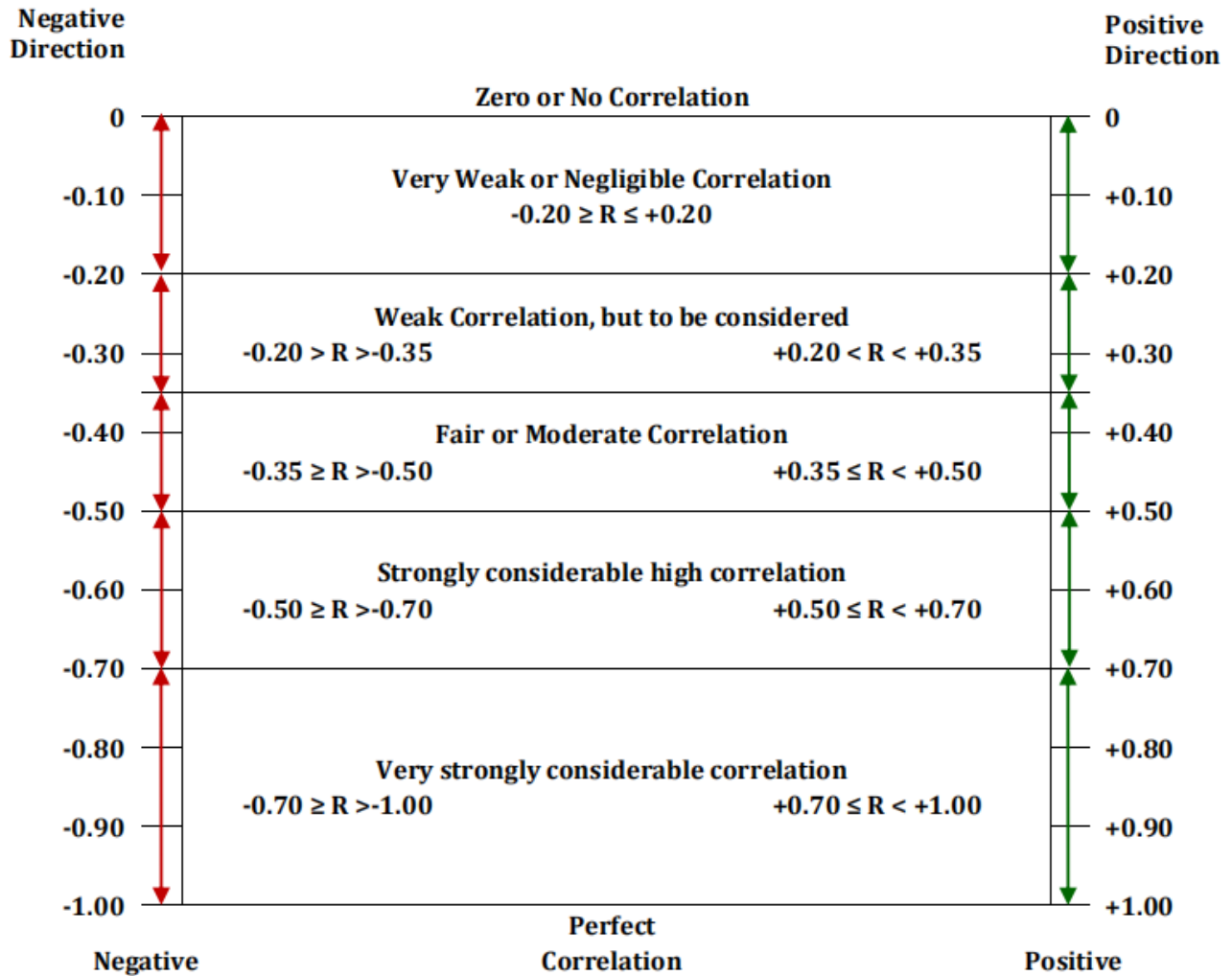


Figure 4: The ideal spectrum of the correlation coefficient spectrum in social sciences. (Senthilnathan, 2019).

n: number of observations

x: measures of variable 1

y: measures of variable 2

In general:

$r = 0$: no association or correlation between the two variables.

$0 < r < 0.25$: weak correlation.

$0.25 \leq r < 0.75$: intermediate correlation.

$0.75 \leq r < 1$: strong correlation.

$r = 1$: perfect correlation.

2.3.2. Standard Normal Distribution vs Student t test

In statistics, the normal distribution is characterised by the mean and standard deviation of a dataset (Trkulja and Hrabač, 2020). While these parameters can be computed even with a small sample size, a more accurate normal distribution requires a relatively large sample size with a substantial number of observations to calculate the standard deviation (Trkulja and Hrabač, 2020).

To address the challenge of small sample sizes, Gosset, while working for Guinness as a student, introduced the student t test (Trkulja and Hrabač, 2020), a statistical tool developed in 1908, which has been used for over a century. This test is employed in data analysis when the standard deviation is unknown, and it can be applied to scenarios with either one or two samples group (Al-Achi, 2019).

The purpose of the one-sample student t test is to determine whether the calculated mean from a sample data collected from a single group differs significantly from an expected value in a study (Al-Achi, 2019; Trkulja and Hrabač, 2020). Gosset's study on the acidity difference of beer in two different sample groups highlighted the need for an alternative method due to the small number of observations, leading to the development of the student t test (Trkulja and Hrabač, 2020). The distribution shape of the student t test is symmetric and varies with the number of measurements, resulting in different distribution shapes for each sample size (Trkulja and Hrabač, 2020).

For Single Sample Test:

$$t = \frac{\text{Sample Mean} - \mu}{\text{Standard Error}} \quad (8)$$

$$\text{Standard Error (S.E)} = \frac{\text{Standard Deviation}}{\sqrt{n}} \quad (9)$$

To draw a conclusion, the t value (t stat) is compared to the t distribution (t critical).

2.4. Measurements And Calculations in Brewing

2.4.1. Composition of barley (grain)

According to Fox (2010), the structural composition of barley grains utilised in brewing significantly impacts their quality. The grain's structure comprises the embryo, aleurone, and husk, with the embryo being the most crucial tissue containing starch, lipids, and protein. The aleurone, on the other hand, constitutes living tissue that contains lipids, protein, and starch, forming a layer approximately three cells thick that encloses the endosperm. Following harvest, barley retains a protective husk (Fox, 2010).

The chemical composition of the barley endosperm plays a pivotal role in determining grain quality (Fox, 2010). Starch is the predominant component, accounting for approximately 60% of the total grain weight (Goldammer, 2008; Fox, 2010). The starch consists of two distinct polymers, namely amylose and amylopectin, with a ratio of 3:1 (Fox, 2010). As described in the brewer's handbook by Goldammer (2008), starch is the most crucial constituent, representing around 60 to 65 percent of the malt's weight. It is composed of amylose, which breaks down into maltose and maltotriose, and of amylopectins which decomposes into glucose during the brewing process.

2.4.2. Real Extract vs Apparent Extract

As per the beer and brewing literature, the real extract measurement in beer is observed to be higher than the apparent extract (Parkes, n.d). This discrepancy arises due to the compositional changes that occur during fermentation. As the fermentation progresses, the solute in the liquid is transformed from pure water to a mixture of water and alcohol (Parkes, n.d).

The specific gravity of alcohol is lower than that of water, leading to the real extract, or "true" extract, being greater than the apparent extract (Parkes, n.d). The term "apparent" denotes a direct measurement of the extract. Hence, the difference between the real and apparent extract values is attributed to the presence of alcohol in the solution (Parkes, n.d).

2.4.3. Sugar Calculation

In a report on mash efficiency, Poisson (2021) presented two methods for expressing and calculating sugar extract, namely using Plato or Brix units. The equations for each method are as follows:

- Degree of Brix = $\frac{\text{Grams of Sucrose}}{100 \text{ Grams of Liquid}}$ (10)

- Degree of Plato = $\frac{\text{Grams of Sugar and of Solubles}}{100 \text{ Grams of Wort}}$ (11)

Several researchers have proposed sugar calculations at different stages of the brewing process. Notably, Cutaia's research published in 2009 provides equations for determining the original extract (OE), apparent extract (AE), and real extract (RE) as follows:

- Original Extract (OE) = $100 \times (2.0665 \times A_{w/w} + RE) / (100 + 1.0665 \times A_{w/w})$ (12)

- Apparent Extract (AE) = $2.569 \times 10^2 \times (SG-1) + 6.7126 \times 10^0 \times (SG-1)^2 - 1.4482 \times 10^4 \times (SG-1)^3 + 5.1758 \times 10^5 \times (SG-1)^4 - 1.0746 \times 10^7 \times (SG-1)^5 + 1.3011 \times 10^8 \times (SG-1)^6 - 8.5079 \times 10^8 \times (SG-1)^7 + 2.3231 \times 10^9 \times (SG-1)^8$ (13)

- Real Extract (RE) = $0.496815689 \times A_{w/w} + 1.001534136 \times AE - 0.000591051 \times A_{w/w} \times AE - 0.000294307 \times AE^2 - 0.0084747 \times A_{w/w}^2 + 0.000183564 \times A_{w/w}^3 + 0.000011151 \times AE^3 + 0.000002452 \times A_{w/w}^2 \times AE^2$ (14)

In a brewing process optimisation report written at the Worcester Polytechnic Institute by Poisson et al, in 2021, a formula is proposed to find the total sugars calculation. This formula converts the value obtained by a hydrometer into degrees of Plato, which represents the amount of sugar in grams per 100 grams of wort:

$$\text{Degrees of Plato} = [135.997 \times SG^3] - [630.272 \times SG^2] + [1111.14 \times SG] - 616.868 \quad (15)$$

2.4.4. Potential Alcohol Yield

According to Gombert and Maris (2015), the maximum theoretical yield of ethanol is 0.51 grams per gram of hexose sugar. This value can also be corroborated through stoichiometric calculations as demonstrated below:



2.4.5. Brewing Efficiency (Concept of Potential Grain Points)

In brewing, each grain possesses an inherent potential, which represents the amount of sugar that a pound of the grain can yield (Smith, 2014). A hydrometer can be used to calculate the specific gravity which on its turn, can be used to calculate the potential point (Smith, 2014). For instance, a specific gravity of 1.037 corresponds to 37 points.

For example, pale malt may have a potential of 1.037. To estimate the original gravity, brewers take the potential of the grain and convert it to points by dropping the "1" and multiplying the remainder by 1000. Therefore, a pale malt with a 1.037 potential contributes 37 points per pound of grain (Smith, 2014).

$$\text{Overall Potential} = \frac{\text{Nbr Pound of Malt x Potential Points for each malt}}{\text{Volume of the recipe in gallon}} \quad (20)$$

The assessment of efficiency achieved through various brewing recipes provides valuable insights into the effectiveness of both equipment and brewing techniques employed (Homebrewjournals, n.d). If the efficiency is observed to be notably lower than anticipated or exhibits substantial variability from batch to batch, it signals the need for adjustments in the applied brewing techniques (Homebrewjournals, n.d).

2.4.6. Mash Efficiency and Ethanol Concentration

According to homebrew journals (n.d.), the mash efficiency is in the 80 % range of the brewing efficiency. From the example of brewing efficiency, the mash efficiency will be calculated as such:

$$80 \times \frac{110}{100} = 88 \text{ points}$$

High mash efficiency is defined as a sugar recovery percentage ranging from 75% to 90%, while low mash efficiency falls within the range of 60% to 75% (Brewhaequipement, 2023).

Mathew et al. (2015) reported that traditional fermentation typically takes 50 to 70 hours to reach the maximum ethanol concentration of 7 to 8% (v/v).

The common way to express the mash efficiency is to calculate the **Points Per Pound Per Gallon (ppg)**

$$\text{Potential} = \frac{\text{Volume of the recipe in Gallon x Potential Points}}{\text{Nbr Pound of Malt}} \quad (21)$$

2.4.7. Brewhouse Efficiency

Brewhouse efficiency is an important parameter in brewing, quantifying the conversion of potential fermentables in wort to sugar (Carr, 2015). It accounts for a variety of losses, including those caused by mashing, lautering, hop trub, and transfers (Aiche, n.d). This comprehensive evaluation of losses occurs immediately before yeast pitching and the commencement of fermentation (Carr, 2015; Aiche, n.d).

The brewhouse efficiency is calculated by dividing the **grain points in wort (Actual)** by the **recipe grain points (Potential)**:

$$\frac{\text{Actual Grain Points}}{\text{Potential Grain Points}} \quad (22)$$

To determine the brewhouse efficiency, the following steps are taken:

- Obtain a specific gravity reading of the wort before yeast pitching.
- Convert the specific gravity to grain points by subtracting 1 and multiplying the result by 1000.
- Divide the obtained grain points by the recipe's grain points to obtain the brewhouse efficiency.

2.4.8. Alcohol by Volume Calculation and Estimate (ABV)

As mentioned in a Brewtogether's article (2020), the estimation of Alcohol by Volume (ABV) can be achieved by subtracting the final gravity (FG) reading, taken after fermentation, from the original gravity (OG) reading, taken before fermentation, and then multiplying the result by a factor of 131.25. It is important to note that this formula is specifically suitable for low alcohol concentration estimations.

$$\text{Mathematically, the ABV can be expressed as: } ABV = (OG - FG) \times 131.25 \quad (23)$$

2.4.9. Calculations for Economic Evaluation

2.4.9.1. The Return on Investment (ROI)

ROI is defined as the ratio of the profit to the capital investment, which is an approximate measure of an investment's profitability (Anderson and Fennell, 2013).

$$ROI = \frac{(\text{Net Present Value} - \text{Initial Investment})}{\text{Initial Investment}} \times 100 = \frac{\text{Profit}}{\text{Initial Investment}} \times 100 \quad (24)$$

The acceptable return on investment (ROI) value to justify an investment varies based on several factors (Anderson and Fennell, 2013). Factors such as a company's size, the investment's risk level, the quality and quantity of alternative opportunities, prevailing economic conditions impacting borrowing costs and availability of funds, as well as the industry, all play a role in determining the acceptable ROI threshold for an investment (Anderson and Fennell, 2013).

2.4.9.2.Net Present Value (NPV)

The net present value (NPV) represents the total of all discounted cash flows produced over the project's active years (Anderson and Fennell, 2013). It reflects the cumulative cash flow that a project would yield if all the revenues and costs associated with it were consolidated to a single point in time, specifically the present (Anderson and Fennell, 2013).

$$NPV_n = \sum_1^n \text{Discounted Cash Flow} \quad (25)$$

2.4.9.3.Payback period

The payback period represents the duration needed for a project to recoup its initial investment (Anderson and Fennell, 2013). This metric is determined by calculating the returns generated each year and comparing them to the initial investment (Anderson and Fennell, 2013). The payback period is reached when the total returns surpass the investment amount (Anderson and Fennell, 2013). It can be computed using either discounted or undiscounted returns. A shorter payback period signifies that a business can recover its investments more swiftly, thereby reducing exposure to risk (Anderson and Fennell, 2013).

2.4.9.4.Break-Even Point (BEP):

This consist of estimating the production level at which the total production revenue is equal to the total production cost (Mitchell, 2024).

CHAPTER 3: METHODOLOGY

3.1. Process Description

3.1.1. Facilities

The study took place at Primal Spirit Distillery, whose historical data was collected and utilised. The facility is in Johannesburg, South Africa.

The figure bellow illustrates the setup of the system from which brewing and distilling processes are carried out.

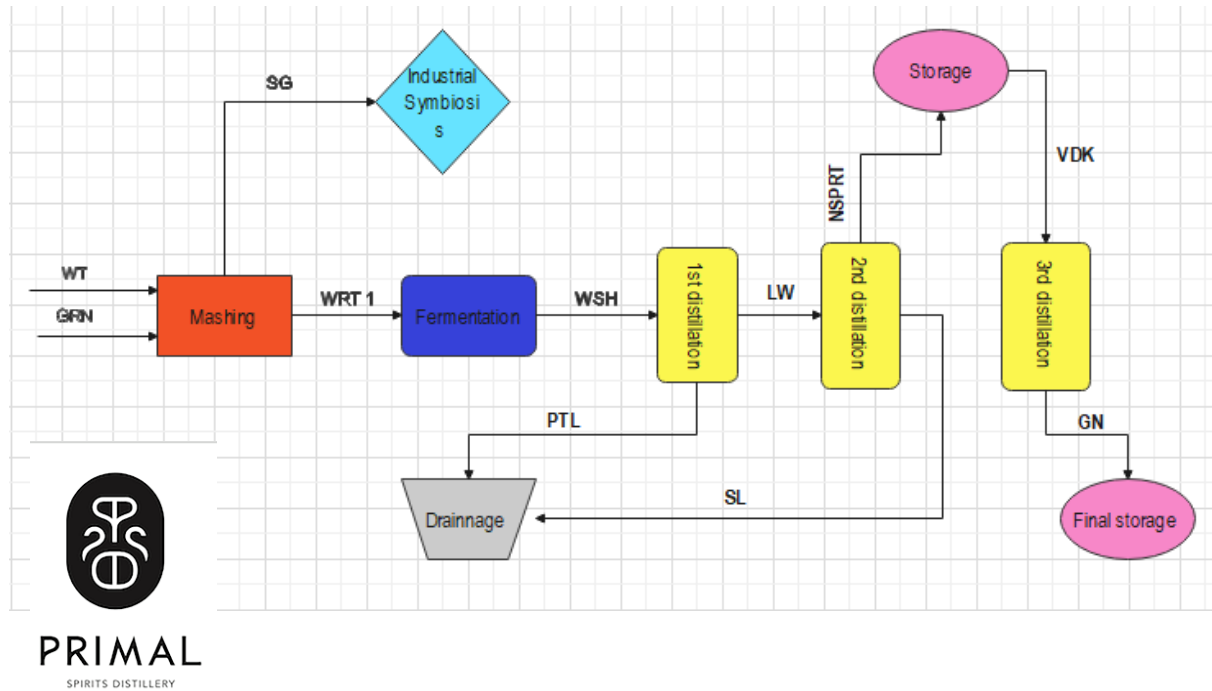


Figure 5: Block Flow Diagram of brewing and distilling at Primal Spirit Distillery.

Table 1: Primal Spirit Distillery Stream information

Stream ID	Stream component name	Quantity
WT	Water	2000 L
GRN	Grain	500 kg
SG	Spent grain	360 kg
WRT	Wort	1800 L
WSH	Wash	1800 L
LW	Low wines	513 L
PTL	Pot ale	1260 L
NSPRT	Neutral Spirit	152 L
SL	Spent lees	352 L
VDK	Vodka	224 L
GN	Gin1	122 L

3.1.2. Description

Mashing is the first process which involves crushing and combining dry, unmalted grain with hot water at a 4:1 ratio within a continuously stirred mixing tank, designated as a mash tun. During this phase, the grain reaches the appropriate level of hydration, and enzymes are introduced to facilitate the conversion of starches into soluble sugars, yielding a sweet and viscous liquid known as wort. The wort is filtered and cooled down to ambient temperature. The wort is transferred to a cylindrical vessel, leaving behind a residual bed of sweet grain. This grain bed is subsequently utilised for composting and other purposes, while the wort advances to the fermentation tank.

Within the fermentation tank, yeast and additional nutrients are introduced to initiate the fermentation process, which spans a duration of four days, leading to the formation of a substance termed the wash. Following fermentation, the wash is transferred to a pot distillation still, a system employing batch distillation principles, where the alcohol is separated from the wash, resulting in a murky-clear (cloudy clear) liquid referred to as the low wines, typically possessing an alcohol by volume (ABV) of 35%. Following the separation and storage of the distillate in a stainless-steel vessel, the residual hot and concentrated grain and water mixture, known as the pot ale, is subsequently discarded.

The low wines are then subjected to further distillation to produce a neutral spirit base with an ABV of 96%, along with spent lees, comprising alcohol-deprived water with an ABV lower than 0.5%. The neutral spirit is securely stored in a fire-proof alcohol safe, while the spent lees are discarded.

Subsequently, the neutral spirit undergoes blending with water and botanicals, encompassing herbs, roots, fruits, and similar constituents, and is then subjected to distillation in a copper pot distillation still. The culmination of this process yields the final product: gin.

3.1.3. Glossary of Terms

- Pot ale refers to the mixture of fermented grain and water, from which alcohol has been extracted after distillation.
- Low wine denotes the first distillate obtained during the grain-to-glass process, typically attaining an alcohol by volume (ABV) of 35%.
- Spent Grain: The desiccated residual grain remaining after the mashing process, retaining its sweet properties.

- Wash denotes the fermented wort, resulting from the enzymatic conversion of starches in the grain into soluble sugars.
- Wort: Signifies the saccharine mixture comprised of dissolved grain sugars and water.

3.2. Procedure

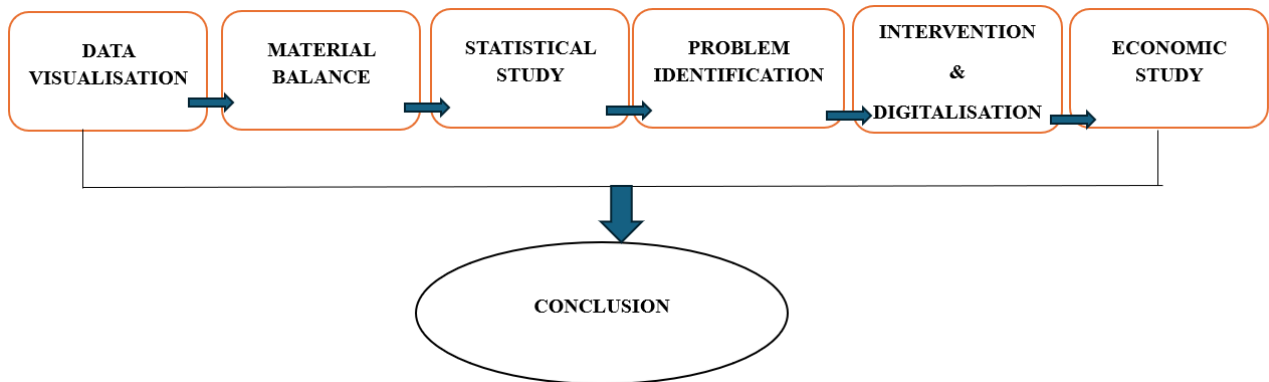


Figure 6: Research procedure.

3.2.1. Data Collection

The historical process data utilised in this study was acquired from Primal Spirit Distillery. The primary dataset comprises information from various batches collected between May 2019 and June 2022. This dataset includes details such as: the batch start and end dates, adjunct type and code, adjunct quantity, yeast amount, and water volume. Additionally, a secondary dataset was assembled, consisting of data on the resulting wort volume, original and final gravity, and potential alcohol by volume. A comprehensive table containing the gathered historical data is available in the study's appendix.

During the data collection process, both measured values and estimates were considered. The primary data concerning water volume involved estimating the volume flow rate of water from a specific source, which directly influenced the wort quantity data. Measurement of both original and final gravity was accomplished using a hydrometer. Moreover, the potential alcohol content was initially calculated, and a subset of these values was later verified at the Wits microbrewery located in Braamfontein, Johannesburg.

3.2.2. Data Visualisation and Analysis

In this study, data visualisation techniques were employed to assess trends and validate the reliability of the collected data. For instance, alcohol levels are expected to increase as yeast consumption progresses. To validate the veracity of this, a graphical representation can be

constructed by plotting the alcohol by volume (ABV) against the corresponding time points. The resultant trend line is anticipated to exhibit a decreasing tendency, as any other pattern would suggest potential anomalies or inconsistencies in the dataset.

To explore the relationship between the ABV and other pertinent parameters, few visualisations were performed. The ABV was plotted against the original gravity, revealing a direct proportionality between these variables. Conversely, when the ABV was plotted against the final gravity, an inverse proportionality relationship was observed.

These data visualisations provided valuable insights into the dynamics of alcohol production and corroborated the interdependencies between ABV, original gravity, and final gravity, thereby enhancing the credibility of the collected data.

3.2.3. Material Balance

The comprehensive analysis of mass balance, along with its associated graphs and interpretations, was integrated into the study. Mass balance calculations were conducted for the two principal unit operations, namely the mash tun and fermentation processes. Additionally, an overall mass balance assessment was executed to enable a comparative analysis between the potential alcohol content and the actual alcohol produced through the consumption of sugar introduced into the system. Any deviations or discrepancies between these parameters and other ones were thoroughly examined.

The mass balance approach employed in this study ensures a thorough evaluation of the material flow throughout the key stages of the process, providing valuable insights into the conversion of sugar into alcohol and identifying potential inefficiencies or inaccuracies. By scrutinising the mass balance data and comparing the expected outcomes with the actual results, this analytical approach contributes to a robust and reliable assessment of the system's performance and alcohol production dynamics.

3.2.4. Statistical study

A variety of statistical tools was employed to clarify the data and derive valuable insights. Specific measures of location, variance, and relationship were selected to interpret the dataset and draw conclusions, including arithmetic mean, mode, correlation, and the student t-test.

Correlation analysis was applied to assess the interrelationships between variables, leading to the identification of potential opportunities for digitalisation aimed at enhancing productivity

within the system. Moreover, the Student t-test was utilised to ascertain whether the calculated mean from a sample data, collected from a single group, significantly deviated from an anticipated value known as the hypothesized mean.

These statistical techniques played a pivotal role in comprehensively exploring the dataset, extracting meaningful information, and guiding the formulation of strategic decisions, ultimately contributing to the overall data analysis and its practical implications.

3.2.5. Problem Identification

The process of problem identification involved a comprehensive analysis and interpretation of all the information gathered from the preceding steps, which includes data visualisation, mass balance calculations, and the application of statistical methods. By closely scrutinizing and interpreting this collated data, the issues stemming from the absence of digitalisation of the process data were identified and delineated. This systematic approach enabled a thorough understanding of the challenges and limitations associated with the current data management practices, paving the way for informed decision-making and potential remedies in the pursuit of enhanced efficiency and optimisation within the process.

3.2.6. Intervention and digitalisation

The determination of the specific digitalisation approach for process data was driven by an analysis and interpretation of the findings derived from the problem identification phase. By carefully comprehending the implications and insights obtained during the problem identification process, a well-informed decision was made regarding the most appropriate and effective method of digitalising the process data. This strategic approach ensures that the chosen digitalisation solution aligns precisely with the identified issues.

3.2.7. Economic Study

This study aims to analyse the financial implications and profitability resulting from the digitisation of process data in a distillery. It involves assessing the investment's viability by examining changes in the distillery's cash flow, increased revenue, return on investment, and payback period.

3.2.8. Conclusion

Subsequently, following the successful determination of digitalisation approach, a comprehensive framework was elaborated to assess the benefits resulting from the digitalisation of process data. This framework entails a structured methodology for evaluating the positive impacts of incorporating digital technologies in the data management process.

By establishing a systematic and well-defined framework, the assessment process can be conducted rigorously, providing objective insights into the quantifiable gains and qualitative improvements that arise from the implementation of digitalisation measures. This ensures that the benefits of digitalising process data are thoroughly examined and can serve as a valuable reference for decision-makers in optimising data-driven operations and achieving enhanced process efficiency and productivity.

CHAPTER 4: ANALYSIS OF THE HISTORICAL DATA ACCURACY

4.1. Background

The historical process data exhibited significant variability, with certain parameters, such as the water volume for mashing, being estimated rather than directly measured, and the mass of adjuncts remaining nearly constant across batches. These factors raised concerns about the reliability and relevance of the data. The absence of a digital data collection mechanism, such as sensor-based monitoring, hindered the ability to accurately quantify and address these issues. Despite these limitations, a comprehensive statistical analysis of the historical data concluded that it remains viable for assessing the benefits of digitalisation. Statistical tools such as correlation, standard deviation calculations and normal distribution demonstrated the data accuracy and that the developed framework is sufficiently robust for evaluating the potential advantages of digitalisation strategies. Nonetheless, while these tools indicate the data's relevance and trustworthiness for the study, higher correlation coefficients would provide stronger validation.

4.2. Adjunct Amount.

The historical data includes the adjunct amount, yeast weight, alcohol yield per batch, and other production indicators. The adjunct quantity is recorded as nearly constant at 500 kg for most batches, which raises concerns about the reliability of the measuring equipment and data recording processes. Achieving precisely 500 kg consistently is unlikely in practical operations, suggesting potential issues with measurement accuracy or data capturing.

Given the difficulty of determining the exact amount of sugar added to and retained in the mash tun, the correlation between the adjunct quantity supplied and the sugar content in the wort was analysed. The correlation coefficient was calculated as **0.51**, indicating a moderate-to-strong positive relationship. This result supports the assumption that the historical data is sufficiently consistent for analysis.

Additionally, the correlation between sugar content in the wort and the alcohol yield produced was found to be **0.55**, further demonstrating a strong relationship between these variables. While this correlation indicates the data's relevance and trustworthiness for the study, a higher coefficient would provide stronger validation.

To improve data accuracy and reliability, implementing a digital scale with automated recording for adjunct measurements is recommended. Such a system would reduce dependence

on manual estimation and approximation, ensuring more precise data collection for future analyses.

4.3. Mash Tun Volume.

The mashing liquor, consisting primarily of adjuncts and water, is prepared by adding water to the mash tun to extract sugars from grains. The distillery staff indicated that the mash volume is estimated, though they consider it reliable. However, there is no process valve to measure the exact amount of water supplied; instead, the water is delivered through a fully open tap, with the supply time controlled by a timer.

To assess the validity of the dataset, the correlation between the water volume supplied to the mash tun and the resulting wort volume was analysed. The calculated correlation coefficient is **0.81**, indicating a strong positive correlation. This suggests that the water input data is consistent and supports the reliability of the recorded mash volume values.

4.4. Alcohol by Volume (ABV) & Normal Distribution

The input sugar for the system averages 451.1 kg per batch, with a statistical mode of 500 kg. Yeast input remains consistent at 1 kg for most batches. Based on these inputs, one might expect the alcohol content per volume to fall within a predictable range. However, the historical data reveals significant variability in alcohol yield across batches.

According to the literature, the acceptable alcohol content produced via fermentation of wort into beer is between 7% and 8% (Mathew et al, 2015). Analysis of historical data indicates that only 53.66% of batches achieved alcohol content within this range. The calculated standard deviation of the dataset is 1.94, which is notably high compared to the desired range of 0.25 to 0.5 in statistics. This level of variability suggests considerable inconsistency in the fermentation process, likely warranting further investigation, hence the focus of the study.

From figure 6 below, it is noticeable that, despite a standard deviation of 1.94, most ABV values are clustered near the mean value of 7.05%. Consequently, 53.66% of the data points fall within the 7–8% alcohol content range following fermentation.

It is essential to note that the ABV is an outcome derived from the fermentation process rather than a direct measurement of raw data. ABV is analysed to validate the accuracy of the raw data, but this analysis is predicated on the assumption that the fermentation process operates without any deviations or flaws.

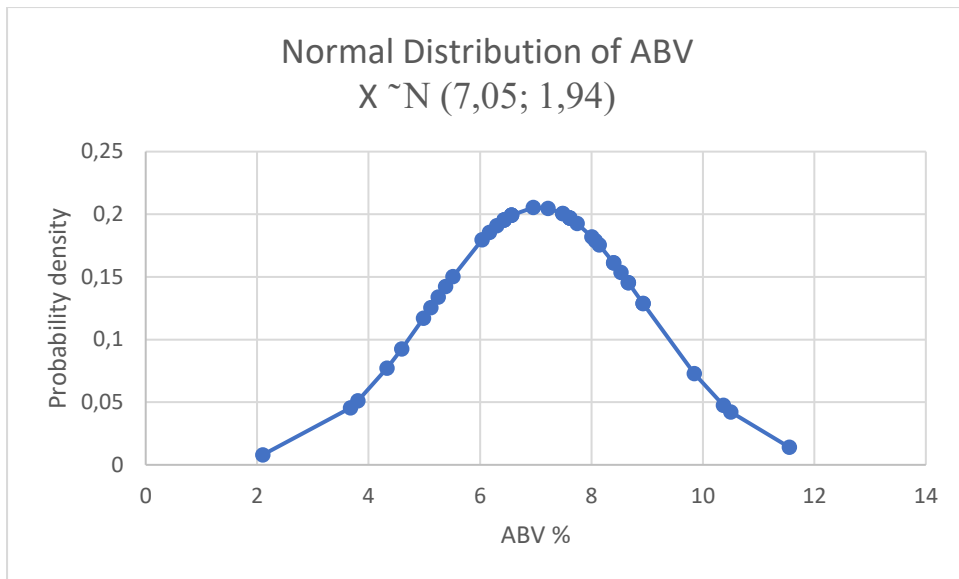


Figure 7: Normal distribution of ABV

CHAPTER 5: RESULT, ANALYSIS & DISCUSSION

5.1. Mass Balance

The objective of this section is to utilise historical data for process flow analysis, specifically to calculate the amount of sugar supplied, lost, and retained in the system for alcohol production. Mass balance is crucial to compare the actual ethanol production with the distillery's alcohol potential capacity. This analysis aims to quantify the advantages of digitalising process data and underscore the necessity of performing mass balance through digitalisation. Details of calculations can be found under the appendix section.

Mass balance was conducted for the mash tun to assess the discrepancy between the sugar supplied to the mash tun and the amount extracted during the mashing process, which is indicated by the sugar content in the wort, to quantify the sugar loss in the process.

The purpose of the mass balance over fermenter is to compare the amount of sugar in the wort that enters the fermenter, the amount lost during the fermentation process and the quantity used up to produce ethanol. For this calculation, the sugar content in wort and fermented product are expressed in degree Plato of the specific gravity.

Table 2 below, is the summary of mass balance calculation over mash tun. It is giving details on the amount of sugar supplied into the system, the extract in wort and sugar lost.

Note:

- More information about calculation can be found in the appendix section.
- Tables 2 and 3 below are not raw data but the results of mass balance conducted over the mash tun and the fermentation vessel. It is therefore pertinent to keep them on the result section and not in the appendix.

Table 2: Result of the Mass Balance over mash tun

Batches	Sugar Supplied (kg)	SG (Original Gravity OG)	Extract Degree Plato (g/100g wort)	Volume of Wort (L)	Mass of Wort (kg)	Sugar in Wort (kg)	Sugar Lost (kg)	Sugar Lost (%)
1	500	1,05	14,76	875	918,75	135,65	364,35	72,87
2	500	1,047	13,79	1540	1612,38	222,28	277,72	55,54
3	475	1,05	14,76	1706,8	1792,14	264,60	210,40	44,29
4	485	1,043	12,50	1800	1877,40	234,65	250,35	51,62
5	500	1,045	13,14	2227	2327,22	305,78	194,22	38,84
6	500	1,048	14,11	1870	1959,76	276,53	223,47	44,69
7	500	1,113	38,05	2550	2838,15	1079,94	-579,94	-115,99
8	500	1,08	25,20	1800	1944,00	489,96	10,04	2,01
9	500	1,078	24,47	1836	1979,21	484,34	15,66	3,13
10	300	1,072	22,30	1296	1389,31	309,88	-9,88	-3,29
11	500	1,076	23,74	1987	2138,01	507,65	-7,65	-1,53
12	500	1,074	23,02	1678,19	1802,38	414,94	85,06	17,01
13	500	1,081	25,57	1799,74	1945,52	497,51	2,49	0,50
14	500	1,062	18,80	1415	1502,73	282,49	217,51	43,50
15	500	1,065	19,84	2040,8	2173,45	431,14	68,86	13,77
16	500	1,066	20,19	1853,6	1975,94	398,85	101,15	20,23
17	500	1,065	19,84	1853,6	1974,08	391,59	108,41	21,68
18	500	1,076	23,74	1772	1906,67	452,72	47,28	9,46
19	500	1,071	21,95	1626	1741,45	382,22	117,78	23,56
20	500	1,065	19,84	1876	1997,94	396,33	103,67	20,73
21	500	1,065	19,84	1982	2110,83	418,72	81,28	16,26
22	500	1,057	17,09	1750	1849,75	316,21	183,79	36,76
23	500	1,081	25,57	1970	2129,57	544,58	-44,58	-8,92
24	175	1,086	27,43	460,23	499,81	137,11	37,89	21,65

25	500	1,072	22,30	1860	1993,92	444,74	55,26	11,05
26	250	1,081	25,57	800	864,80	221,15	28,85	11,54
27	400	1,078	24,47	1746	1882,19	460,59	-60,59	-15,15
28	100	1,053	15,76	250	263,25	41,48	58,52	58,52
29	365	1,089	28,57	1250	1361,25	388,85	-23,85	-6,53
30	375	1,068	20,89	1549	1654,33	345,53	29,47	7,86
31	500	1,082	25,94	1079	1167,48	302,86	197,14	39,43
32	500	1,068	20,89	2127	2271,64	474,47	25,53	5,11
33	150	1,065	19,84	456,56	486,24	96,45	53,55	35,70
34	500	1,058	17,43	1849,96	1957,26	341,21	158,79	31,76
35	500	1,059	17,77	1737,059	1839,55	326,93	173,07	34,61
36	500	1,068	20,89	2014	2150,95	449,26	50,74	10,15
37	500	1,062	18,80	1800	1911,60	359,36	140,64	28,13
38	500	1,061	18,46	1790	1899,19	350,50	149,50	29,90
39	480	1,063	19,14	1958	2081,35	398,44	81,56	16,99
40	490	1,061	18,46	1999	2120,94	391,43	98,57	20,12
41	450	1,06	18,11	2256	2391,36	433,15	16,85	3,74

The negative losses are an indication of wrong estimate and measurement of the input quantity into the mash tun; hence, the necessity of digitalisation instead of relying on human observations and judgment.

Table 3 below, is the summary of mass balance over fermenter. It is giving details on the amount of sugar supplied into the system, the extract in wort, the alcohol by volume (and by weight) produced, final extract, the sugar loss across the fermenter and its equivalent in kilogramme of ethanol.

Table 3: Mass Balance over fermenter.

Batches	SG (Original Gravity)	Initial Extract (°P)	Alcohol by volume ABV (A _{v/v})	Alcohol by weight (A _{w/w})	Final Extract (°P)	Sugar Loss across Fermenter (°P)	Sugar Loss across Fermenter (kg)	Ethanol Loss (kg)
1	1,05	14,76	6,56	4,94	17,00	2,23	20,53	10,47
2	1,047	13,79	7,61	5,75	16,43	2,65	42,68	21,77
3	1,05	14,76	6,56	4,94	17,00	2,23	40,05	20,42
4	1,043	12,50	3,81	2,89	13,71	1,21	22,68	11,56
5	1,045	13,14	4,99	3,77	14,79	1,65	38,38	19,57
6	1,048	14,11	6,17	4,65	16,20	2,09	40,96	20,89
7	1,113	38,05	9,84	6,99	41,64	3,59	47,45	24,20
8	1,08	25,20	7,22	5,29	27,64	2,44	43,42	22,15
9	1,078	24,47	6,56	4,81	26,67	2,19	27,77	14,16
10	1,072	22,30	6,04	4,45	24,30	2,00	45,85	23,39
11	1,076	23,74	6,43	4,73	25,89	2,14	52,99	27,03
12	1,074	23,02	8,53	6,28	25,96	2,94	41,77	21,30
13	1,081	25,57	6,43	4,70	27,72	2,15	22,10	11,27
14	1,062	18,80	4,59	3,42	20,27	1,47	46,79	23,86
15	1,065	19,84	6,43	4,77	21,99	2,15	34,75	17,72
16	1,066	20,19	5,38	3,99	21,94	1,76	27,06	13,80
17	1,065	19,84	4,33	3,22	21,21	1,37	39,96	20,38
18	1,076	23,74	6,30	4,63	25,84	2,10	29,72	15,16
19	1,071	21,95	5,25	3,88	23,65	1,71	57,98	29,57
20	1,065	19,84	8,40	6,24	22,74	2,90	23,83	12,16
21	1,065	19,84	3,68	2,73	20,97	1,13	47,49	24,22
22	1,057	17,09	7,48	5,60	19,66	2,57	78,87	40,22
23	1,081	25,57	10,50	7,68	29,28	3,70	18,27	9,32
24	1,086	27,43	10,37	7,55	31,09	3,66	59,67	30,43

25	1,072	22,30	8,66	6,39	25,30	2,99	26,73	13,63
26	1,081	25,57	8,93	6,53	28,66	3,09	48,73	24,85
27	1,078	24,47	7,61	5,58	27,06	2,59	4,82	2,46
28	1,053	15,76	5,51	4,14	17,58	1,83	56,23	28,67
29	1,089	28,57	11,55	8,39	32,70	4,13	38,82	19,80
30	1,068	20,89	6,96	5,15	23,23	2,35	36,09	18,40
31	1,082	25,94	8,93	6,52	29,03	3,09	68,10	34,73
32	1,068	20,89	8,66	6,41	23,88	3,00	12,40	6,32
33	1,065	19,84	7,48	5,55	22,39	2,55	32,72	16,69
34	1,058	17,43	5,12	3,83	19,10	1,67	48,99	24,98
35	1,059	17,77	7,74	5,78	20,44	2,66	62,31	31,78
36	1,068	20,89	8,40	6,22	23,78	2,90	53,66	27,37
37	1,062	18,80	8,14	6,06	21,61	2,81	52,88	26,97
38	1,061	18,46	8,07	6,02	21,24	2,78	57,34	29,24
39	1,063	19,14	8,01	5,96	21,90	2,75	11,76	6,00
40	1,061	18,46	2,10	1,57	19,01	0,55	62,43	31,84
41	1,06	18,11	7,61	5,68	20,72	2,61	20,53	10,47

5.2. Mashing

5.2.1. Sugar Loss (kg)

Figure 8 below, is illustrating the sugar lost in percentage (vertical axe) during mashing for every batch (horizontal axe).

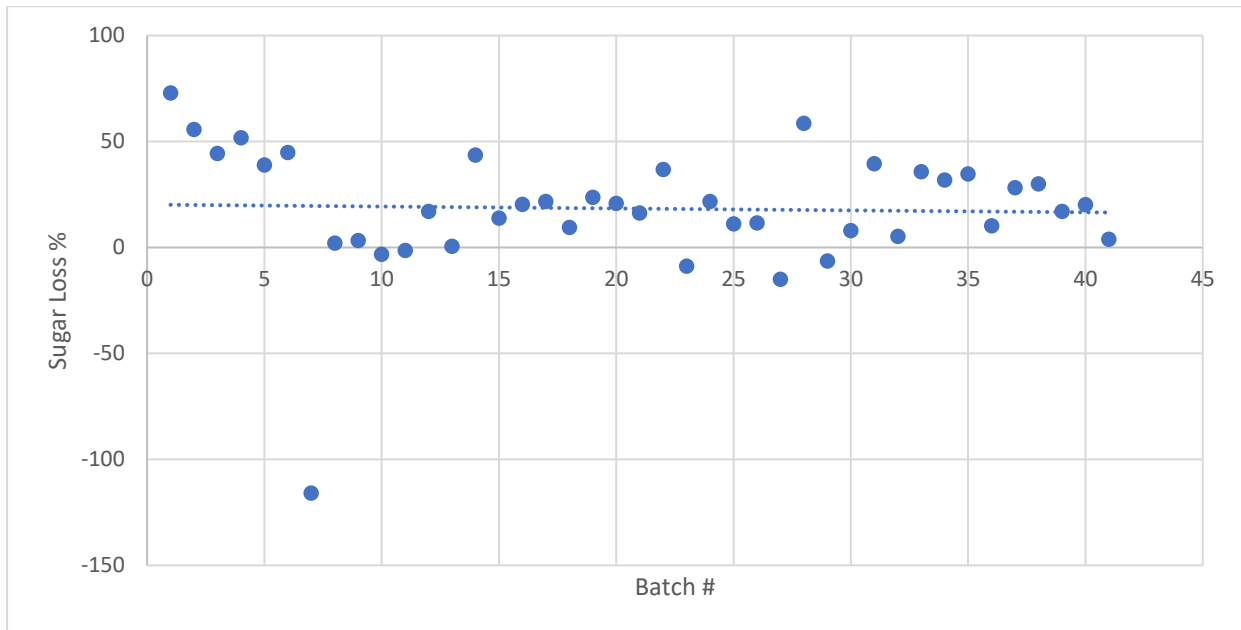


Figure 8: Sugar loss per batch in percentage.

- The input of sugar into the system remains stable, purposefully maintained to ensure production consistency as shown by the trendline on figure 7 and facilitate precise analytical assessments.
- The line is slightly inclined showing a little decrease in supply to the mashing tun. However, it is almost a perfect horizontal line indicating consistency.
- The mean sugar input is recorded at approximately 451.10 kg, with a statistical mode of 500 kg. In theory, sugar loss of the same order is anticipated for each batch.
- Notably, the most significant trends in losses transpire between batch 1 and 6, primarily attributable to the initial trial-and-error phase before achieving production consistency. Batch 7 registers a negative value, presumably due to inconsistencies involving factors such as parallax errors in readings, overestimations, and mismeasurements. For a better analysis, batch 7 is removed from the dataset for the rest of this study.
- From batch 8 through 41, the observed losses exhibit a notable consistency. The average loss, constituting 16.45%, corresponds to a mass loss of approximately 69.19 kg.

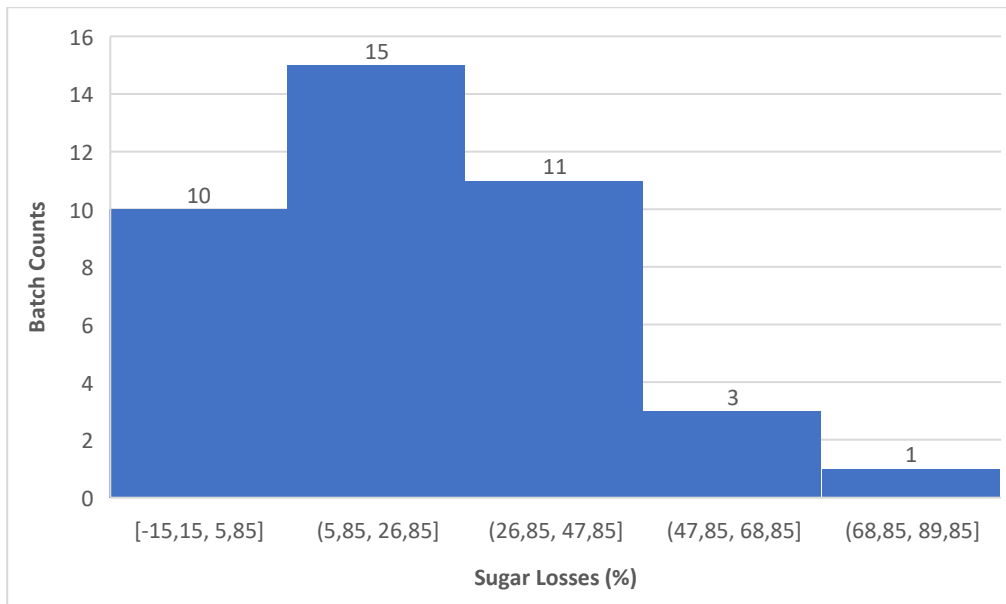


Figure 9: Sugar loss per batch in percentage.

- The mashing tun experienced increased losses from batch 1 to 6, and a consistent trend from batch 8 through 41. These observations indicate a notable amount of sugar loss during the mashing process, with an average loss of 16.45% or 69.19 kg. Digitalising process data could minimise these losses by providing useful information about deviations.
- Figure 9 shows that the most losses (15 times) were in the interval between 5.85 % and 26.85 % of the mash tun sugar inputs. The interval [5.85, 26.85] is the modal interval, containing the average loss of 16.45 % corresponding to 69.19 kg, as previously calculated.
- The first interval [-15.15, 5.85] contains a few negative values which emanates from measurement errors and bad estimate from the input into the mash tun. In any case, digitalising process data could solve this problem instead of relying on the human observation.
- Batch 7 registered a big negative value indicating probable inaccuracy in measurement, parallax error or overestimation, as the output cannot be greater than input during mashing. A few other negative values were recorded probably due to bad human observation and estimate, hence the importance of digitalising process data.

While this valuable data is accessible, it is not readily available, making it challenging to implement adjustments during production or anticipate significant deviations. The historical data alone did not offer this level of analysis, interpretation, and insight.

5.2.2. Sugar In vs Sugar Out

Figure 10 is a combination of the sugar entering the mash tun in kg (blue dots) and the sugar coming out of it (orange dots) for every batch (horizontal axe).

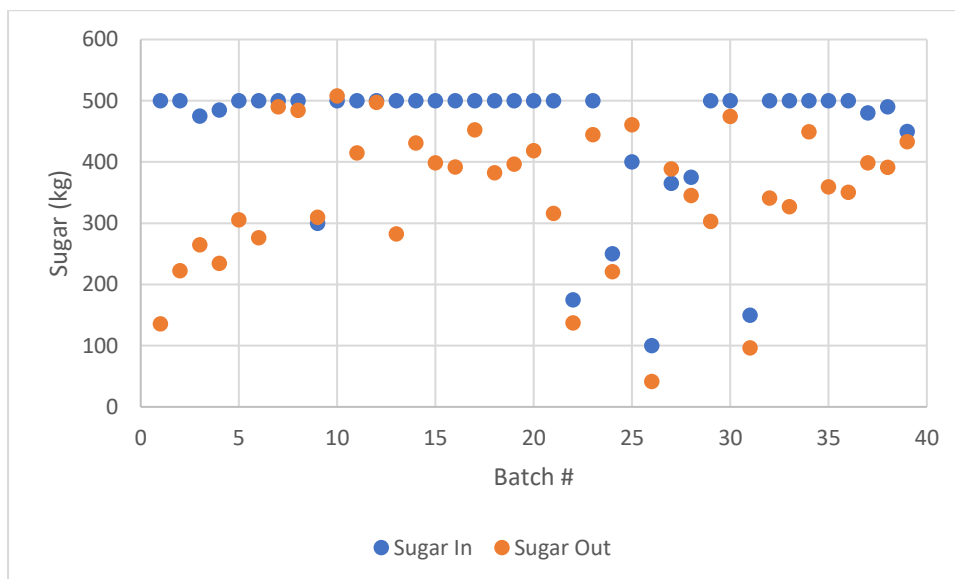


Figure 10: Sugar input and output comparison.

As previously mentioned, the abnormal results observed in batch 7 can be attributed to mismeasurement, erroneous estimation, or parallax errors. It is impossible to have a scenario where the amount of sugar lost exceeds the sugar input into the system. Therefore, batch 7 is excluded from the analysis. Furthermore, it is impossible for the loss to be negative as this scenario would yield to more ethanol produced than technically possible.

Upon visual inspection of the graph, a consistent trend emerges in the difference between sugar input and output from batch 8 through 41. In contrast, there is a gradual increase in this difference from batch 1 to 6. It appears that during batches 1 to 6, the distillery was in an adjustment phase, which likely accounts for these variations.

5.2.3. Sugar In vs Sugar Lost

Figure 11 is a combo of the sugar entering the mash tun in kilogramme (blue columns) and the sugar lost in the process (orange columns) for every batch (horizontal axe).

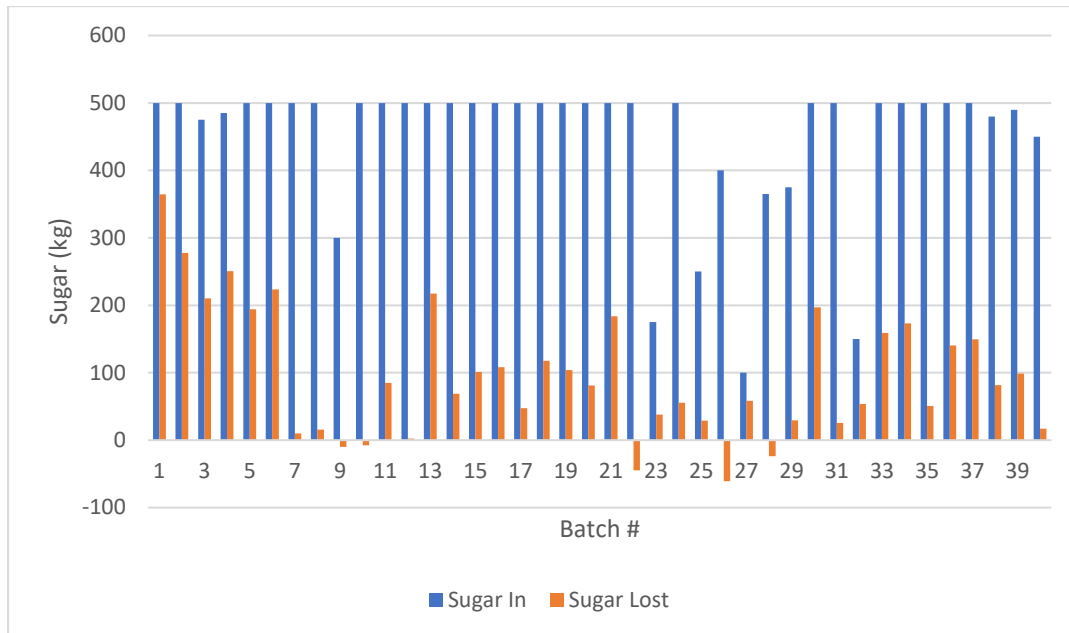


Figure 11: Sugar input and output comparison with gap lines.

- The blue columns illustrate a consistent pattern observed in batches 1 to 9, 11 to 23, 31 to 32, and from 34 to 41, where each batch received an input of 500 kg of sugar into the mashing tun. Sugar loss is initially high for the first six batches but reduces over time for the remaining batches.
- However, the historical data for the mashing process shows a flaw where a few batches exhibit negative losses, implying that the output is greater than the input. This analysis potentially reveals the need for a better approach to recording process data, which is the core of the research.
- From batch 24 to 33, where fluctuations in the quantity of sugar introduced into the mash tun are evident, the losses were observed to be proportional to sugar input.

5.3. Fermentation

5.3.1. Ethanol Loss during fermentation

The following chemical equation succinctly represents the process of ethanol fermentation, whereby a single hexose molecule undergoes conversion into two ethanol molecules and two carbon dioxide molecules:



The stoichiometric calculation performed on the above equation confirms that for each 1g of hexose, approximately 0.51 g of ethanol is yielded. Moreover, Gombert and van Maris (2015), argues that 0.51 g is the actual maximum theoretical yield of ethanol per gramme hexose sugar.

Knowing the relationship between hexose sugar and maximum theoretical yield of ethanol, the fermentation losses expressed in degree Plato can be converted into kilogramme of hexose sugar, then multiplied 0.51 to find the equivalent in kilogramme of ethanol.

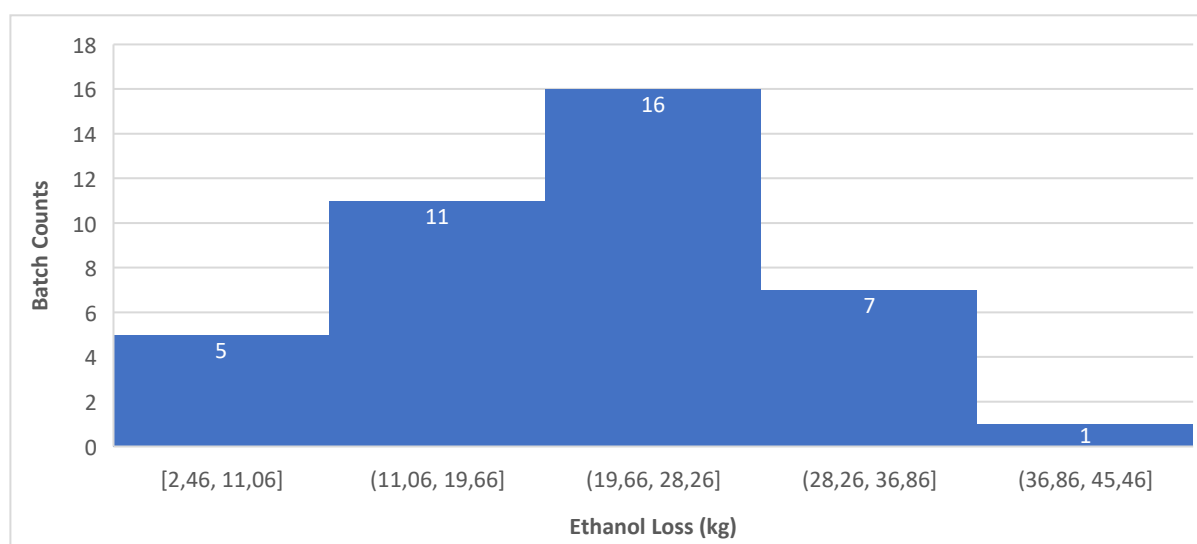


Figure 12: Ethanol losses (kg) per batch.

- The highest loss of **40.22 kg** ethanol occurred at batch 22.
- The most losses (16 times) recorded masses between 19.66 kg and 28.26 kg, which makes it the modal interval.
- The most losses occurred around the average of 20.72 kg of ethanol per batch.

Storing process data on a platform that enables such analyses can offer valuable insights into losses, facilitating timely interventions to minimise high losses throughout the fermenter.

5.3.2. Sugar Loss during Fermentation

To analyse the sugar loss in degree Plato ($^{\circ}\text{P}$), the sugar extract difference is evaluated and plotted on figure 13 below. The sugar extract is the difference between the apparent extract (AE: before fermentation) and the real extract (RE: after fermentation).

As per information from the beer and brewing website (n.d), the real extract measurement has a bigger numerical value than the apparent extract. This discrepancy arises from the transformation occurring during fermentation, where the solute ceases to be in a state of pure water and instead becomes a composite blend of water and alcohol.

After the fermentation process, an apparent extract (AE) value was determined and recorded at 0. Following this, the real extract (RE) was computed and subsequently compared to the initial apparent extract value, which was measured prior to the commencement of the fermentation process.

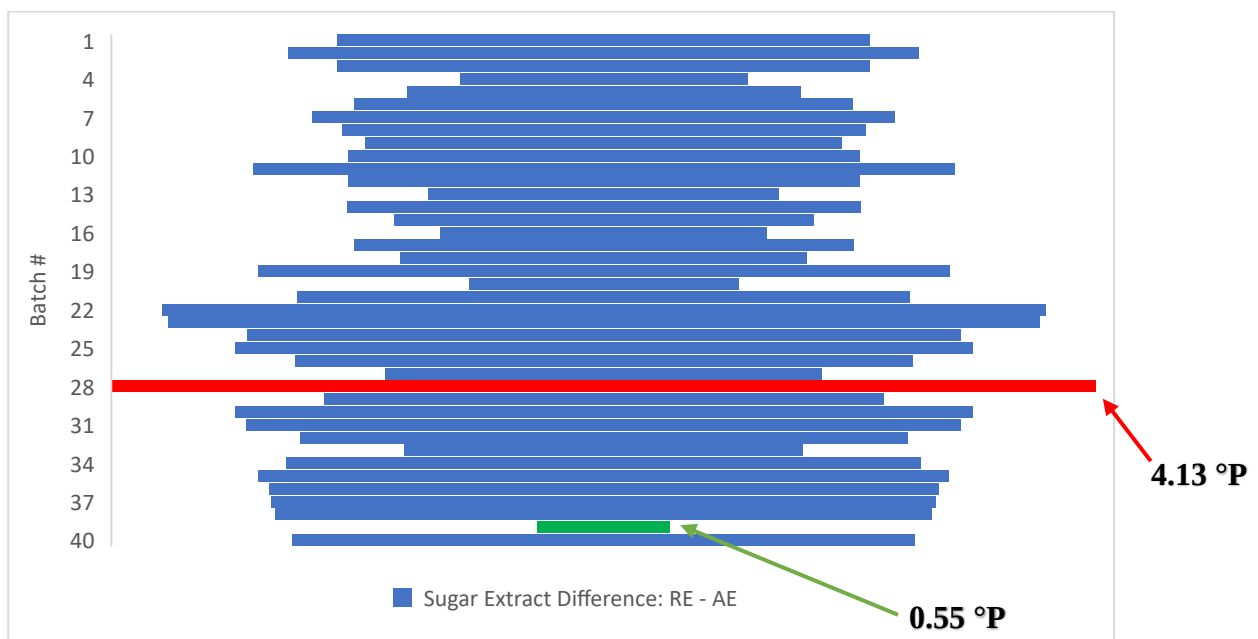


Figure 13: Sugar Loss ($^{\circ}\text{P}$) during fermentation.

It is important to note that the longer the funnel (horizontal column) on figure 13, the bigger the sugar extract difference, and most importantly, the smaller the sugar loss.

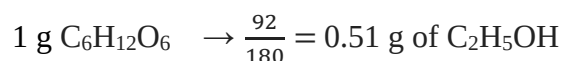
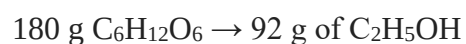
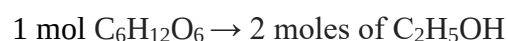
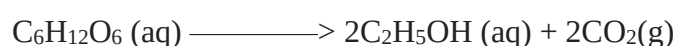
- The highest sugar loss was recorded during batch 39 (green funnel), which corresponds to the smallest sugar extract difference of **0,55 $^{\circ}\text{P}$** (6 kg).
- The smallest sugar loss was recorded during batch 28 (red funnel), which corresponds to the largest sugar extract difference of **4,13 $^{\circ}\text{P}$** (28.67 kg).

- The difference is almost constant as illustrated on the graph. The average difference is **2,4 °P** and the statistical mode is **2,23 °P**.
- The ratio between final extract and initial extract looks also constant. Its average is **1,11 °P** and the mode is **1,15 °P**.

Note: The highest ethanol loss occurred during batch 22, as indicated in section 5.3.1. In contrast, the highest sugar extract loss was observed during batch 28. These discrepancies can be attributed to variations in wort volume entering the fermenter. For detailed calculations, refer to the appendix, section 11.3.2.

5.3.3. Alcohol by volume range analysis

Gombert and Maris (2015) stated after experiment that the maximum theoretical yield of ethanol is 0.51g per g hexose sugar. It is also verifiable via stoichiometric calculations.



The acceptable range of alcohol after normal fermentation of beer is between 7 % and 8% (Mathew et al, 2015). However, it was observed that many batches recorded either lower or higher alcohol by volume percentage. The following are outside the acceptable range of 7-8 %:

Table 4: Alcohol by volume outside acceptable range.

Batch Number	Alcohol by volume ABV (A_{v/v})
4	3,81
5	4,99
6	6,17
7	9,84
10	6,04
11	6,43
13	6,43
15	6,43
16	5,38
17	4,33
18	6,3
19	5,25
21	3,68
23	10,5
24	10,37
28	5,51
29	11,55
34	5,12
40	2,1

Out of 41 batches, 22 fall within the acceptable range for alcohol percentage. This corresponds to **53.66 %**. This also means that **46.34 %** of time, fermentation, or the previous process (mashing) goes wrong and is more likely to be premature.

5.3.4. Comparison between Potential and Produced alcohol.

Figure 14 below is the comparison of the potential and actual produced alcohol produced from the sugar entering the mash tun.

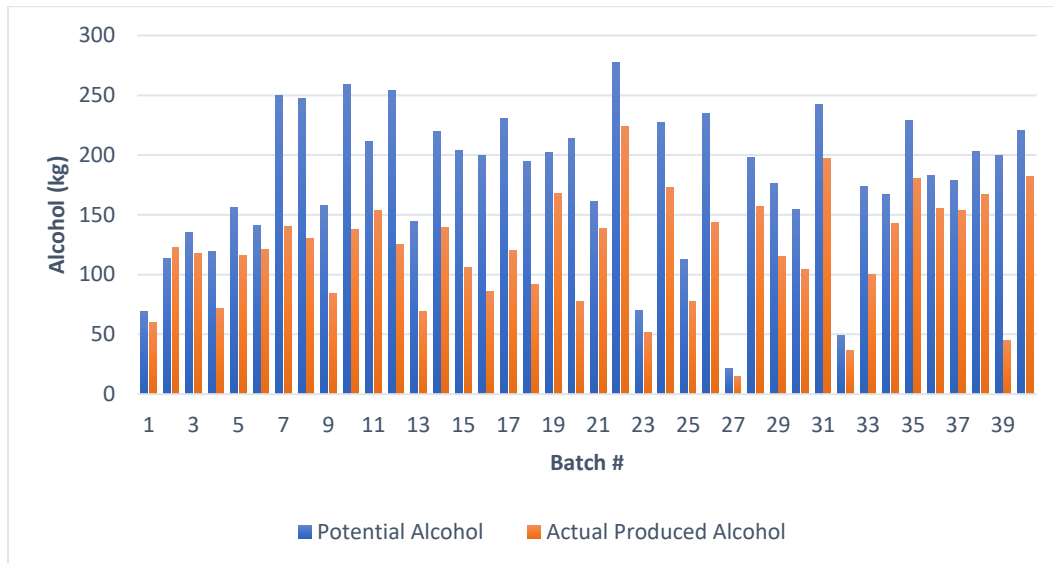


Figure 14: Potential and produced alcohol comparison with gap lines.

- The disparity between the measured and potential quantities of alcohol, expressed in kilogrammes, exhibits variability. This variation may be positive or negative, contingent on which of the two quantities exceeds the other. This disparity was quantified by subtracting the actual value from the theoretical value.
- The mean deviation equates to 32.29 %, equivalent to 65.37 kg for 500 kg of sugar input into the system.
- Among the 41 batches examined, merely 14 demonstrated a deviation equal to or less than 20%. This implies that the distillery documented substantial deviations approximately 65.85% of the time, a notably high occurrence.

5.3.5. Percentage of the Actual Alcohol Produced in comparison with the Potential Alcohol.

Percentage of alcohol produced in comparison with potential is calculated in this manner:

$$\frac{\text{Actual Alcohol} \times 100}{\text{Potential Alcohol}} \quad (25)$$

Note: Here, we assume the potential alcohol to be higher than the actual one.

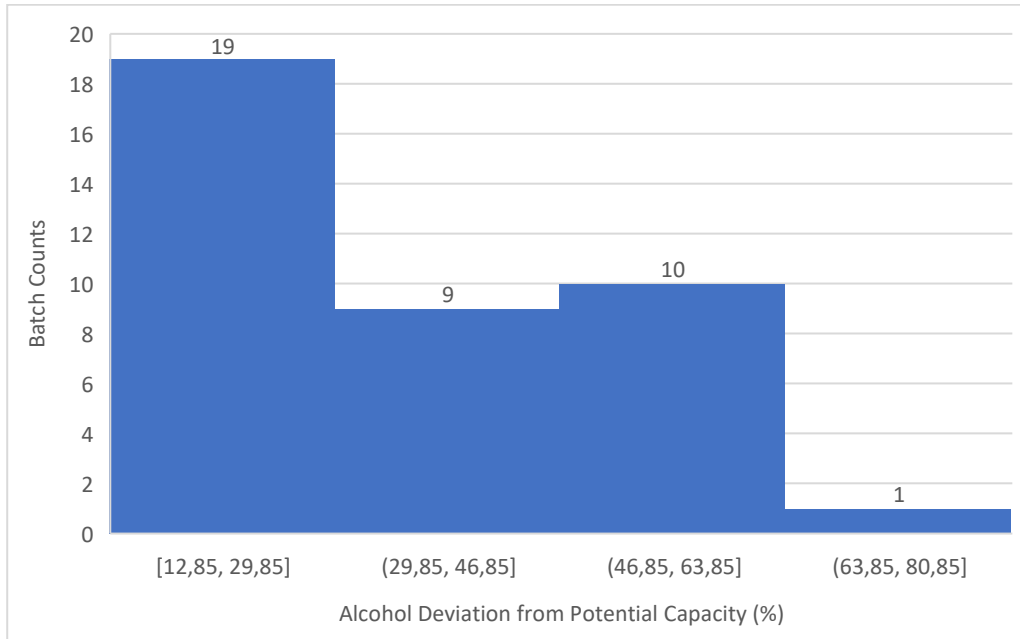


Figure 15: Deviation histogram.

- Figure 15 shows that most deviations (19 times) occurred between the 12.85 % and 29.85 % interval.
- The highest deviations of 87.15 % occurred at batch 1 and 3.

Figure 16 below, is showing the percentage of the actual alcohol produced of the total potential capacity of the distillery.

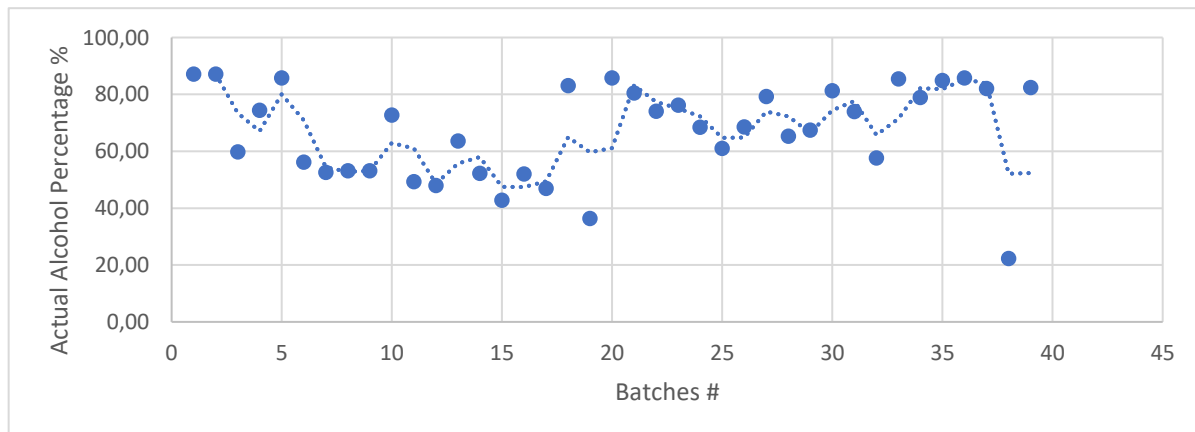


Figure 16: Produced alcohol of the total potential capacity with trendline.

- The moving average shows that from batch 1 to approximately 20, alcohol produced is on average lower than the production from batch 21 to 40. In fact, there is a decrease followed by an increase in alcohol production.
- The highest percentage, reaching 87.15%, was observed for batches 1 and 3. This indicates that the distillery attained 87.15% of the potential alcohol production for these batches.
- The lowest percentage was 22.31% for batch 39, signifying that the distillery's actual alcohol output only amounted to 22.31% of the potential capacity.

On average, the distillery is achieving **67.7 % $\approx$ 68 %** of the potential alcohol production capacity.

This data carries considerable significance for proactive measures aimed at minimising losses within the system. It is noteworthy that this information could not be directly obtained solely from historical data, suggesting the potential utility of digitalisation.

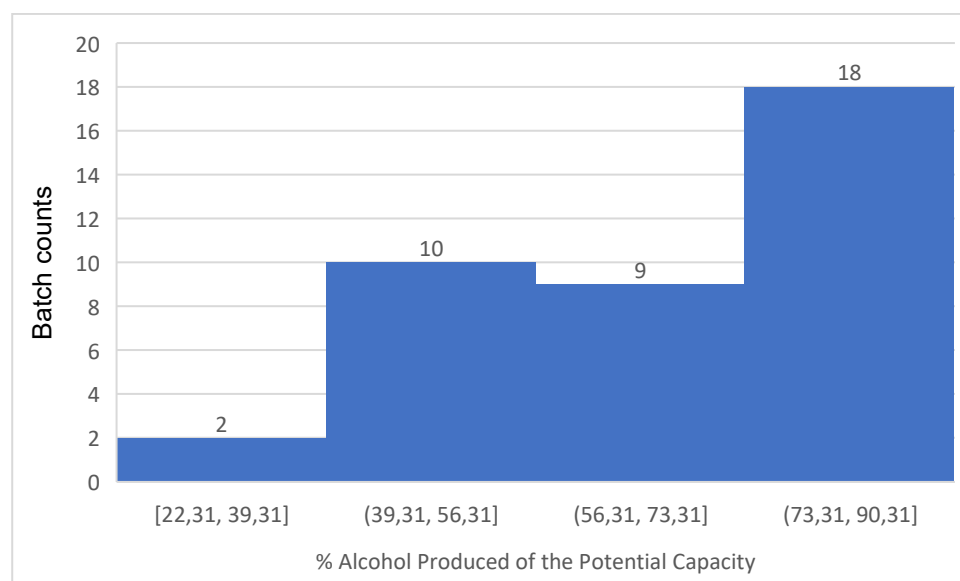


Figure 17: Produced alcohol of the total potential capacity.

- Figure 17 shows that the distillery produced between 73 % and 90% of the potential capacity 18 times out of the 40 batches.
- The distillery produces less than 70% of its potential capacity 21 times.

5.3.6. Deviation (%) between produced and potential alcohol yield.

Figure 18 below, is showing how much the actual alcohol produced by the distillery is deviating from the potential alcohol produced after fermentation.

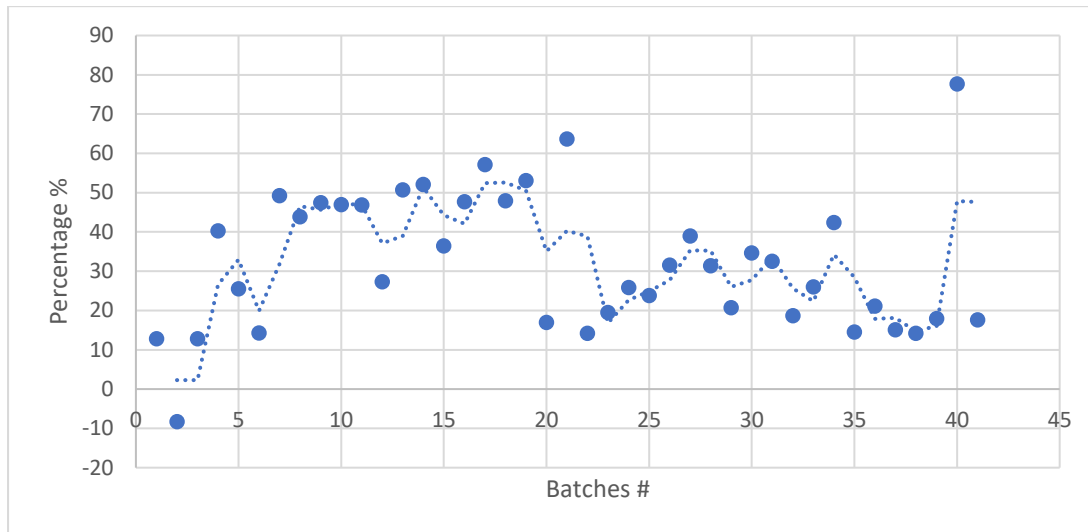


Figure 18: Deviation of alcohol production.

- On Figure 18, it can be noticed that the deviation between the potential alcohol and actual alcohol is not uniform, as it increased from batch 1 to 19, reduces between 19 and 21 then remain around 20 %.
- The average deviation stands at **32.29 %**.
- In numerical terms, this average deviation is equivalent to **65.37 kg** for every 500 kg of sugar introduced into the system.
- Among the 41 batches analysed, merely 14 exhibited a deviation less than or equal to 20%. Consequently, it is apparent that the distillery experienced high deviations approximately **65.85%** of the time, indicating a substantial degree of variability.

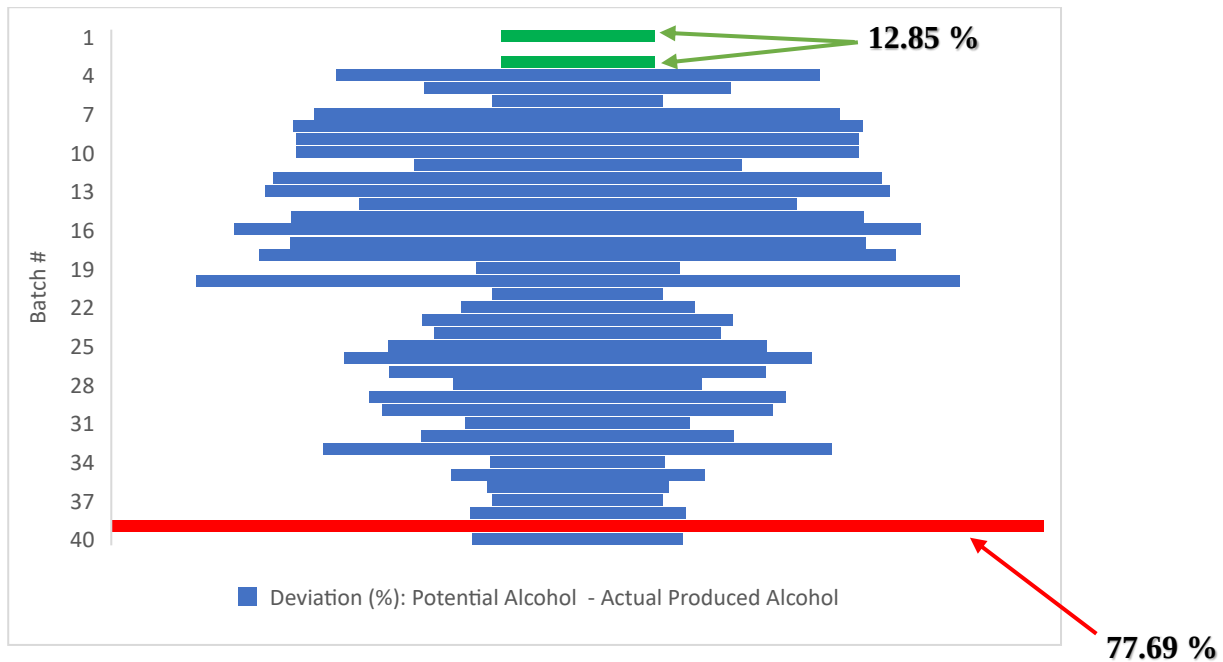


Figure 19: Deviation = Potential alcohol minus Produced alcohol in kg

Figure 19 above, shows the deviation percentage between potential and produced alcohol.

- Batch 39, highlighted in red, recorded a difference of 155 kg making it the highest deviation of 77.69 %.
- Batch 1 & 3, highlighted in green, recorded a difference of 8 kg, making it the smallest deviation of 12.84 %.

➤ High Deviation:

A deviation exceeding 20% is considered significantly high for this research, given that the optimal scenario aims for minimal deviation (close to zero). The most substantial deviation, at 77.69 %, occurred during the 37th batch, corresponding to 155.088 of alcohol. Notably, the data indicates that the alcohol by volume (ABV) at the end of fermentation reached approximately 2.1%, whereas it should ideally fall within the range of 7-8% (Mathew et al., 2015). This abnormal fermentation process is the primary cause of this substantial loss.

The ABV data, while available, did not provide substantial insight into the implications of premature fermentation. Enhanced computational methods, thorough analysis, and advanced data visualisation can facilitate the anticipation of fermentation impacts, thereby enabling informed planning and the rectification of issues at earlier stages. This underscores the significance of digitalization in these processes. Besides batch 40th, few other batches recorded high deviations. The following batches recorded deviations higher than 20 %:

Table 5: High deviation vs alcohol amount in kilogramme.

Batch #	Deviation %	Deviation (kg)
4	40,288	48,213
5	25,572	39,880
7	49,2746	271,389
8	43,840	109,549
9	47,417	117,126
10	46,925	74,160
11	46,89	121,398
12	27,338	57,853
13	50,687	128,61
14	52,085	75,040
15	36,43	80,102
16	47,727	97,084
17	57,187	114,210
18	47,974	110,765
19	53,098	103,505
21	63,674	135,974
24	25,89	18,104
25	23,849	54,093
26	31,566	35,602
27	39,004	91,622
28	31,396	6,641
30	34,696	61,143
31	32,541	50,264
33	26,051	12,815
34	42,427	73,83
36	21,143	48,443
40	77,689	155,088

There were 27 batches that documented deviations surpassing the 20% threshold. This implies that, on the one hand, the distillery is experiencing a substantial divergence between the actual alcohol yield and the maximum achievable yield in **65.85%** of the instances. Subsequently, **34.14 %** of the time, the distillery does not record high deviations.

➤ Lower Deviation

The lowest deviations of 12.85 % were observed in the 1st and 3rd batches, corresponding to 8.89 kg and 17.34 kg, respectively. Several other batches also exhibited deviations of 20 % or less, including batches 6, 20, 22, 23, 29, 32, 35, 37, 38, 39, and 41.

Table 6: Low deviation vs amount in kilogramme.

Batch #	Deviation %	Amount in kg
1	12.848	8,888
3	12.848	17,339
6	14,280	20,14
20	16,969	34,3
22	14,19	22,884
23	19,49	54,13
29	20,72	41,09
32	18,678	45,198
35	14,565	24,286
37	15,122	27,715
38	14,240	25,456
39	17,995	36,567
41	17,594	38,866

Out of the 41 batches examined, only 14 exhibited deviations lower than 20 %, which are considered for this research as low deviations. This implies that the brewing process achieves the desired outcome merely **34.17 %** of the time in the distillery. Furthermore, the calculated average deviation of **32.29 %** significantly exceeds the **20%**.

While the data was accessible, it did not provide a detailed breakdown of these deviations. Thus, the implementation of digitalisation becomes pivotal to identify batch issues, forecast results, and enact necessary corrections in a timely manner before transitioning to subsequent unit operations. This proactive approach facilitates the optimisation of plant operations.

CHAPTER 6: STATISTICAL ANALYSIS

6.1. Overview

6.1.1. Introduction

Statistical studies are conducted for the purpose of data analysis, aiming to extract relevant information from process data to enhance the significance of digitalisation efforts. In addition to computing averages, modes, plotting graphs, and making other observations on the data, two statistical tools, correlation analysis, and the single-sample Student's t-test, were utilised to derive several useful findings from the data.

6.1.2. Correlation Analysis

Correlation analysis is a statistical method employed to elucidate the relationships between variables, with a particular emphasis on quantifying the strength and direction of these associations (Gogtay and Thatte, 2017; Senthilnathan, 2019). It is essential to note that correlation does not establish causation but provides insights into how variables are interrelated. This analysis can reveal whether the relationship is positive, negative, or even non-existent (Gogtay and Thatte, 2017). Additionally, correlation quantifies the degree of closeness or proximity between two variables (Senthilnathan, 2019).

6.1.3. Single Sample Student t Test

The one-sample Student t test serves the purpose of determining whether the calculated mean, derived from a sample data collected from a single group, significantly differs from an expected value specified in a study (Al-Achi, 2019; Trkulja and Hrabač, 2020). This statistical test is a valuable tool in assessing whether the observed data deviates from the anticipated values, contributing to robust hypothesis testing and informed decision-making.

6.2. Correlation Analysis

6.2.1. Correlation Tables

Table 7: Correlation of mash tun parameters.

	Adjunct Quantity (kg)	Sugar supplied (Kg)	Specific Gravity	Extract (g/100g wort)	Volume of Wort (L)	Mass of Wort (kg)	Sugar in Wort (kg)	Sugar Lost (kg)	Sugar Lost (%)
Adjunct Quantity (kg)	1								
Sugar supplied(kg)	1	1							
SG (Original Gravity OG)	-0,112	-0,112	1						
Extract Degree Plato (g/100g wort)	-0,110	-0,110	0,999	1					
Volume of Wort (L)	0,809	0,809	0,026	0,033	1				
Mass of Wort (kg)	0,801	0,801	0,073	0,080	0,999	1			
Sugar in Wort (kg)	0,508	0,508	0,644	0,655	0,742	0,774	1		
Sugar Lost (kg)	0,159	0,159	-0,822	-0,832	-0,250	-0,292	-0,769	1	
Sugar Lost (%)	-0,078	-0,078	-0,828	-0,838	-0,442	-0,482	-0,886	0,957	1

Table 8: Correlation of alcohol production parameters.

	Mass of Wort	ABV (%)	Sugar in Wort (kg)	Potential Alcohol (kg)	Actual Alcohol (kg)	Deviation (kg)	Deviation (%)	Actual produced vs Potential (%)
Mass of Wort	1							
ABV (%)	-0,118	1						
Sugar in Wort (kg)	0,774	0,218	1					
Theoretical Potential Alcohol (kg)	0,774	0,218	1	1				
Actual Alcohol (kg)	0,708	0,588	0,791	0,791	1			
Deviation (kg)	0,517	-0,241	0,793	0,793	0,254	1		
Deviation (%)	0,157	-0,593	0,307	0,307	-0,305	0,788	1	
Actual produced vs Potential (%)	-0,157	0,593	-0,307	-0,307	0,305	-0,788	-1	1

Table 9: Correlation of fermentation parameters

	SG (Original Gravity OG)	Initial Extract Degree Plato (g/100g wort)	Alcohol by volume ABV (Av/v)	Alcohol by weight (Aw/w)	Final Extract: Real Extrat	Sugar: Lost Final -Initial
SG (Original Gravity OG)	1					
Initial Extract Degree Plato (g/100g wort)	0,999	1				
Alcohol by volume ABV (Av/v)	0,551	0,552	1			
Alcohol by weight (Aw/w)	0,514	0,515	0,999	1		
Final Extract: Real Extrat	0,992	0,993	0,645	0,610	1	
Sugar: Lost Final -Initial	0,552	0,555	0,999	0,998	0,647	1

Correlation Legend

	Perfect Positive Strongly Considerable High
	Perfect Negative Strongly Considerable High
	Fair or Moderate
	Very Weak Negligeable

6.2.2. Correlation Interpretation - Mash Tun

6.2.2.1. Adjunct quantity

- There is a positive, strong, considerable, and high correlation between the adjunct quantity and both the wort volume as well as the sugar in wort ($r = 0.81$ and $r = 0.51$).
- The positive relation between the adjunct quantity and the volume of wort and sugar in wort means that they increase or decrease simultaneously. The quantity of sugar extracted from the grain starch is intricately linked to the amount of adjunct supplied. As the source of sugar and starch, represented by the adjunct quantity, increases, there is a proportionate augmentation in the sugar extracted from the grain. This implies that to optimise sugar yield in brewing, it is advisable for the brewer to furnish the mash with the maximum feasible amount of adjunct.

Therefore, the wort volume (or sugar in wort) can be predicted or controlled by monitoring the amount of adjunct supplied into the mash tun.

6.2.2.2. Original (Initial) Specific Gravity (SG)

- A highly significant negative relationship exists between the original gravity and sugar lost during the mashing process ($r = -0.82$). This signifies that as sugar loss during mashing is minimised, the original gravity of the process solution is kept high. Mashing, which involves extracting sugar in a mash tun using warm water, directly impacts sugar extraction and, subsequently, sugar content in the wort, quantified as initial specific gravity, before the onset of fermentation. This interconnection justifies the incorporation of initial specific gravity in sugar loss computations.
- A Perfect relationship exists between the original gravity and the sugar extracted during mashing ($r = 0.99$), as the latter is derived from the former.
- There is a robust correlation between the original gravity and the sugar content in the wort ($r = 0.64$). The original specific gravity serves as an indicator of the sugar concentration within the wort.
- A very weak relationship ($r = 0.026$) is observed between the original gravity and the volume of wort (or wort mass). Therefore, the original specific gravity of the process solution does not depend on the wort volume or its mass.

6.2.2.3. Sugar Extract (°P)

- There is a strong negative correlation between sugar extraction and sugar loss ($r = -0.83$), indicating that higher sugar extraction during mashing is associated with lower sugar losses in the process.
- Sugar extraction has minimal impact on wort volume; an increase in sugar extraction does not significantly affect wort volume ($r = 0.033$).

6.2.2.4. Volume of Wort (L) | Mass of Wort (kg)

- The wort volume (or mass) exhibits a negative moderate to strong influence on sugar loss during mashing, indicating an inverse relationship. When sugar loss is minimised, wort volume (or mass) is enhanced ($r = -0.44$ and $r = -0.48$).
- The wort volume (mass) is positively correlated to the quantity of sugar supplied to the mash tun ($r = 0.81$). An increase in the sugar supplied to the mashing tun leads to a higher wort volume (mass).
- There is a significant positive correlation between the wort volume (mass) and the sugar content in wort ($r = 0.74$). An increase in sugar content is associated with a higher wort volume (mass).

6.2.3. **Correlation Interpretation - Potential & Produced Alcohol Balance**

- The mass of wort exhibits a highly significant positive correlation with both potential alcohol and produced alcohol ($r = 0.77$ and 0.71). This suggests that as the wort becomes heavier, it results in higher alcohol production. This correlation can be explained by the fact that wort mass is closely related to its sugar content, which in turn influences alcohol production.
- The mass of wort shows no significant correlation with alcohol by volume (ABV). The correlation is either very weak or negligible ($r = -0.1179$), indicating that the wort mass has little impact on the ABV.
- The alcohol by volume (ABV) exhibits a considerable negative relationship with the deviation results between the potential alcohol and the actual produced alcohol ($r = -0.59$). This implies that, the more alcohol is produced for a single batch, the smaller the gap between the potential alcohol and the produced one.

- A perfect positive correlation exists between sugar in wort and potential alcohol yield ($r = 1$). The potential alcohol production is entirely dependent on the sugar content in the wort. More sugar in the wort will result in a higher alcohol yield.
- It is observed in the correlation analysis, that the higher the potential alcohol mass to produce, the higher the deviations between the potential and produced alcohol ($r = 0.79$).

6.2.4. Correlation Interpretation - Fermentation

- There is a positive strong relationship between the initial gravity and the alcohol by volume (by weight) produced. The higher the initial gravity, the higher the alcohol by volume produced. The sugar loss was observed to be related to both original and final extract. Thus, a big difference between the two parameters leads to big losses.
- However, high original gravities also led to considerable high losses. This is an abnormal situation. It could mean that fermentation did not go as expected due to unforeseen situations. The correlation coefficient $r = 0.55$ (considerable).
- There is a positive considerable correlation between the final extract and the alcohol by volume (by weight). The higher the final extract, the higher the ABV (or weight) and vice versa.

6.3. Student t Test

6.3.1. Introduction

The test was conducted to derive useful information from historical data and assess the accuracy of data gathering. Sample data of parameters such as original gravity, final gravity and alcohol produced, were compared against their respective expected sample means. The results of this analysis on process data, could be useful to possibly spot production issues on time, manipulate process inputs to get desired results, in occurrence, expected sample mean of process data.

The t test may apply for both a single sample and two samples' scenarios (Al-Achi, 2019). In this research, two samples of the same nature such as original gravity of brewery A and brewery B, are not being compared. Thus, the aim is to analyse the distribution of data from a single sample around their hypothesized mean value, for each case. Hence, the single sample student t test is the chosen method.

The historical data parameters analysed are the following:

- Original Specific Gravity: 1.060 – 1.065
- Final Specific Gravity: 0.999 – 1.01
- Expected Alcohol: 7 – 8.5 %

6.3.2. Original Specific Gravity

Table 10: Student t test on original gravity of the distillery's historical data

t-Test: One Sample Test for Original Gravity (SG)				
	<i>SG (Original Gravity OG)</i>			
Mean	1,067414634			
Variance	0,000187649			
Observations	41			
Hypothesized Mean	1,0625			
df	40			
t Stat	2,29726052			
P(T<=t) one-tail	0,013457816			
t Critical one-tail	1,683851013			
P(T<=t) two-tail	0,026915631			
t Critical two-tail	2,02107539			
Mean	1,0625			
Hypotheses:				
Null Hypothesis $H_0: \mu \leq$	1,0625			
Alternative Hypothesis $H_1: \mu >$	1,0625			
Rejection Region: Reject H_0 if t stat > t critical =	1,683851013			
Test Statistic: t stat =	2,29726052			
p Value:	0,013457816			
DECISION CONCLUSION				
stat > t critical : 2,29726052 > 1,683851013	Reject null hypothesis			
p Value < α : 0,013457816 < 0,05	Reject null hypothesis			
There is enough evidence to infer that the mean original gravity is significantly greater than 1,0625				

The purpose of the test was to assess the proximity of the collected original gravity values to the hypothesised mean value in a typical brewing process. In fact, it aimed to confirm if the calculated mean of the original gravity sample data differed significantly from the expected mean.

At Primal Spirit Distillery, the expected range for original gravity is between 1.060 and 1.065. hence, every collected valued was compared to the interval mean of 1.0625.

t stat is greater than t critical ($2.297 > 1.684$), it can be concluded that the difference between the sample mean, and the hypothesised (expected) mean is significantly different. The conclusion of the student t test is that there is enough evidence to infer that the mean original gravity is significantly greater than 1.0625 (the hypothesised mean). This means that the original gravity tends to be greater than 1.0625.

The null hypothesis, which posits that the mean is inferior than or equal to 1.0625 ($H_0: \mu \leq 1.0625$), is rejected. This leads to the conclusion that the alternative hypothesis is true, where the mean is greater than 1.0625 ($H_1: \mu > 1.0625$).

6.3.3. Final Specific Gravity

The final gravity is expected to be between 0.999 and 1.01 at Primal Spirit Distillery, hence, every collected valued was compared to the interval mean of 1.0045.

With a t statistic greater than the critical t value ($4.33 > 1.68$), it can be deduced that the disparity between the sample mean, and the hypothesized mean is statistically significant. Consequently, based on the findings of the student's t-test, there is substantial evidence to support the assertion that the mean final gravity exceeds 1.0045 (the hypothesized mean). This implies a tendency for the final gravity to surpass 1.0045.

The null hypothesis, asserting that the mean is less than or equal to 1.0045 ($H_0: \mu \leq 1.0045$), is rejected in favour of the alternative hypothesis. The alternative hypothesis posits that the mean is greater than 1.0045 ($H_1: \mu > 1.0045$).

Note: The student t-test table of calculations for the final SG is on the appendix section.

6.3.4. Alcohol by Volume (%)

The alcohol by volume is expected to be between 7 and 8.5 % at Primal Spirit Distillery, hence, every collected valued was compared to the interval mean of 7.75 %.

With a t statistic lower than the critical t value ($-2.289 < 1.683$), it is concluded that there is insufficient evidence to suggest that the mean alcohol by volume is significantly greater than

7.75% (the hypothesized mean). This indicates a tendency for the alcohol by volume to be lower than 7.75%.

The null hypothesis, which states that the mean is less than or equal to 7.75% ($H_0: \mu \leq 7.75\%$), is not rejected. The alternative hypothesis, which posits that the mean is greater than 7.75% ($H_1: \mu > 7.75\%$), is deemed incorrect based on the analysis.

Note: The student t-test table of calculations for alcohol by volume is on the appendix section.

6.3.5. Student t test summary

The student t test analysis conducted on the original gravity and the final gravity showed that the sample mean of historical process data is significantly different from the expected mean. They both have the tendencies of being higher than their respective hypothetical mean.

Nonetheless, the analysis on the alcohol by volume did not give enough evidence to suggest that the mean alcohol by volume is significantly greater than 7.75% (the hypothesized mean). This indicates a tendency for the alcohol by volume to be lower than 7.75%.

If the process data was digitalised, the information would have been readily accessible and process data manipulated to avoid affecting future production.

CHAPTER 7: DIGITALISATION & INTERVENTION

7.1. Mashing Mass Balance Analysis Summary

7.1.1. Sugar Loss Analysis

The brewing process exhibited notable variations in sugar losses across batches, with higher losses observed in the initial batches (1-6), an aberrant negative value in batch 7 due to measurement errors, and a consistent trend from batches 8 to 41. The anomalous data in batch 7 were attributed to parallax errors, incorrect estimates, or mismeasurements. It is not sensible to have a situation whereby, the loss is higher than the sugar coming into the system.

Therefore, there is a substantial amount of sugar being lost during mashing, averaging at 16.45 % or 69.19 kg across the batches.

7.1.2. Sugar Input vs. Output

Visual inspection of the graph indicated a consistent difference between sugar input and output from batches 8 to 41, gradually increasing from batches 1 to 6. The adjustments in parameters during batches 1 to 6 suggest a refinement phase in the distillery's process.

7.1.3. Comparing Sugar Input and Loss

Theoretically, under consistent production conditions, losses should align with the same order as input. This theoretical expectation was substantiated by the observed consistency in the difference between sugar input and loss. Specifically, batches 1 to 9, 11 to 23, 31 to 32, and finally, 34 to 41 showcased a uniform trend in sugar input. Even during batches 24 to 33, marked by variations in sugar fed into the mash tun, the losses maintained a consistent pattern akin to the stable segments, emphasizing the need for more comprehensive data to identify issues.

Digitalisation and Intervention:

The mashing phase reveals a notable loss of sugar, primarily attributed to suboptimal extraction processes. It also revealed that measurement of process data was somehow inaccurate resulting in having negative losses which are impossible to get theoretically.

- Therefore, digitalising process data and having it recorded or stored for instance on an online platform, would increase precision, better accessibility, and manipulations of process inputs based on historical data information.
- Manual data collection presents a clear bottleneck in addressing the intricacies of the issue. An advanced approach involves the implementation of simple digital devices capable of automating data collection, recording, and providing real-time displays for operators. This digital infrastructure enables instantaneous analysis and decision-making, especially crucial in scenarios where deviations need prompt attention.
- Effective monitoring, coupled with precise process control involving calculated prediction and real-time rectification, emerges as a viable solution. The efficacy of problem-solving strategies derived from data analysis, is compromised without the integration of proper digitalisation, specifically adapted to the distillery.
- Despite the availability of valuable information, accessibility and visibility pose challenges in the absence of proper digitalisation. The intricacies of adjustment during production, especially pre-emptive actions before deviations attain significance, become challenging without real-time data insights. Historical data, in its conventional form, lacks the direct capacity for the level of analysis, interpretation, and decision-making afforded by digital tools, underscoring the necessity of technological advancements for streamlined processes. For instance, there was clearly an error in measuring parameters for batch 7. It was later considered and taken into account by the distillery. It could have been removed from the dataset from the beginning and serve as adjustments for the rest of the batches.

7.2. Fermentation Mass Balance Analysis

- Among the 41 batches analysed, 22 fall within the acceptable alcohol percentage range (7-8%), accounting for 53.66% of the total. This further implies that the fermentation process or its precursor such as mashing, deviated from the optimal parameters in many instances.
- 18 losses (the most) out of 40 batches recorded masses between 1.12 kg and 1.53 kg, which makes it the interval mode. Furthermore, it shows that the most losses occurred around the average of 1.29 kg of ethanol per batch.
- The distillery produced between 73 % and 90% of the potential capacity 18 times out of the 40 batches. The distillery produces less than 70% of its potential capacity 21 times.
- The highest deviation between potential alcohol and the actual production is 155 kg (77.69 %). The smallest deviation is 8 kg (12.84 %).
- The most deviations (19 times) occurred between the 12.85 % and 29.85 % interval. The highest deviations between 63.85 % to 80.85 % occurred once.
- The disparity between initial extract and final extract remains relatively constant, as depicted in the fermentation analysis graph (figure 13). The average deviation is quantified at 2.4 °P, with a statistical mode of 2.23 °P. This implies that, on average, the distillery experiences a loss of 2.29 °P per fermentation batch, with the most probable loss being 2.23 °P.
- The ratio between final extract and initial extract exhibits a consistent trend. The mean ratio is calculated as 1.12 °P, with a mode of 1.15 °P. This indicates that the final extract tends to be 1.15 °P greater than the initial extract for each batch, with the most probable ratio being 1.12 °P.

Digitalisation and Intervention:

Having process data digitised and stored on a platform which makes this analysis could provide useful information about losses on time which could eventually lead to interventions put in place to minimize high losses across the fermenter.

Fermentation was executed 41 times in the distillery, with only 22 instances yielding alcohol within the acceptable range. The historical data, in its raw form, did not inherently provide insights of this nature, necessitating calculation, representation, and interpretation.

Accessing this valuable information is non-trivial and lacks inherent visibility. The process of visualizing and resolving issues demands time and effort, but this can be instantaneously addressed through digitalization.

7.3. Potential alcohol versus Actual alcohol produced:

- Analysis of data and graphical representations reveals an average deviation of 32 % between potential and actual alcohol, equivalent to 65.37 kg for 500 kg of sugar fed into the system.
- Among 41 batches, merely 14 exhibited a deviation equal to or below 20%, signifying that the distillery experienced high deviations 65.85% of the time, a statistically significant occurrence.
- The average alcohol production, relative to potential capability, is approximately 68 %.

Digitalisation and Intervention:

Understanding the potential alcohol output based on the supplied sugar allows for proactive prediction and intervention in the event of substantial deviations.

To mitigate the variance between the theoretical target (potential alcohol) and the realized alcohol yield, a comprehensive monitoring approach is imperative, ensuring that mashing is executed according to specifications and fermentation is carried out normally; hence, the pivotal role of digitalisation in process data management for real-time monitoring, computational analysis, alarm systems, and control mechanisms.

The instantaneous availability and storage of critical information in a cloud-based system could enhance production efficiency, minimising losses. This facilitates important adjustments before subsequent unit operations, allowing for the exploitation of feedback control mechanisms to further refine the process.

7.4. Correlation Analysis Summary & Digitalisation

7.4.1. Mashing

7.4.1.1. Adjunct quantity | Sugar supply

There is a positive, strong, considerable, and high correlation between the adjunct quantity and both the wort volume as well as the sugar in wort ($r = 0.81$ and $r = 0.51$).

Interventions and Benefit of Digitalisation:

- **Solids flow meters and digital scales**, such as centriflow solids mass flow meters, can be utilised for feedforward process control. This ensures a predetermined amount of adjunct is measured before entering the mash tun. Digitalisation facilitates the regulation of adjunct flow into the system. Excess adjunct can lead to a higher wort volume, resulting in excess sugar that may not be fully consumed by the yeast to produce alcohol.

Digitalisation of process data enhances timely access to information. By digitally monitoring and controlling the quantity of adjunct supplied to the mash tun, one can predict the wort volume, assuming constant mash efficiency.

- **Level Sensor:** In case of a feedback process control, a level sensor related to a volume measurement could help an actuator to adjust the adjunct intake into the mash tun to enhance consistency in sugar supply. The feedback benefit is to get a determined amount of adjunct for the process.

7.4.1.2. Original Gravity and Sugar Loss Analysis:

A highly significant negative relationship exists between the original gravity and sugar lost during the mashing process ($r = -0.82$). A Perfect relationship exists between the original gravity and the sugar extracted during mashing ($r = 0.99$). There is a robust correlation between the original gravity and the sugar content in the wort ($r = 0.64$).

Interventions and Benefit of Digitalisation:

The process data should be digitally stored on a platform such as a data analytics online cloud or a hard drive, ensuring timely accessibility. The platform should be equipped with programmed algorithms to perform correlation calculations, enabling the extraction of useful information from the process data.

7.4.1.3. Sugar Extract (°P) and Sugar in Wort (kg):

There is a strong negative correlation between sugar extraction and sugar loss ($r = -0.83$), indicating that higher sugar extraction during mashing is associated with lower sugar losses in the process. This signifies that higher sugar extraction during mashing corresponds to lower sugar losses in the process, a logical association given their simultaneous occurrence.

Intervention and Digitalisation Advantages:

- **Predictive analysis:** Armed with the knowledge of sugar extract, predictions regarding losses can be made. The evaluation of mashing effectiveness becomes feasible, allowing for proactive measures to mitigate potential losses. A predictive analysis performed on a digital platform would be reducing losses.
- **Digital data processing:** Through digitalisation, the continuous monitoring of original gravity, as detailed earlier, facilitates the instantaneous computation of sugar extract. This can be achieved manually or through a calculator.

In essence, digitalisation, in conjunction with continuous monitoring, empowers brewers to make informed decisions and interventions based on real-time data, enhancing overall process efficiency.

7.4.1.4. Sugar in Wort and Alcohol yield:

The sugar content in wort demonstrates a robust positive correlation with the actual alcohol produced, as indicated by a correlation coefficient of $r = 0.79$. This implies that an increase in sugar concentration directly corresponds to an elevation in alcohol production during the fermentation process, on the condition that enough yeast has been supplied.

Digitalisation for Precision and Prediction:

- **Monitoring specific gravity:** Utilising digital tools to continuously monitor the specific gravity of the wort provides valuable information on its sugar content. This real-time data is important in predicting potential alcohol production accurately.
- **Extract computation:** By relating specific gravity readings to the extract or sugar concentration in the solution, a precise determination of sugar content in the wort can be achieved. This information serves as a crucial factor in forecasting the potential alcohol yield. Specific gravity process data could be stored on a platform which is also able to make calculations and conversions.

- Comprehensive alcohol prediction: Leveraging digitalisation for this purpose not only aids in determining the sugar content in the wort but also enables the accurate prediction of the total potential alcohol production. This integration of data contributes to informed decision-making and optimisation in the brewing process.

7.4.1.5. Volume of Wort (L) | Mass of Wort (kg)

- A discernible correlation exists between the volume (mass) of wort and both sugar in wort and sugar supplied. When sugar loss is minimised during mashing, wort volume (or mass) is enhanced ($r = -0.44$ and $r = -0.48$).
- An increase in the sugar supplied to the mashing tun leads to a higher wort volume (mass) ($r = 0.81$).
- An increase in sugar content is associated with a higher wort volume (mass).

Intervention and Digitalisation Advantages:

- Maintaining an optimal or predetermined set point for the volume of wort is crucial to prevent downstream sugar loss. Utilising interventions such as level (volume) measurement and control become essential. This approach parallels the monitoring strategy employed for adjunct quantity.
- Achieving the desired and accurate volume (mass) of wort necessitates the careful scaling and monitoring of sugar input into the system. This monitoring occurs at the commencement of mashing and during the measurement of wort post-formation.
- To ensure precise sugar measurement during mashing initiation, digital scales or solid flow meters can be employed. Following wort formation, level sensors, integral to volume measurement, serve as effective tools for monitoring and maintaining the targeted wort volume. A strategic combination of digital tools for measurement and control is paramount for ensuring the volume of wort aligns with production objectives and mitigating downstream sugar losses.

7.4.2. Fermentation

During fermentation, it was observed that higher initial gravity corresponded to higher alcohol by volume, on the condition that the process occurs as expected. Sugar loss was found to be correlated with both original and final extract, indicating that a significant difference between

these parameters leads to increased losses. Additionally, higher final extract was associated with higher ABV, and vice versa.

Interventions and Benefits of Digitalisation

The analysis conducted in this study aided in determining the efficiency of fermentation. Utilising process data on a platform will enable the calculation of mass balance over the fermenter to get useful information about alcohol production, to help to avoid further losses, by manipulating important parameters that influence the overall process.

7.4.3. Correlation between Potential Alcohol and Actual Alcohol

The mass of wort exhibits a robust correlation with both potential and actual alcohol production, denoted by correlation coefficients $r = 0.71$ and $r = 0.77$, respectively. This correlation underscores the direct relationship between the weight of the wort and the resultant alcohol content. This relationship is intricately tied to the sugar content within the wort.

The derivation of mass of wort involves considerations of volume, a parameter strongly associated with the sugar content in the wort. An augmented sugar content, theoretically reaching its maximum, correlates with an increased potential for alcohol production. This dynamic relationship is contingent upon the presence of yeast in the requisite quantity for fermentation.

Intervention and Digitalisation Strategies:

The interplay between mass of wort, potential alcohol, and actual alcohol underscores the critical role of digital tools in enhancing measurement accuracy and process control, ultimately contributing to optimised alcohol production. First, a digital scale can be utilised to maintain control over the brewing process and optimising alcohol production. Secondly, a practical implementation of level sensor can be executed for volume determination.

7.4.4. Additional Intervention for overall process

- **Deviation computation software:** Employing specialised software capable of real-time computation facilitates the continuous monitoring of the variance between potential and actual alcohol production. This software can generate signals prompting timely adjustments upstream, offering intervention opportunities during critical stages such as mashing and fermentation.
- **Manual deviation computation:** In parallel, manual computation methods, if meticulously executed, can serve as an alternative to software solutions. These methods involve continuous monitoring of sugar and yeast quantities, enabling intervention measures to be implemented during pivotal stages of the brewing process.

7.5. Student t Test Analysis Summary & Digitalisation

7.5.1. Original Gravity

Optimising original gravity necessitates a meticulous approach involving accurate water volume control, standardised adjunct quantity, and immediate adjustments guided by precise measurements.

Upon statistical analysis, the observed difference between the sample mean and the hypothesized (expected) mean of 1.0625 is found to be significantly divergent. This implies that the target original specific gravity may not be attained post-mashing at Primal Distillery. Furthermore, the trend indicates a tendency for the original specific gravity to surpass 1.0625. There is a necessity for precise process control. Achieving the specific gravity of 1.0625 demands meticulous control over adjunct quantity and precise water volume measurement. Employing a digital apparatus capable of accurately quantifying both adjunct and water becomes imperative.

The proposed technical measures have the capacity to ensure the attainment of the targeted specific gravity:

- **Flow Meter for Water Quantification:**

Implementing a flow meter facilitates the precise measurement of water entering the mash tun. This aids in maintaining a standardised water-to-adjunct ratio crucial for specific gravity control.

- **Alternative Approach - Level Sensor:**

An economical alternative involves utilising a level sensor to gauge the liquid level in the mash tun. If the adjunct quantity is standardised, correlating the liquid level with volume allows for halting water supply once the desired level is reached. This provides a cost-effective substitute for pricier flow meters.

- **Automated Specific Gravity Measurement Tools:**

Employing automated tools such as a hydrometer (SG Meter) or refractometer becomes pivotal. If the desired density of 1.0625 is not achieved pre-fermentation, a feedback signal triggers an adjustment in adjunct quantity within the mash tun.

7.5.2. Final Gravity

The difference between the sample means and the hypothesised (expected) mean came up significantly different. This means that the final specific gravity of 1.0045 is likely not to be achieved after fermentation. In fact, the final specific gravity tends to be greater than 1.0045.

If the measurements are correct for the original gravity, the final gravity will also be positively impacted. The focus should be to achieve a specific gravity of 1.0625 before fermentation, and finally get a final gravity of 1.0045 (close to 1) after fermentation.

In case there is an abnormal fermentation, where the final gravity does not reduce to a value close to 1, a digital device should be used to give the instant gravity reading before considering any kind of intervention.

Hence, an automated specific gravity measurement with either a hydrometer or a refractometer could be used. The adjustments include the yeast and sugar quantity in the solution at the correct temperature.

CHAPTER 8: ECONOMIC STUDY

8.1. Introduction

The purpose of this study is to assess the financial benefit, and the profitability associated with the digitalisation of process data within the distillery. This entails evaluating the viability of the investment through analysis of the distillery cash flow change, its improved revenue, the return on investment and the payback period. The methodologies employed in this study are applicable to diverse production or manufacturing entities.

8.2. Temperature Control Irrelevance

As stated in the literature review, for traditional breweries, temperature control is paramount for monitoring fermentation. The production of beer depends heavily on specialized yeast strains that are highly temperature sensitive (Tamo and Hilario-Tacuri, 2020). These strains function effectively only within a limited temperature range to generate the intended flavour characteristics (Tamo and Hilario-Tacuri, 2020). Even minor temperature fluctuations can result in unwanted off-flavours, such as esters or fusel alcohols, which can significantly alter the beer's taste (Tamo and Hilario-Tacuri, 2020). Maintaining precise temperature control during fermentation is essential for achieving the distinct flavour profile of each beer style (Tamo and Hilario-Tacuri, 2020).

In contrast, spirit production typically involves yeast operating in high-alcohol environments, where the subtle flavours from fermentation are less critical because they are largely refined or eliminated during the distillation process. In this study, every batch was distilled to attain an alcohol content between 93 and 94%.

Therefore, there is no need to include temperature sensors in the investment estimate in table 11 for the investment estimate on point 8.3.

8.3. Investment Estimate

Table 11: Equipment price estimate

Keg Monitoring system: Level	CAD = USD 156	(Kegworks, 2023)
SCADA Licence keys and accessories & Development and installation	USD 95 + USD 620 = USD 715	(Icpdas, 2023)
Flow meter for Solids: digital scale	USD 1800 or USD 7000	(Alibaba, 2023)
Tank level sensor (Water)	USD 65 – USD 120	(Alibaba, 2023)
Level Switch for Sticky Solids and Liquids	USD 182	(Sapco Instruments, 2023)
Brewing Grain Storage Scale Kit	USD 65 - USD 100	(Northern Brewer, 2023)
CO₂ Harvester Kit: CO₂ gather and store during fermentation.	USD 50 NB: use 3 to 6 depending on brew volume.	(IC Controls, 2023) (Norcal Brewing Solutions, 2023)
Airlock - Plastic - Double Bubble	USD 2	(CO ₂ Meter, 2023)
Industrial Water Meter	USD 245 – USD 366	(Flows, 2024) (Measurement Control Systems, 2024)

8.3.1. Cost of digital insertion.

Total: USD 3283 = R 62 377 (using rate: 1USD = R19)

Installation and commissioning estimate (30%) = USD 1163.7 = R 18 713

Miscellaneous (5%) = USD 193.95 = R 3118.85

Total of equipment, installation and commissioning = USD 4 432.045 = R 84 208.85

8.3.2. General Training and Digital Systems Training: 5-10%

R 84 208.85 x 10% = **R 8 420.885**

8.3.3. Increase cost due to process improvements.

- Estimated Increase Maintenance Cost: 10 – 20%

Maintenance is done about 3 times a year. It is a better financial decision to use the upper limit of 20%.

$$R\ 84\ 208.85 \times 20\% = \mathbf{R\ 16\ 841.77}$$

- Estimated Increase Operational Cost: 5 – 10%

$$R\ 84\ 208.85 \times 10\% = R\ 8\ 420.885$$

This price is an estimate for about 3 months before maintenance. To account for 12 months of production, it is necessary to multiply by 3.

$$\text{Therefore, } R\ 8\ 420.885 \times 3 = \mathbf{R\ 25\ 262,655}$$

$$\mathbf{\text{Total cost of process improvement} = R\ 16\ 841.77 + R\ 25\ 262,655 = R\ 42\ 104,425}$$

- **Grand Total:** $R\ 84\ 208.85 + R\ 8\ 420.885 + R\ 42\ 104,425 = R\ 134\ 734,16$

For estimation purposes, it is recommended to overprice to overcome any unexpected expenses. Therefore, the investment is worth **R 200 000**.

Note: The total investment covers 12 months of production. For subsequent years, costs will be limited to maintenance and operations as the digital implementation is a one-time investment unless component replacement becomes necessary.

8.4. Productivity Improvement Calculation

Question to answer:

By how much will the productivity of the micro distillery be improved if the sugar loss is mitigated from 16.5% to below 5%, fermentation efficiency is elevated from 53.66% to 70%, the actual alcohol yield surpasses 70%, aligning with the theoretical alcohol yield, as opposed to 67.71% and the deviation rate is minimised from 65.85 % to ideally close to 0?

To calculate the potential improvement in productivity of the micro distillery based on the given changes, an initial productivity factor was derived, compared to a derived improved productivity factor, to deduce an improvement productivity factor. The following steps were taken:

- **Initial Productivity Factor:**

Derivation of the initial productivity factor of the micro distillery based on the given parameters:

Initial sugar loss = 16.5% = 0.165

Initial fermentation efficiency = 53.66% = 0.5366

Initial alcohol yield = 67.71 % = 0.6771

Initial deviation rate = 65.85% = 0.6585

Initial productivity factor = Initial sugar loss × Initial fermentation efficiency × Initial alcohol yield × (1 - Initial deviation rate) (27)

- **Improved Parameters:**

Definition of the improved values for each parameter:

Target sugar loss = 5% = 0.05

Improved fermentation efficiency = 70% = 0.70

Improved alcohol yield = >70% = 0.80 (for calculation purposes)

Target deviation rate = 5 % = 0.05

- **Improved Productivity Factor:**

Derivation of the improved productivity factor using the improved parameters:

$$\text{Improved productivity factor} = \text{Target sugar loss} \times \text{Improved fermentation efficiency} \times \text{Improved alcohol yield} \times (1 - \text{Target deviation rate}) \quad (28)$$

- **Overall Improvement Factor:**

Calculation of the overall improvement factor as the ratio of improved productivity to initial productivity:

$$\text{Improvement Factor} = \frac{\text{Improved Productivity Factor}}{\text{Initial Productivity Factor}} \quad (29)$$

- **Calculate Improvement Percentage:**

Calculation of the improvement percentage by subtracting 1 from the improvement factor and multiplying by 100:

$$\text{Improvement percentage} = (\text{Improvement factor} - 1) \times 100 \quad (30)$$

The values from the provided data are plugged and calculation is performed:

$$\text{Initial productivity factor} = 0.165 \times 0.5366 \times 0.6771 \times (1 - 0.6585) = \mathbf{0.02}$$

$$\text{Improved productivity factor} = 0.05 \times 0.70 \times 0.80 \times (1 - 0.05) = \mathbf{0.0266}$$

$$\text{Improvement factor} = \frac{0.0266}{0.02047284198} = \mathbf{1.299}$$

$$\text{Improvement percentage} = (1.299282241 - 1) \times 100 = 29.9282241 \% = \mathbf{29.93 \%}.$$

Therefore, if the specified improvements are achieved, the productivity of the micro distillery is estimated to improve by approximately **29.93% ≈ 30%**

8.5. Performance Analysis

The productivity improvement of 30% can be utilised to compute the ROI, determine the payback time, the breakeven point, and to make an informed decision on the viability of the investment.

The following steps are taken:

- **Operating Cash Flows:**

Estimation of the annual production cashflow after the digitalisation has been implemented, including revenue growth on the craft distillery's operations.

- **Calculate Net Cash Flows:**

Subtraction of the post-digitalisation operating cash outflows from the cash inflows to determine the net cash flow for a year.

- **Return on Investment (ROI):**

The ROI is calculated by dividing the net profit (Net Present Value of post-digitalisation cash flows minus initial investment) by the initial investment (Anderson and Fennell, 2013).

$$\text{ROI} = \frac{(\text{Net Present Value} - \text{Initial Investment})}{\text{Initial Investment}} \quad (31)$$

NB: The ROI is negative until the investment amount is fully recovered.

- **Payback Time:**

It is the time it takes to recover the initial investment from the project's post-digitalisation cash flows (Anderson and Fennell, 2013).

The cumulative cash flow is calculated for a year until it becomes greater than the investment amount of R 200 000.

- **Break-Even Point (BEP):**

This consist of estimating the production level at which the total production revenue is equal to the total production cost. (Mitchell, 2024).

8.6. Operating Cashflow

Table 12: Cash Flow Projection before investment

Months	Production Cost	Cost to Produce 1 L (ZAR)	Selling Price for 1L (ZAR)	Profit per L (ZAR)	Total Profit (ZAR)
1	94720	378,88	533,33	154,45	38613,33
2	94720	378,88	533,33	154,45	38613,33
3	94720	378,88	533,33	154,45	38613,33
4	94720	378,88	533,33	154,45	38613,33
5	94720	378,88	533,33	154,45	38613,33
6	94720	378,88	533,33	154,45	38613,33
7	94720	378,88	533,33	154,45	38613,33
8	94720	378,88	533,33	154,45	38613,33
9	94720	378,88	533,33	154,45	38613,33
10	94720	378,88	533,33	154,45	38613,33
11	94720	378,88	533,33	154,45	38613,33
12	94720	378,88	533,33	154,45	38613,33
1 136 640				1 853,44	463 360

The initial investment amount equals R 200 000. Adding the digital investment to the production cost, will help find the new production capital:

- $200\,000 + 94\,720 = \mathbf{294\,720}$ (for the 1st month)
- Number of runs: 4 /month
- Cost per run: R 29 600
- Total Production cost = R 118 400 / month to produce 312.5 L or 78.125 L per run
- R 1 420 800 / year to produce 3750 L.

Therefore, to produce 1L the distillery spends = $\frac{1\,420\,800}{3750} = \mathbf{R\,378.88}$

With an average price of R 400 for a bottle of 750 ml, the distillery makes **R 533.33 per L.**

Which means $3750 \times 533.33 = \mathbf{R\,1\,999\,987.5}$ per year.

8.7. State of the Distillery After Investment.

8.7.1. Basis of calculation

Prior to investing in digitalising process data, the distillery's fermentation efficiency stood at 53.66% with a deviation rate of 32.29%. To achieve a fermentation efficiency of at least 70% with minimal deviations, the overall process productivity must be increased by 30%, as determined through calculation.

Verification: $53.66 + (53.66 \times 0.3) = 69.758 \% \approx 70\%$.

The current volume of alcohol produced by the distillery is known. A 30% improvement indicates a reduction in alcohol loss during the process, resulting in a 30% increase in production. To determine the extent of the improvement in alcohol volume, 30% can be added.

$250 + (250 \times 30\%) = 325 \text{ L/month (minimum amount)}$.

After achieving a 30% increase in overall productivity, calculations were made for the new monthly volume (3.2 runs), new production costs, and profits. Additionally, the return on investment (ROI) was determined, and estimates were made for the payback time and breakeven point.

Assumptions: *The below tables are constructed on the minimum basis that the distillery makes 500 bottles per month (size), with an average of 3.2 runs per month, producing 250 Liters. The distillery can make more than that, however, for calculation and prediction purposes, it is better to base the analysis on the minimum production capacity of the distillery.*

8.7.2. Initial distillery Cash flow

Table 13: Cashflow before investment.

Months	Volume per Month Before	Volume per run Before	Profit per Month Before
1	250	78,125	38613,33
2	250	78,125	38613,33
3	250	78,125	38613,33
4	250	78,125	38613,33
5	250	78,125	38613,33
6	250	78,125	38613,33
7	250	78,125	38613,33
8	250	78,125	38613,33
9	250	78,125	38613,33
10	250	78,125	38613,33
11	250	78,125	38613,33
• 12	250	78,125	38613,33

Table 14: Production cost and Profit before investment

Months	Production Cost	Cost to Produce 1 L (ZAR)	Selling Price for 1L (ZAR)	Profit per L (ZAR)	Total Profit (ZAR)
1	94720	378,88	533,33	154,45	38613,33
2	94720	378,88	533,33	154,45	38613,33
3	94720	378,88	533,33	154,45	38613,33
4	94720	378,88	533,33	154,45	38613,33
5	94720	378,88	533,33	154,45	38613,33
6	94720	378,88	533,33	154,45	38613,33
7	94720	378,88	533,33	154,45	38613,33
8	94720	378,88	533,33	154,45	38613,33
9	94720	378,88	533,33	154,45	38613,33
10	94720	378,88	533,33	154,45	38613,33
11	94720	378,88	533,33	154,45	38613,33
12	94720	378,88	533,33	154,45	38613,33
	1136640			1853,44	463360

8.7.3. Improved production state of the distillery after investment

Table 15: Cumulative Profit after investment.

Months	Digitalisation Investment	Production cost after Investment	Profit Increase Per Run (29,93%)	Cost Per Run Before Investment	Profit Per Run Before Investment	Profit per Run After Investment	Profit Per month After Investment	Cumulative Profit Per Month After Investment
1	200000	294720	0,2993	29600	12066,667	15678,22	50170,304	50170,304
2	0	94720	0,2993	29600	12066,667	15678,22	50170,304	100340,61
3	0	94720	0,2993	29600	12066,667	15678,22	50170,304	150510,91
4	0	94720	0,2993	29600	12066,667	15678,22	50170,304	200681,22
5	0	94720	0,2993	29600	12066,667	15678,22	50170,304	250851,52
6	0	94720	0,2993	29600	12066,667	15678,22	50170,304	301021,82
7	0	94720	0,2993	29600	12066,667	15678,22	50170,304	351192,13
8	0	94720	0,2993	29600	12066,667	15678,22	50170,304	401362,43
9	0	94720	0,2993	29600	12066,667	15678,22	50170,304	451532,74
10	0	94720	0,2993	29600	12066,667	15678,22	50170,304	501703,04
11	0	94720	0,2993	29600	12066,667	15678,22	50170,304	551873,34
12	0	94720	0,2993	29600	12066,667	15678,22	50170,304	602043,65
		1336640					602043,65	

Table 16: Profit and ROI after investment.

Months	Increase Per Run (29,93 %)	Volume per Month After	Total Production Cost per month	Selling Price for total production	Profit per Month After	Cumulative Net Profit Per month	Return on Investment (ROI)
1	0,2993	324,825	123069,696	173240	50170,304	50170,304	-74,914848
2	0,2993	324,825	123069,696	173240	50170,304	100340,61	-49,829696
3	0,2993	324,825	123069,696	173240	50170,304	150510,91	-24,744544
4	0,2993	324,825	123069,696	173240	50170,304	200681,22	0,340608
5	0,2993	324,825	123069,696	173240	50170,304	250851,52	25,42576
6	0,2993	324,825	123069,696	173240	50170,304	301021,82	50,510912
7	0,2993	324,825	123069,696	173240	50170,304	351192,13	75,596064
8	0,2993	324,825	123069,696	173240	50170,304	401362,43	100,68122
9	0,2993	324,825	123069,696	173240	50170,304	451532,74	125,76637
10	0,2993	324,825	123069,696	173240	50170,304	501703,04	150,85152
11	0,2993	324,825	123069,696	173240	50170,304	551873,34	175,93667
12	0,2993	324,825	123069,696	173240	50170,304	602043,65	201,02182

8.7.4. Interpretations of results from tables 15 and 16.

From The above tables, the following can be identified:

- Production volume was increased from 250 L/month to 324.825 L/month.
- The monthly profit was increased from R 38 613.3 to R 50 170.304 per month.
- The production cost increased by R 200 000 only for the first month after investment.
- The return on investment (ROI) is negative until the investment amount is recovered, therefore the ROI that was taken into consideration, is after the breakeven point.

ROI = 0.34 % (4th month)

ROI = 25.43 % (5th month)

This means that, after investing R 200 000 to digitalise process data of the craft distillery, one can recover the full amount and make 0.34 % of the total investment on the 4th month or 25.43 % on the 5th month after investing.

- The Payback time = **4th month** after investment.
- The breakeven point is during the **4th month** after investment.

8.7.5. Return on Investment (ROI)

It is an approximate measure of an investment's profitability (Anderson and Fennell, 2013).

$$\text{ROI (\%)} = \frac{\text{Profit}}{\text{Amount Invested}} \times 100 \quad (32)$$

Profit = Net Present Value - Initial Investment

$$\text{ROI} = \frac{250851.52 - 200000}{200\ 000} \times 100 = 25.43 \%$$

This ROI means; after investing R 200 000 into the distillery to implement digitalisation of process data, one can recover the full amount and make 25.43 % of the total investment on the 5th month after investing.

8.7.6. Payback time and Breakeven point

From tables 15 and 16, the payback time is on the **4th month** after investing R 200 000 into the project. The breakeven point can be noticed on the graph below to be on the **4th month** as well. Figure 20 below, show that the investment is made once (blue line), the result is an increase in profit every month (orange line).

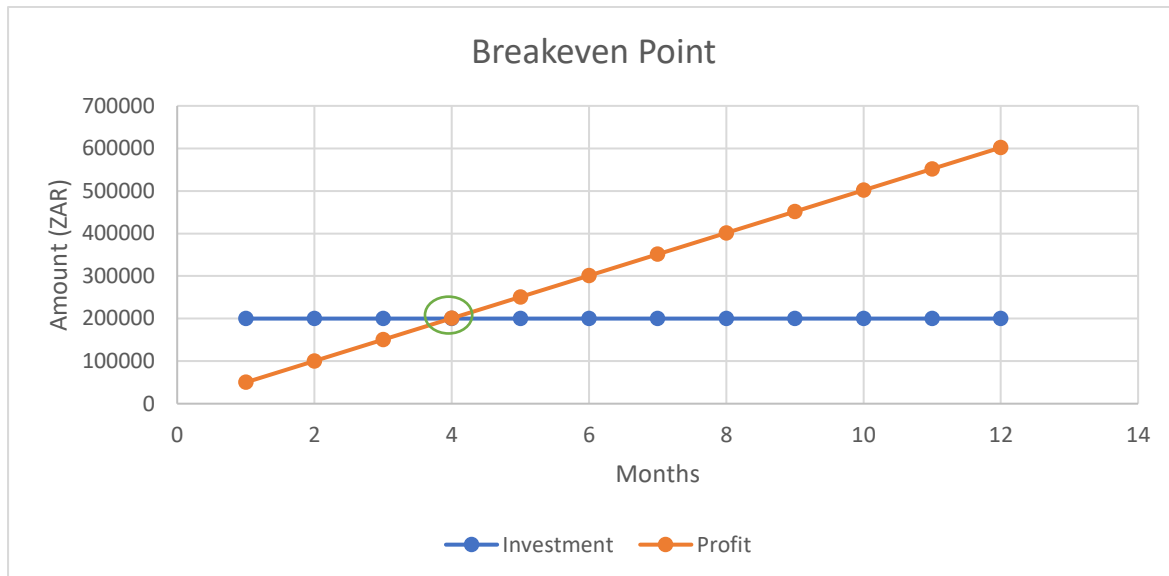


Figure 20: Breakeven point of the project Investment.

8.7.7. Simulation for 10 % and 20 % productivity increase

- **For 10 % Productivity increase**

The payback time is on the 5th month. This means that the amount is fully recovered on the 5th month after investment.

$$\text{ROI} = \frac{212373.33 - 200000}{200000} \times 100 = 6.19 \%$$

This ROI means, after investing R 200 000 into the craft distillery to implement digitalisation, and reaching a productivity increase of 10 %, one can fully recover the investment money after 5 months and get an additional 6.19 % return on the investment after the same period.

- **For 20 % Productivity increase**

The payback time is also on the 5th month.

$$\text{ROI} = \frac{231680 - 200000}{200000} \times 100 = 15.84 \%$$

This ROI means, after investing R 200 000 into the distillery to implement digitalisation, and reaching a productivity increase of 20 %, one can fully recover the investment money after 5 months and get an additional 15.84 % of the investment after the same period of time.

8.7.8. Comparison of the 10%, 20% and 30% productivity increase.

Table 17: Productivity vs ROI

Productivity Increase	Return on Investment (ROI) after 5 months
10 %	6.19 %
20 %	15.84 %
30 %	25.43 %

From table 17, the higher the increase in productivity, the higher the ROI for the same period. This means that one gets more profit by increasing productivity.

In statistics, the best ROI predicts the best investment profitability. Therefore, the best economic decision is to strive for 30 % productivity increase to get 25.43 % profit from the investment after 5 months while fully recovering the investment within the 4th month.

8.8. Summary Of the Economic Study

The economic study showed that investing R 200 000 to digitalise process data of the distillery, would increase productivity by 30 %. The investment money will be fully recovered after 4 months and 25.43 % of the investment money will be gained in profit at the end of the 5th months after investment.

Maximising productivity increase is economically advantageous as it directly contributes to increased profitability for the craft distillery. This was established by comparing the ROI of the same investment for three productivities increase of 10, 20 and 30 %. The best ROI predicts the best investment profitability. The best ROI was identified to be equal to 25.43 % for a productivity increase of 30 %. This result is the maximum possible, with a possibility to hit between 10 and 20% actual increase profitability due to unforeseen situations.

CHAPTER 9: CONCLUSION

- The analysis and results demonstrated that productivity of a craft distillery or brewery can be significantly improved by digitalising process data. Essential production indicators must be readily available and easily accessible, ideally in real time monitoring to facilitate effective production planning, problem identification, and prompt adjustments and rectifications.
- The accuracy of historical process data was analysed. It revealed significant variability due to manual estimations for adjunct weights and water volumes, as well as inconsistencies in fermentation outcomes. However, statistical analyses demonstrated moderate-to-strong correlations, such as a 0.51 correlation between adjunct quantities and wort sugar content and strong correlation of 0.81 between water volume and wort volume, confirming the data's relevance for evaluating digitalisation benefits.
- Mass balance analysis revealed significant sugar losses during mashing, indicating a potential area for improvement with digitalization. The average sugar loss during mashing stands at 16.45 %.
- Fermentation often resulted in alcohol levels within the acceptable range (7 to 8 %) in only 53.66% of instances, with an average deviation of 32.29%. The implementation of digitalisation has the potential to reduce these deviations substantially. This means that the distillery, on average, produced 67.71% alcohol of its potential (ideal) capability. Among the 41 batches examined, merely 14 demonstrated a deviation equal to or less than 20%. This implies that the distillery documented substantial deviations, approximately 65.85% of the time, a notably high occurrence.
- Correlation analysis and the student t test revealed that a few variables (parameters) must be monitored carefully to reduce deviations and enhance productivity.
- While more economical alternatives could be considered, the most optimal and effective solutions entail utilising affordable data analytics and storage platforms that offer enhanced accessibility and analysis of process data. Additionally, implementing process control instrumentation devices such as sensors and flow meters providing real-

time process visibility and enables better manipulation of process inputs, addressing most issues.

- The economic study showed that investing R 200 000 to digitalise process data of the distillery, would increase productivity by 30 %. The investment money will be fully recovered after 4 months and 25.43 % of the investment money will be gained in profit after 5 months after investment.
- Maximising productivity is profitable as it directly contributes to the distillery's profitability. This was evidenced by comparing the return on investment (ROI) for three productivity increases: 10%, 20%, and 30%. The highest ROI, indicating the most profitable investment, was achieved with a 30% productivity increase, reaching 25.43%.
- The research also proved that the developed framework is efficient in quantifying the benefits of digitalisation of process data of a craft distillery. The framework consists of:
 - Collection of historical data from the distillery. They were already organised in a tabular format but had to be reorganised, checked and validated before conducting the research.
 - Visualisation of the data, including trend comparisons against established and known brewing patterns to validate their reliability. This involves for instance, plotting variables like original gravity against alcohol by volume and assessing whether the regression is positive or different from background knowledge.
 - Validation of data accuracy by conducting a comprehensive statistical analysis of the historical data. Statistical tools such as correlation, standard deviation calculations and normal distribution were used to demonstrate that the historical data was accurate enough and could be utilised for the study.
 - Mass balance with all its pertinent analysis and graphs interpretation: perform mass balance over each unit operations such as mash tun and fermentation, and overall mass balance to compare potential alcohol and actual alcohol produced from the sugar entering the system.
 - Application of statistical analysis methods such as correlation and student t test. Correlation was used to explain the relationship between variables and facilitate the identification of areas where digitalisation could enhance productivity. The student

t test was used to determine whether the calculated mean from a sample data collected from a single group was different from an expected value, referred to as the hypothesised mean.

- Use all analysis, identified issues to determine the necessary interventions for the distillery and the specific type of digitalisation required.
- Conduct an economic study to determine the viability of the investment based on the profitability of the distillery. This entails estimating and computing the productivity improvement, return on investment (ROI), payback time, breakeven point and deduce an informed conclusion.

CHAPTER 10: RECOMMENDATION

- In future analyses, it is advisable for the facility to document pH and CO₂ emission data during the fermentation process. Analysing this data could provide valuable insights into further quantifying the benefits of digitalising process data for improved fermentation efficiency.
- Additionally, the facility should maintain organised historical data for the distillation process, detailing all brew mixtures, to facilitate further analysis and quantification of the benefits of digitalisation.
- The analysis of the historical process data revealed significant variability due to manual estimations for adjunct weights and water volumes. Therefore, it is recommended to implement digital measurement and monitoring systems to enhance historical data reliability and recording. Furthermore, abnormalities in historical data, such as batch 7, also highlighted the importance of accurate data collection facilitated by digitalisation.

CHAPTER 11: APPENDIX

11.1. Data Visualisation

Data visualisation techniques were utilised to analyse trends and validate the reliability of the data. For example, as yeast consumption progresses, alcohol levels are expected to rise. To verify this, a graphical representation can be created by plotting the alcohol by volume (ABV) against the corresponding time points. The resulting trend line should show a decreasing trend, as any deviation would indicate potential anomalies or inconsistencies in the data set.

Several visualisations were conducted to examine the relationship between ABV and other relevant parameters. When ABV was plotted against original gravity, a direct proportionality was observed. Conversely, plotting ABV against final gravity revealed an inverse proportionality.

These visualisations offered valuable insights into alcohol production dynamics and confirmed the relationships between ABV, original gravity, and final gravity, thereby strengthening the credibility of the data collected.

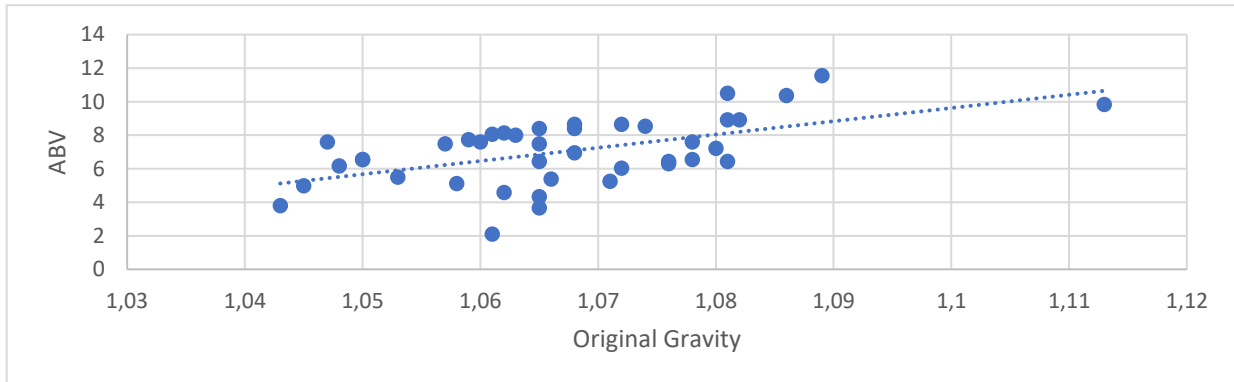


Figure 21: Historical data representing original gravity vs ABV in percentage.

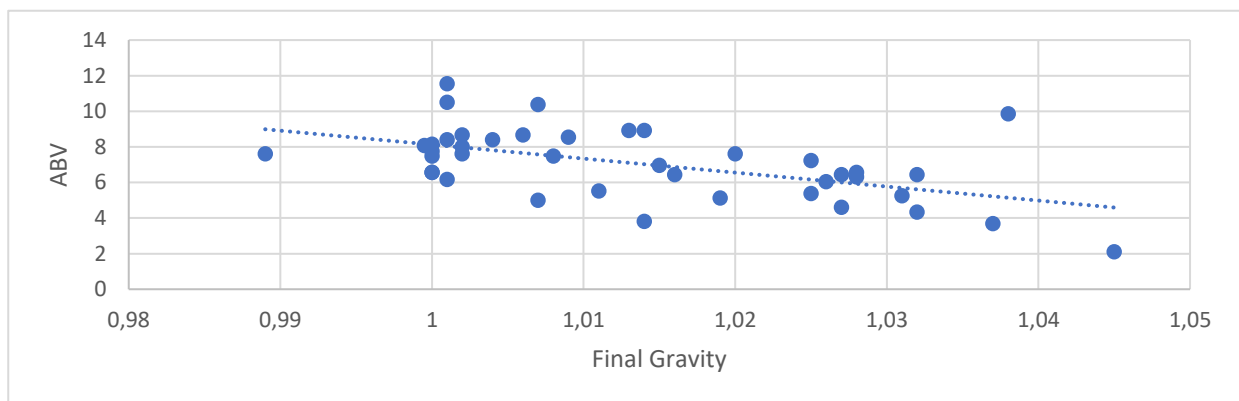


Figure 22: Historical data representing final gravity vs ABV in percentage.

11.2. Mass Balance Over Mash Tun

11.2.1. Purpose of mash tun mass balance

Mass balance was conducted for the mash tun to assess the discrepancy between the sugar supplied to the mash tun and the amount extracted during the mashing process, which is indicated by the sugar content in the wort, to quantify the sugar loss in the process.

11.2.2. Determination of sugar supplied into the system.

$$\text{Sugar in (in the grain)} = \text{Sugar in wort} + \text{Sugar lost} \quad (31)$$

In accordance with an online article from Brewhaequipment (2023), it's established that high mash efficiency is achieved when sugar recovery rates fall within the range of 75-90%, while a lower percentage, typically between 60-75%, is categorized as low mash efficiency.

Sugar content is generally calculated using the following rationale: As outlined in the Brewer's Handbook and the work of Fox (2010), starch constitutes the predominant component in grains, comprising up to 60% of the total grain weight (Fox, 2010).

In the context of this study, the adjunct provided to Primal Spirit Distillery consists entirely of starch. It is assumed that this starch contains a combination of both fermentable and unfermentable sugars. This assumption underlies the calculation, where it is considered that 500 kg of sugar is entering the mash tun. Therefore, Sugar in = 500 kg.

11.2.3. Sugar extract calculation

Sugar extract is the amount of sugar content in wort and expressed either in kg or degree of Plato. For calculation purposes, the specific gravity (SG) measurement is converted into degrees Plato using the following equation:

$$\text{Degree of Plato} = \frac{\text{Grams of sugar and of soluble}}{100 \text{ Grams of wort}} \quad (32)$$

According to Cutaia et al in 2009, the extract is obtained using the following formula:

$$\begin{aligned} \text{Extract (Degrees of Plato)} = & 2.569 \times 102 \times (\text{SG}-1) + 6.7126 \times 100 \times (\text{SG}-1)^2 - 1.4482 \times 104 \times \\ & (\text{SG}-1)^3 + 5.1758 \times 105 \times (\text{SG}-1)^4 - 1.0746 \times 107 \times (\text{SG}-1)^5 + 1.3011 \times 108 \times (\text{SG}-1)^6 - 8.5079 \\ & \times 108 \times (\text{SG}-1)^7 + 2.3231 \times 109 \times (\text{SG}-1)^8 \end{aligned} \quad (33)$$

For batch 1:

$$\begin{aligned} \text{Extract} = & 13,1019 + 1,67815 - 0,0188266 + 0,00339661875 - 0,000035992125 + \\ & 0,00000219560625 - 0,0000007178540625 + 0.00000000989132421875 = \\ & \mathbf{14,76458551426851 \approx 14.76 \text{ g sugar / 100 g sugar}} \end{aligned}$$

$$\begin{aligned} 100 \text{ g wort} & \rightarrow 14.76458551426851 \text{ g sugar} & (\text{from extract calculation}) \\ 0.1 \text{ kg wort} & \rightarrow 0.01476458551426851 \text{ kg sugar} \end{aligned}$$

However, batch 1 has a volume of 875 L

$$\text{Mass of wort} = V \times \rho = 875 \text{ L} \times 1.05 = 918.75 \text{ kg}$$

If, 0.1 kg wort $\rightarrow$ 0.01476458551426851 kg sugar

$$918.75 \text{ kg} \rightarrow \frac{0.01476458551426851}{0.1} \times 918.75 = \mathbf{135,649629412342 \approx 135.65 \text{ kg sugar}}$$

Therefore, there is 135.649629412342 kg of sugar in 875 L of wort.

$$\mathbf{\text{Sugar lost} = \text{Sugar in} - \text{Sugar in wort} = 500 - 135,649629412342 = \mathbf{364,35 \text{ kg of sugar lost.}}}$$

The mashing process recorded a sugar loss of **364.35 kg for batch 1.**

11.3. Mass Balance Over Fermenter

11.3.1. Introduction

The purpose of the mass balance over fermenter is to compare the amount of sugar in the wort that enters the fermenter, the amount lost during the fermentation process and the quantity used up to produce ethanol. For this calculation, the sugar content in wort and fermented product are expressed in degree Plato of the specific gravity.

11.3.2. Calculations and Balance

For Batch 1:

$$\begin{aligned} \text{Original Gravity} = \text{AE} &= 13,1019 + 1,67815 - 0,0188266 + 0,00339661875 - \\ &0,000035992125 + 0,00000219560625 - 0,0000007178540625 + 0,00000000989132421875 \\ &= \mathbf{14,76 \text{ g sugar / 100 g wort}} \end{aligned}$$

$A_{w/w}$ is alcohol by weight is needed to calculate the final gravity:

$$A_{w/w} = A_{v/v} \times 0.7907 / \text{SG} \quad (34)$$

(28) is the balling equation which relates the original extract to the real extract and alcohol.

$$\rightarrow A_{w/w} = 6.5625 \times 0.7907 / 1 = \mathbf{5,189}$$

Final gravity can be expressed in real extract (RE) according to equation 17 of Cutaia et al, 2009 from Cutaia et al, 2009.

$$\begin{aligned} \text{Final gravity} = \text{RE} &= 0.496815689 \times A_{w/w} + 1.001534136 \times \text{AE} - 0.000591051 \times A_{w/w} \times \text{AE} - \\ &0.000294307 \times \text{AE}^2 - 0.0084747 \times A_{w/w}^2 + 0.000183564 \times A_{w/w}^3 + 0.000011151 \times \text{AE}^3 + \\ &0.000002452 \times A_{w/w}^2 \times \text{AE}^2 \end{aligned} \quad (35)$$

$$\begin{aligned} \rightarrow \text{RE} &= 2,577961084730719 + 12,40665133521799 - 0,0379922341176691 - \\ &0,0451625269858494 - 0,2281846593158323 + 0,0256466519692949 + \\ &0,0211972869654703 + 0,0101311843637826 = \mathbf{16,999 \text{ g sugar / 100 g wort}} \end{aligned}$$

$$\text{Sugar Loss} = \text{Final Extract} - \text{Initial Extract} = 16,99928351 - 14,76458551426851 = \mathbf{2,24 \text{ }^\circ\text{P}}$$

$$\text{Ethanol Loss (kg)} = \frac{\text{Sugar Loss (}^\circ\text{P)}}{100} \times \text{Wort Mass} \times 0.51 \quad (36)$$

$$\text{Ethanol loss} = \frac{2.23843066}{100} \times 918.75 \times 0.51 = \mathbf{10.47 \text{ kg of ethanol.}}$$

11.4. Example of a few other calculations

11.4.1. Brewing Efficiency (Concept of Potential Grain Points)

$$\text{Overall Potential} = \frac{\text{Nbr Pound of Malt} \times \text{Potential Points for each malt}}{\text{Volume of the recipe in gallon}} \quad (37)$$

10 lbs (pound) of 1.037 malt A and 5 lbs (pound) of 1.036 malt B in the same 5-gallon recipe

$$\text{Malt A: } 10 \times \frac{37}{5} = 74 \text{ points}$$

$$\text{Malt B: } 5 \times \frac{36}{5} = 36 \text{ points}$$

Total Potential grain point = 110 points. This is the points if the brewery efficiency is 100%.

The assessment of efficiency achieved through various brewing recipes provides valuable insights into the effectiveness of both equipment and brewing techniques employed (Homebrewjournals, n.d). If the efficiency is observed to be notably lower than anticipated or exhibits substantial variability from batch to batch, it signals the need for adjustments in the applied brewing techniques (Homebrewjournals, n.d).

11.4.2. Mash Efficiency and Ethanol Concentration

$$\text{Potential} = \frac{\text{Volume of the recipe in Gallon} \times \text{Potential Points}}{\text{Nbr Pound of Malt}} \quad (38)$$

Example:

8.5 pounds of malt was mashed to produce 6 gallons of wort that yielded a gravity of 1.038

$$6 \times 38 = 228 \text{ points}$$

$$\frac{228}{8.5} = 26.8 \text{ ppg}$$

11.4.3. Brewhouse Efficiency

$$\frac{\text{Actual Grain Points}}{\text{Potential Grain Points}} \quad (39)$$

Example: We have 3 types of yeast with different grain points:

Maris Otter with a gravity of 1.037 and mass of 7 lbs, Carapis with a gravity of 1.035 and mass 1 lb and lastly, Victory with a gravity of 1.037 and mass 0.75 lbs all in 5-gallon recipe solution.

Potential Grain points of the recipe or Brewing efficiency calculation:

$$\text{Maris Otter} : 37 \times \frac{7 \text{ lbs}}{5 \text{ gallons}} = 51.8$$

$$\text{Carapis: } 35 \times \frac{1 \text{ lbs}}{5 \text{ gallons}} = 7$$

$$\text{Victory: } 37 \times \frac{0.75 \text{ lbs}}{5 \text{ gallons}} = 5.55$$

$$\text{Total Recipe Grain Points} = 51.8 + 7 + 5.55 = 64.35$$

Total grain point in wort given by the hydrometer for example equal to 52.

$$\text{Brewhouse efficiency} = \frac{52}{64.35} = 80.8 \%$$

11.5. A few relevant tables

Table 18: Production timeline.

Production timeline:		
PERIOD #	Start date (Month)	End date (month)
1	Apr-19	Sep-19
2	Oct-19	Mar-20
3	Jun-20	Dec-20
4	Jan-21	May-21
5	Jun-21	Nov-21
6	Dec-21	May-22
7	Jun-22	Nov-22
8	Dec-22	May-23
9	Jun-23	Nov-23
10	Dec-23	May-24

Table 19: Adjunct type.

Adjunct register	
Type	Code
Wheat (organic hard-red)	A
Wheat (malted)	B
Wheat (non-organic hard-red)	C
Barley (malted)	D
Barley (unmalted)	E
Rye	F
Oat	G
Sugar (refined)	H
Biscuit Malt	I

Table 20: Primary Historical Data

	Date	Adjunct type	Adjunct QTY (kg)	Yeast amount (kg)	Water volume (L)	Production period	Wort volume (L)	Original SG	Final SG	Potential ABV
MA-1	2019/05/15	A	500	1	1500	1	875	1,05	1	6,563
MA-2	2019/05/18	A	500	1	1500	1	1540	1,047	0,989	7,612
MA-3	2019/06/21	A	475	1	1900	1	1706,8	1,05	1	6,563
MA-4	2019/06/28	A	485	1	1940	1	1800	1,043	1,014	3,806
MA-5	2019/07/02	A	500	1	2000	1	2227	1,045	1,007	4,988
MA-6	2019/07/06	A	500	1	2000	1	1870	1,048	1,001	6,169
MA-7	2019/07/16	A	500	1	2000	1	2550	1,113	1,038	9,844
MA-8	2019/07/19	A	500	1	2000	1	1800	1,08	1,025	7,219
MA-9	2019/08/16	A	500	1	2000	1	1836	1,078	1,028	6,563
MA-10	2019/09/05	A	300	0,6	1200	1	1296	1,072	1,026	6,038
MA-11	2019/09/19	A	500	1	2000	1	1987	1,076	1,027	6,431
MA-12	2019/09/26	A	500	1	1500	1	1678,19	1,074	1,009	8,531
MA-14	2019/10/07	A	500	1	2000	2	1799,74	1,081	1,032	6,431
MA-15	2019/10/21	A	500	1	2000	2	1415	1,062	1,027	4,594
MA-16	2019/11/14	A	500	1	2000	2	2040,8	1,065	1,016	6,431
MA-17	2019/12/04	A	500	1	2000	2	1853,6	1,066	1,025	5,381
MA-18	2019/12/10	A	500	1	2000	2	1853,6	1,065	1,032	4,331
MA-19	2020/01/21	A	500	1,5	2000	2	1772	1,076	1,028	6,3
MA-20	2020/01/28	A	500	1	2000	2	1626	1,071	1,031	5,25
MC-1	2020/02/11	C	500	1	2000	2	1876	1,065	1,001	8,4
MF-1	2020/02/25	F	500	1	2000	2	1982	1,065	1,037	3,675
MC-2	2020/03/10	C	500	1	2000	2	1750	1,057	1	7,481
MD-1	2020/06/17	D	500	1	2000	3	1970	1,081	1,001	10,5
MD-2	2020/07/23	D,G,I	175	0,5	525	3	460,23	1,086	1,007	10,369
MB-1	2020/08/11	B	500	1	2000	3	1860	1,072	1,006	8,663
MB-2	2020/09/20	B	250	0,5	1000	3	800	1,081	1,013	8,925
MB-3	2020/10/27	B	400	1	1600	3	1746	1,078	1,02	7,613
MF-2	2020/11/29	F	100	0,4	400	3	250	1,053	1,011	5,513
MB-4	2020/12/15	B	365	1	1460	3	1250	1,089	1,001	11,55
MD-3	2021/03/10	D	375	1	1500	4	1549	1,068	1,015	6,956
MB-5	2021/05/20	B	500	1	2000	4	1079	1,082	1,014	8,925
MC-2	2021/06/09	C	500	1	2000	5	2127	1,068	1,002	8,663
MF-3	2021/06/24	F	150	0,5	600	5	456,56	1,065	1,008	7,481
MC-3	2021/09/01	C	500	1	2000	5	1849,96	1,058	1,019	5,119
MC-4	2021/10/13	C	500	1	2000	5	1737,059	1,059	1	7,744
MC-5	2021/11/05	C	500	1	2000	5	2014	1,068	1,004	8,4
MC-6	2022/02/04	C	500	1	2000	6	1800	1,062	1	8,138
MC-7	2022/03/01	C	500	1	2000	6	1790	1,061	0,9995	8,072
MC-8	2022/05/17	C	480	1	1920	6	1958	1,063	1,002	8,006
MC-9	2022/06/06	C	490	1	1960	7	1999	1,061	1,045	2,1
MC-10	2022/06/28	C	450	1	1940	7	2256	1,06	1,002	7,613

Table 21: Student t test on Final gravity of the distillery's historical data.

t-Test: One Sample Test for Final Gravity (FG)				
	<i>Final Gravity (FG)</i>			
Mean	1,013719512			
Variance	0,000185951			
Observations	41			
Hypothesized Mean	1,0045			
df	40			
t Stat	4,329134392			
P(T<=t) one-tail	4,87157E-05			
t Critical one-tail	1,683851013			
P(T<=t) two-tail	9,74314E-05			
t Critical two-tail	2,02107539			
Mean		1,0045		
Hypotheses:				
Null Hypothesis	$H_0: \mu \leq$	1,0045		
Alternative Hypothesis	$H_1: \mu >$	1,0045		
Rejection Region: Reject H_0 if t stat > t critical =		1,683851013		
Test Statistic: t stat =		4,329134392		
p Value:		4,87157E-05		
DECISION CONCLUSION				
stat > t critical : 4,329134392 > 1,683851013		Reject null hypothesis		
p Value < α : 4,87157E-05 < 0,05		Reject null hypothesis		
There is enough evidence to infer that the mean final gravity is significantly greater than 1,0045				

Table 22: Student t test on Alcohol by Volume (ABV %)

t-Test: One Sample Test for Alcohol by Volume (ABV %)			
	ABV (%)		
Mean	7,047484756		
Variance	3,861523056		
Observations	41		
Hypothesized Mean	7,75		
df	40		
t Stat	-2,289118971		
P(T<=t) one-tail	0,013714406		
t Critical one-tail	1,683851013		
P(T<=t) two-tail	0,027428813		
t Critical two-tail	2,02107539		
Mean	7,75		
Null Hypothesis	H ₀ : μ ≤	7,75	
Alternative Hypothesis	H ₁ : μ >	7,75	
Decision Region:	Reject H ₀ if t stat > t critical =	1,683851013	
Test Statistic:	t stat =	-2,289118971	
p Value:		0,013714406	
DECISION CONCLUSION			
t critical : -2,289118971 < 1,683851013		Do not Rejct null hypothesis	
p Value < α : 0,013457816 < 0,05		Reject null hypothesis	
There is not enough evidence to infer that the mean alcohol by volume is significantly greater than 7,75 %			

CHAPTER 12: REFERENCES

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