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Enhancing Operational Excellence

A Systematic Analysis of Material Flow in Battery Gigafactory Quality Control

Bachelor's thesis in Science in Engineering

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ABSTRACT

As nations strive to reduce their dependence on fossil fuels, the need for high-performance, durable batteries has increased drastically. One of the areas where this is especially important is the automotive industry, and one of the companies that have taken a part of this is Volvo Cars. They have adopted a new electrification strategy, with a decision to sell only electric cars from the year 2030. To meet the increased demand for batteries and ensure that the batteries are tailored for their cars, Volvo has formed a joint venture with the battery manufacturer Northvolt, called NOVO Energy. Spring of 2024, NOVO is in the design phase for a new battery factory that is being built next to Volvo Cars' car factory in Gothenburg. They need to make sure that the material flows within the factory are efficient before the factory is finished, and one of the parts of the factory where this is essential is the quality lab.

The purpose of this project was to identify bottlenecks in the material flow of samples within NOVO Energy's quality lab and propose solutions for how they can be minimized. This was done by analyzing data from Northvolt's factory in Skellefteå, and completing it with updated requirements for NOVO. There were several bottlenecks that were discovered and the biggest three were the instruments CMM, Karl Fischer titration and VMZ. The root causes for them were investigated by the Five Whys and Fishbone Diagram methods, and the analysis revealed that they existed due to the sampling frequency being too high, the instruments being too slow and there being too few instruments of each type in the lab.

Several ways to reduce the three bottlenecks were proposed. These were based on the priority list - in line tools, new technology, more instruments. The CMM could not be moved to in line or exchanged for a faster technology, so the solution was to invest in more instruments and decrease the sampling frequency. The Karl Fischer titration could not be turned to an in line tool either, but it could be replaced by a faster instrument called NIR. The VMZ could be moved in line and be supplemented with a few instruments in the lab for validation purposes.

Key words: Material flow, Bottlenecks, Five Whys, Fishbone Diagram, Quality control, Battery cells

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SAMMANFATTNING

Allteftersom länder strävar efter att minska sitt beroende av fossila bränslen har behovet av högpresterande och hållbara batterier ökat drastiskt. Ett av de områden där detta är särskilt viktigt är bilindustrin, och ett av företagen som har tagit del i detta är Volvo Cars. De har antagit en ny elektrifieringsstrategi, med ett beslut om att endast sälja elbilar från år 2030. För att möta den ökade efterfrågan på batterier och säkerställa att batterierna är anpassade för deras bilar, har Volvo bildat ett samriskföretag tillsammans med batteritillverkaren Northvolt, som kallas för NOVO Energy. Våren 2024 befinner sig NOVO i designfasen för en ny batterifabrik som byggs bredvid Volvo Cars bilfabrik i Göteborg. De behöver säkerställa att materialflödena inom fabriken är effektiva innan fabriken är färdig, och en av delarna i fabriken där detta är särskilt viktigt är kvalitetslabbet.

Syftet med detta projekt var att identifiera flaskhalsar i materialflödet av prover inom NOVO Energys kvalitetslabb och föreslå lösningar för hur de kan minimeras. Detta gjordes genom att analysera data från Northvolts fabrik i Skellefteå och komplettera den med de uppdaterade kraven för NOVO. Det var flera flaskhalsar som upptäcktes och de tre största var instrumenten CMM, Karl Fischer-titrator och VMZ. Grundorsakerna till dem undersöktes med metoderna Fem Varför och Fiskbensdiagram, och analysen visade att de existerade på grund av att provtagningsfrekvensen var för hög, att testinstrumenten var för långsamma och att det fanns för få instrument av varje typ i labbet.

Flera sätt att minska de tre flaskhalsarna föreslogs. Dessa var baserade på prioriteringslistan - in line-verktyg, ny teknik, fler instrument. CMM kunde inte flyttas till in line eller bytas ut mot en snabbare teknik, så lösningen var att investera i fler instrument och minska provtagningsfrekvensen. Karl Fischer-titratorn kunde inte heller göras om till ett in line-verktyg, men den kunde ersättas av ett snabbare instrument som heter NIR. VMZ kunde flyttas till in line och kompletteras med några instrument för validering.

Notera att rapporten är skriven på engelska.

Nyckelord: Materialflöde, Flaskhalsar, Fem Varför, Fiskbensdiagram, Kvalitetskontroll, Battericeller

PREFACE

This Bachelor's thesis was conducted during the spring of 2024 as part of the Bachelor's program in Industrial Management and Production Engineering at Chalmers University of Technology. The project is worth 15 credits and was carried out in collaboration with NOVO Energy, with a specific focus on the quality department.

We would like to thank our supervisor and examiner from Chalmers, Carl Sjöberger, for his guidance and insightful advice regarding this report. Additionally, we are grateful for the teams at NOVO Energy and Northvolt, who have spent time and effort to answer all of our questions about the manufacturing processes and sample collection, as well as showing us around the factory in Västerås. We would also like to especially thank our supervisor from NOVO Energy, Georgios Triantafyllou. His expertise and support have been crucial for this project.

Sofia Abrahamsson and Viviane Dang
Gothenburg, 2024

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1. Introduction

In this chapter, an introduction to the thesis will be presented. It includes background to the battery industry and the company NOVO Energy, purpose, limitations and a specification of the issue that is being investigated.

1.1 Background

This chapter provides an overview of the battery industry's push towards sustainability and renewable energy solutions. It highlights the significance of establishing new battery manufacturing plants in this context. The chapter sets the stage for understanding the challenges and opportunities in sustainable industry practices.

1.1.1 The battery industry

The battery industry is undergoing a transformative shift towards sustainability and electrification (Podmiljšak et al., 2024). As the industry continues to innovate and expand, investments in renewable energy and battery technology are crucial for shaping a more sustainable future for transportation and energy storage. With the global push towards decarbonization and combating climate change, the battery industry plays a big role in facilitating the adoption of electric vehicles and renewable energy sources (Ngo & Natowitz, 2016). Batteries are at the core of these technologies, providing the energy storage needed to power the vehicles and to store renewable electricity for future use.

One of the primary areas where the battery industry has made significant improvements is the development of batteries for the electric vehicles (Ngo & Natowitz, 2016). As countries around the world seek to reduce their reliance on fossil fuels and transition to electric mobility, the demand for high-performance and long-lasting batteries has skyrocketed. Manufacturers are continuously investing in research and development to enhance battery efficiency, increase energy density and reduce production costs to make electrical vehicles more accessible to consumers.

Moreover, the rapid increase in car ownership, driven by the expanding automobile industry, has led to a significant rise in exhaust emissions (Feng et al., 2024). This escalation in pollution has in turn, accelerated the development and adoption of battery electric vehicles. The battery industry, therefore, is essential not only for advancing sustainable energy solutions but also for addressing the environmental challenges posed by increasing vehicle emissions. This underscores the importance of continued innovation and investment in battery technology to support a cleaner, more sustainable future.

1.1.2 NOVO Energy

Northvolt is a Swedish battery manufacturer, which was founded in 2016 (Northvolt, n.d. a). They have operations in eleven different cities, spreading across seven countries, and they create several different products. Among those products are lithium-ion battery cells, which are used in electric cars (Northvolt, n.d. b). One of the customers for the lithium-ion cells is

the car manufacturer Volvo Cars, which was founded in 1927 and has factories spread across the world (Volvo Cars, n.d.). Due to climate change, Volvo Cars has made the decision to sell only pure electric cars from the year 2030, and one step in this direction was shown in March 2024 when they produced their last diesel engine (Zettergren, 2024).

With this shift towards electrification, the need for a new battery factory has emerged to support Volvo's transition to electric vehicles. Torslanda, Gothenburg has been chosen as the location for the factory, due to its proximity to Volvo's biggest car factory, as well as the access to renewable energy and suitable infrastructure (Northvolt, 2022). To make sure that the batteries are tailored to Volvo Cars and their subsidiary Polestar, a joint venture between them and Northvolt has been formed. This has resulted in the company NOVO Energy, which was founded in 2021 (Northvolt, 2021).

The partnership between Volvo Cars and Northvolt to establish a new battery manufacturing plant, is a significant step forward in the battery industry's journey towards sustainability and combating climate change (Volvo Cars, 2022). This partnership aims to address climate change by improving sustainable energy solutions and reducing greenhouse gas emissions from transportation. The establishment of the battery manufacturing plant represents a significant investment in renewable energy infrastructure and technological innovation (Ngo & Natowitz, 2016).

Spring of 2024, NOVO is in the design phase for the battery factory in Torslanda (Northvolt, 2021). Because of this, they want to add everything that is necessary for the first part of the factory, while also planning for further expansion. One important part for the production is the quality of the batteries. All parts need to have high quality to ensure that the batteries are safe and are utilized at maximum capacity. To make sure that this is the situation in NOVO's production, samples of the different parts have to be taken from the manufacturing line to the quality lab (NOVO Energy, 2024b). Optimizing this material flow within the lab is crucial for efficient resource utilization and cost-effectiveness. By carefully managing the flow of materials and personnel, unnecessary expenditures can be avoided. To do this, bottlenecks need to be uncovered, the reasons for them need to be found and minimized, and the waste from the material flow needs to be eliminated so that the processes can be streamlined.

1.2 Purpose

The purpose of this project is to identify bottlenecks in the material flow of samples within NOVO Energy's quality lab and propose solutions for how they can be minimized.

1.3 Project scope limitations

This project outlines a framework for quality control improvement and material flow optimization. Specific technical details, implementation challenges, financial considerations, regulatory compliance nuances, human resource dynamics and external environmental factors are not addressed. These aspects will be considered in practical implementations based on the specific organizational context.

Further, the project will only focus on the material flow of samples within the quality lab of the factory, i.e. not on the material flow before the samples reach the lab or on the flow of waste that leaves the lab. Also, only the three biggest bottlenecks will be addressed, which is to ensure that the project does not become too extensive.

1.4 Problem statement

To achieve the purpose, the following three research questions will be addressed:

- What bottlenecks exist in the material flow within the quality lab, as per the current plan for NOVO's first gigafactory?
- What factors contribute to the bottlenecks that are found?
- What measures can be implemented to minimize the bottlenecks?

1.5 Report structure

The report is divided into eight chapters, which are illustrated in *Figure 1*. They will be summarized below to provide an overview over the report.

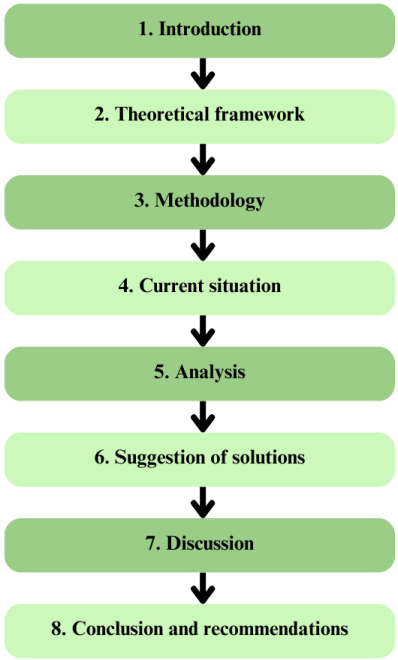

Figure 1: The report structure (own illustration).

1. **Introduction**
   Background to the company is presented, as well as the purpose of the thesis and its limitations. The purpose is also broken down into research questions that are being answered in the report.

2. **Theoretical framework**
   This chapter includes the theoretical information that was used to analyze the current situation in the factory, to find solutions to the problems that are found and to rank the solutions that were suggested.

3. **Methodology**
   In this chapter, the chosen research methodology and types of data collection are presented to describe how the project has been executed. It also contains a discussion regarding the quality criteria of the report.

4. **Current situation**
   The current plan for the flow of samples within the quality lab in the factory is presented. The data is based on testing frequencies from Northvolt's factories in Skellefteå, as well as updated requirements for production in NOVO's new factory in Gothenburg.

5. **Analysis**
   Here, the results from the current situation are analyzed to find the bottlenecks and the biggest problems regarding the current processes. In addition to this, a root cause analysis is carried out to find the reasons for the bottlenecks.

6. **Solutions and improvements**
   Solutions to the root causes that are found in the analysis are presented in this chapter. There is also a cost-benefit analysis for each of the solutions, which provides the basis for a ranking of the suggested solutions.

7. **Discussion**
   A discussion regarding the chosen methodology is presented. The results and suggested solutions are discussed as well, alongside the whole project's contribution to NOVO's design of the factory.

8. **Conclusion**
   A summarization that answers the research questions from the problem statement and a proposal for further studies is provided in this chapter.

2. Theoretical framework

In the following chapter, the theoretical framework upon which the research is based will be presented. The theory covers the areas of battery manufacturing, material flows, bottlenecks, different types of root cause analysis and cost-benefit analysis.

2.1 Battery cells

The components of a lithium battery and an insight into the process steps of battery manufacturing are outlined below.

2.1.1 Components of a lithium battery

A lithium battery, an essential device in the modern world. It provides the power needed for countless applications, from mobile phones and laptops to cars and grid storage (Buriak et al., 2024). A battery consists of several key components, such as an anode, a cathode, electrolyte, separators and two current collectors (Buriak et al., 2024). Each of these elements plays a crucial role in the battery's functionality, working together to store chemical energy in order to convert and deliver electrical energy.

The amalgamation of an anode, cathode, electrolyte, separators and two current collectors, enclosed within a can and lid, constitutes the formation of a battery cell (NOVO Energy, 2024a). The can provides structural support and electrolyte containment for the cell, while the lid seals it. Together, these components create a functional battery cell. How the different components are ordered within the battery is shown in *Figure 2* below.

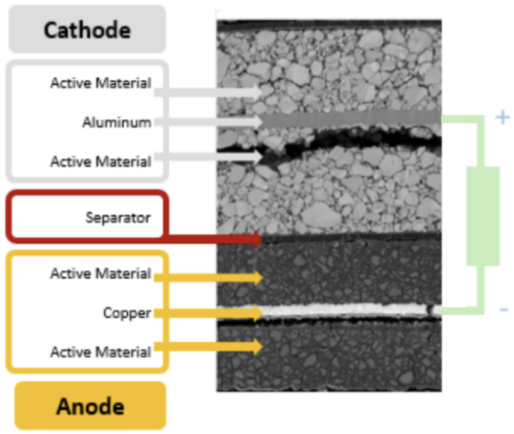

Figure 2: The components of a battery (NOVO Energy, 2024a).

Anode is the electrode where oxidation occurs during the discharge process. The anode contains the active material responsible for storing and releasing ions during the battery's operation (NOVO Energy, 2024a). In lithium-ion batteries, common materials that are used for the anode include graphite or other carbon-based materials.

Cathode is the electrode where reduction occurs during the battery's discharge process. Similar to the anode, the cathode contains an active material that participates in the

electrochemical reactions that generate electrical energy (NOVO Energy, 2024a). Common materials for cathode include lithium metal oxides, such as lithium cobalt oxide.

The separator is a thin membrane that physically separates the anode and cathode within the battery cell. It prevents direct contact between the electrodes, which could lead to short circuits. Separators are typically made of polyethylene (PE) or polypropylene (PP) films with a ceramic coating to enhance their thermal stability and safety (NOVO Energy, 2024a).

The electrolyte is a solution or gel that facilitates the movement of ions between the anode and cathode during battery operation. It contains a solvent and a conductive salt (NOVO Energy, 2024a). The conductive salt dissociates into ions when dissolved in the solvent, allowing for the flow of electric current within the battery.

2.1.2 Process steps in battery manufacturing

Battery manufacturing is generally composed of the following process steps - mixing, coating, calendering, notching, stacking, cell assembly, and formation and aging. The different steps are shown in *Figure 3* and are briefly described below.

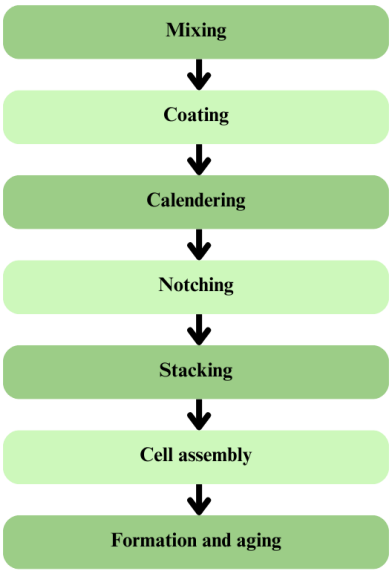

Figure 3: The steps in battery manufacturing (own illustration with inspiration from NOVO Energy, 2024a).

Mixing

The first step of the lithium battery manufacturing is mixing of the anode and cathode slurries (Heimes et al., 2023). In the process of mixing, the active material for anode and cathode, along with conductive carbon and a solvent, are blended to create a viscous liquid. Different types of mixing occur to make sure that the elements are uniformly distributed throughout the slurry, such as distributive mixing for the dry components and dispersive mixing after the solvent is added. A binder is also incorporated into the mixture to bind the components together and improve the overall cohesion of the final product (Heimes et al., 2023). Vacuum is then applied to evacuate any air that may be trapped within the mixture, ensuring a more compact and dense slurry.

Coating
During the coating stage of the manufacturing process, the cathode and anode slurries are applied onto their respective current collector foils using tools like slot dies, doctor blades or anilox rollers (Heimes et al., 2023). This process allows for continuous or intermittent coating, and this can be done on both sides simultaneously or sequentially, depending on the manufacturer's requirements. Following the coating, the coated foil moves through a drying channel that removes the solvent from the coating by heating it up (Heimes et al., 2023). If the solvent that is used contains toxins, it is recovered and processed or recycled to minimize environmental impact. After exiting the dryer, the product is cooled down to room temperature and wound up into a coil, called a jumbo roll, completing the coating process.

Calendering
In calendering, the coated and dried foil undergoes compression by rotating rolls on either side of the foil (Heimes et al., 2023). The material is compacted by the top and bottom rolls, creating a defined line pressure. After calendering, the foil is cleaned and wound again. The next step is to divide the wound up coil into smaller coils, called pancakes, in a process known as slitting (Heimes et al., 2023). Rolling knives are commonly used in this step to cut the big coil into two or more smaller coils. Following the slitting process, the individual smaller coils are cleaned and wound up again.

Notching
During notching, the coil is unwound, and the contour of the electrodes is formed by cutting out the sides of the foil. This is done with a laser or by shear cutting, to ensure that only small tabs are left (Heimes et al., 2023). After notching, the foil can either be rewound or fed directly to the next process where it is cut into individual electrode sheets. After this, the electrode sheets are stored and transported to the next step in the process.

Stacking
Stacking is the step where a cell stack is formed by arranging an anode sheet, separator, a cathode sheet and separator in an alternating pattern (Heimes et al., 2023). These stacks can include up to 120 individual layers, which are typically handled and positioned by vacuum grippers. Various stacking technologies are utilized for this process, often customized and patented by manufacturers.

There are three main stacking methods - single sheet stacking, Z-stacking and winding (NOVO Energy, 2024a). These are illustrated in *Figure 4* below. Each method has its advantages and is suitable for different types of batteries and applications. Single sheet stacking involves stacking individual layers of the battery components, anode, cathode and separator, on top of each other like a sandwich (NOVO Energy, 2024a). It's often used in flat-shaped batteries, which are called prismatic cells, that are commonly used in various electronic devices. In Z-stacking, the layers of battery components are stacked in a zigzag pattern, similar to folding a piece of paper back and forth. This method is often used in batteries called pouch cells. Winding, also known as jelly roll or spiral winding, involves

wrapping the layers of battery components around a central core in a spiral shape, like rolling up a rug (NOVO Energy, 2024a). This method is suitable for cylindrical batteries.

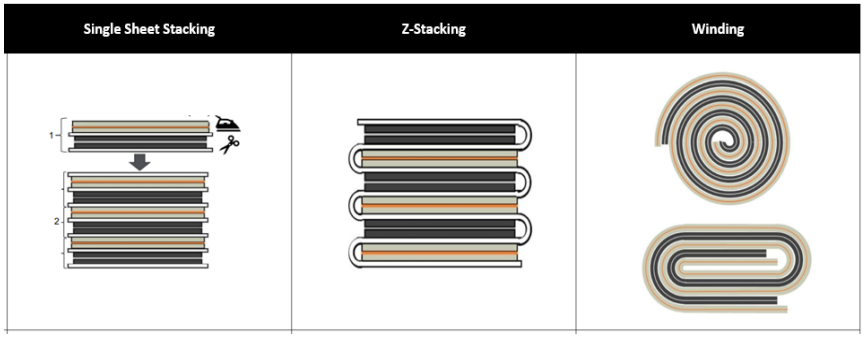

Figure 4: Methods of assembling the components of a battery cell (NOVO Energy, 2024a).

After stacking, the product, which is now called a cell stack, is wrapped with separator material and secured with tape. This ensures the integrity and stability of the cell stack for further processing.

Cell assembly

In cell assembly, a cell lid is placed on the cell stack and the lid is welded to the tabs (Heimes et al., 2023). This is then covered in insulation foil to protect the cell stack, after which, the package is placed in a cell can. The sides of the can are welded together with the lid, leaving just a small fill opening. Different tests to ensure that there can be no leaks along the welded edges during the filling of electrolyte are also made. During filling of electrolyte, a dosing lance is carefully positioned at the opening of the packaging (Heimes et al., 2023). Precise positioning is crucial to prevent electrolyte contamination on the packaging. The electrolyte is then filled into the cell packaging and once it is complete, the opening is sealed with a closure pin, completing the assembly process.

Formation and aging

Formation is the process of the initial charging and discharging of the battery cell (Heimes et al., 2023). During formation, the cells are placed into racks and contacted by contact pins. They are then charged and discharged according to predefined values for current and voltage.

Aging is a crucial step in determining the quality of battery cells and is part of the end-of-line test process (Heimes et al., 2023). During aging, cells are stored in specialized racks or towers designed for this purpose. Two main types of aging are employed - high-temperature and room temperature aging. Cell properties are closely monitored by regularly measuring the voltage over a certain period, which can extend up to three weeks. If there are no significant changes in cell properties during this time, it indicates that the cell is in good condition and is ready to be shipped to the customer.

2.2 Material flows and bottlenecks

For a production company, a material flow is the way that resources and components flow through the company, to then create the products that flow to the customers (Jonsson & Mattsson, 2020). There are two main types of flows - pull and push. A pull flow is initiated by the demand from the customer. When the customer orders a product, a signal is sent to production and only then is the product manufactured. A push flow is initiated by the producer without an order from the customer and the production is based on plans made by the company. To balance the material flow, many types of information are needed (Jonsson & Mattsson, 2020). Among others, information about demand, capacity and resources are used to make sure that the materials flow through a process without causing starvation or blocking, due to bottlenecks, in the other processes.

In the context of production processes, the term “bottleneck” refers to a point where production is limited or delayed, hindering a smooth and efficient flow. Bottlenecks can arise for various reasons, such as overloading of work, insufficient capacity on a machine or workstation, or imbalance in the workflow (Jonsson & Mattsson, 2020). The identification of bottlenecks through detailed analysis of production data and process flows is especially important (Jonsson & Mattsson, 2020). By pinpointing the exact location and root cause of bottlenecks, companies can better understand where and why the delays occur. Bottlenecks have significant implications for overall production efficiency and capacity. They can lead to increased waiting times, suboptimal resource utilization and unnecessary costs (Jonsson & Mattsson, 2020). To address bottlenecks, there are several strategies that can be used. These include increasing capacity at bottleneck points, restructuring workflows to avoid overloading specific stations, and implementing technological solutions that enhance production flow (Jonsson & Mattsson, 2020). By systematically addressing the causes of bottlenecks, organizations can significantly improve their material flows, to increase their production capacity and operational efficiency.

2.3 Five Whys

The Five Whys method, created by Sakichi Toyoda and utilized by the Toyota Motor Corporation, is a technique for identifying the root cause of a problem by repeatedly asking "Why?" (Wolniak & Grebski, 2023). This straightforward, yet effective, tool aims to uncover the deeper reasons behind issues instead of merely addressing their symptoms. By asking "Why?" five times, individuals or teams can reach the core of a problem.

This method promotes critical thinking and prevents hasty solutions, encouraging a thorough and systematic approach to problem-solving (Wolniak & Grebski, 2023). Each "Why?" question helps explore different aspects of the issue and consider various perspectives, fostering open communication and teamwork. While five iterations are typically used, the method is adaptable - some issues may need more or fewer questions to uncover the root cause. The 5 Whys technique can be applied in many areas, from business and healthcare to personal development. It is essential, however, to stay open-minded to unexpected insights that may arise during the process (Wolniak & Grebski, 2023).

2.4 Fishbone Diagram

A Fishbone Diagram, also known as an Ishikawa diagram or a cause-and-effect diagram, is a visualization tool used for categorizing the potential causes of a problem in order to identify its root causes (Tarantino, 2022). The process of creating a Fishbone Diagram typically involves identifying the effect or problem to be analyzed, brainstorming and categorizing potential causes, and analyzing and prioritizing these causes (Tarantino, 2022). The diagram provides a clear and structured framework for problem-solving, enabling teams to develop targeted solutions and drive continuous improvement. The Fishbone Diagram is created with the following steps (Tarantino, 2022):

1. **Identify the process impact**
   The first step is to identify the process impact, which serves as the focal point for analysis and improvement within a process. It involves pinpointing the primary issue or outcome that requires examination or enhancement. This impact becomes the central focus, symbolized at the head of the diagram.

2. **Add the main causes**
   Proceed to add the "ribs" to the fish, which represent the causes contributing to the impact. In this step, all possible causes that could contribute to the effect are identified. These causes are represented as branches or ribs extending from the central symbol.

3. **Add and categorize further causes**
   Encourage the team to suggest all potential causes without criticism. Categorize these causes under various branches, which may include materials, personnel, equipment, method, measurement and environment. These categories can be adapted based on the specific causes being investigated.

2.5 Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis (FMEA) is a systematic, proactive method for evaluating a process to identify where and how it might fail and to assess the relative impact of different failures, in order to identify the parts of the process that are most in need of change (Intellect, 2003).

FMEA includes a review of the steps in the process, identification of potential failure modes for each step, determination of their effect on the system and classification based on the severity and likelihood of the failures (Intellect, 2003). This approach is used to prioritize potential failures according to their frequency and detectability, with the aim of preventing these failures. Through this methodology, recommendations are formulated to mitigate, eliminate or compensate for the risks associated with these failures. The ultimate goal is to preempt major design flaws during the early stages of development, thereby minimizing their occurrence or alleviating their impact in a cost-effective manner (Intellect, 2003).

This methodology enhances the capability to monitor, evaluate, and refine designs and processes, ensuring that products meet the strict demands of contemporary markets in terms of reliability, safety and affordability (Intellect, 2003). Through FMEA, organizations can maintain a competitive edge by guaranteeing that new offerings adhere to the highest standards of quality and performance. Below, the steps for how to perform FMEA is provided (Intellect, 2003):

1. **Define the scope**
   To begin with, it is essential to define the scope of the analysis clearly, specifying the system, subsystem or process to be examined.

2. **List the components and functions**
   Each component or process must be uniquely identified with a serial number or reference designator, ensuring traceability throughout the analysis. This identification should be consistent with those used in functional and reliability block diagrams, which are referenced in the worksheet header for clarity.

3. **Identify failure modes**
   Identifying potential failure modes is a critical part of FMEA. This involves determining all possible ways each component or process can fail by examining outputs and functional outputs in block diagrams and schematics, as well as reviewing historical data.

4. **Assess the Effects of Failures**
   The effects of each failure mode on the operation, function or status of the item are then assessed. This assessment considers the impact at different levels - local effects (immediate impact on the specific item), next higher level effects (impact on items at the next indenture level above) and end effects (overall impact on the system's highest level).

5. **Determine the Occurrence, Detection, Severity and risk priority number**
   To prioritize these failure modes, the likelihood of occurrence, the ability to detect the failure before it causes harm and the severity of the consequences are evaluated. Each of these factors is typically rated on a scale from 1 to 10. The Risk Priority Number (RPN) is calculated by multiplying the ratings for severity, occurrence and detection. Higher RPN values indicate more critical issues that need immediate attention.

2.6 Cost-benefit analysis (CBA)

Cost-Benefit Analysis (CBA) offers a comprehensive framework for evaluating projects by assessing their overall impact on society (Nas, 2016). Unlike financial analysis, which primarily quantifies costs and benefits in monetary terms, CBA considers both the direct financial effects and the broader societal implications. This approach ensures that the true

value of a project is measured, taking into account social utility gains and losses, thereby providing a more holistic understanding of its benefits and costs.

One key aspect of CBA is its inclusion of external costs and benefits in the overall evaluation (Nas, 2016). These externalities, such as environmental impact or social changes, are crucial in determining the true value of a project to society. In financial analysis, all relevant costs and benefits are typically measured using observed market prices. However, CBA adjusts these prices to correct for possible market distortions. The process of conducting a cost-benefit analysis involves four stages (Nas, 2016):

1. **Identification of relevant costs and benefits**
   The first phase involves identifying all relevant costs and benefits associated with the project. The analysis distinguishes between historical costs, which have no relevance to present or future resource allocation decisions, and economic costs, which reflect the value that resources could generate in their next best use.

2. **Measurement of costs and benefits**
   In this phase, the identified costs and benefits are quantified. This includes distinguishing between real output effects, which reflect changes in total physical production possibilities and societal welfare, and pecuniary effects, which are distributional and do not create real welfare gains.

3. **Comparison of cost and benefit streams occurring during the lifetime of a project**
   The phase involves calculating the present value of future benefits and costs. This is done by applying a discount rate, which differs from the market rate of interest used in financial analysis. The choice of discount rate is critical, as it influences the benefit-cost ratios and the overall assessment of the project's viability.

4. **Project selection**
   In the final stage, projects are ranked based on criteria such as benefit-cost ratios, net present value and internal rate of return. A project is deemed acceptable if its benefit-cost ratio exceeds one, its net present value is positive, and/or its internal rate of return is higher than the market rate or another socially acceptable rate of return.

3. Methodology

The methodology chapter is a guide for how the project was constructed. It includes which research strategy, approach and design that were chosen, and how the literature review and data collection were conducted to achieve the purpose of the project. Moreover, it also includes a discussion regarding the trustworthiness of the study.

3.1 Research methodology

The following subchapter outlines the chosen research strategy, approach and design.

3.1.1 Strategy

There are two types of strategies when it comes to how research is made - qualitative research and quantitative research (Bell et al., 2019). Qualitative research focuses on words and images, as well as how people interpret the world. Its goal is to create new theory from the research. In contrast, quantitative research focuses more on numbers and variables. There, research is made from already existing theories. This project was mostly based on the quantitative research strategy, since the focus was on interpreting and analysing numerical data to improve the material flows, rather than descriptive data of people's attitudes and experiences.

The quantitative research strategy has a structure that consists of 11 main steps, but these are rarely followed exactly (Bell et al., 2019). This is because research often isn't straightforward or linear, so it is difficult to adhere to the steps in the order they are described. Following, are the steps that are used in the ideal quantitative research (Bell et al., 2019):

1. **Elaborate theory**
   The quantitative research strategy is based on theory that already exists. First, the current theory is analyzed, which is to make sure that the same research is not done twice.

2. **Devise hypothesis**
   The most common way to continue the project is with a hypothesis that is based on the theory. Although, some quantitative research does not do this and the theory instead acts as a frame of reference for how the researcher does the data collection.

3. **Select research design**
   An appropriate research design is chosen for the project. This affects, among other things, how the research is validated.

4. **Devise measures of concepts**
   The ways that the research is quantitatively measured is chosen. This dictates how the research will be carried out.

5. **Select research site(s)**
   The setting for where the research is going to be conducted is chosen. It can be a single site or several sites that will be compared to each other.

6. **Select research subjects/respondents**
   The people who will be involved in the research are chosen. This can be, for example, subjects that experimental research will be made with or respondents who answer social survey questions.

7. **Administer research instruments/collect data**
   When everything that describes how the research will be made is chosen, the research can be carried out. For example, the subjects are tested, the interviews are being held or the observations are made.

8. **Process data**
   The information that was collected in the previous step is being transformed into data that can be analyzed.

9. **Analyze data**
   The data is analyzed, for example by reducing the data to focus on the variables that were chosen, and then testing different relationships between the variables. Then, the analyzed data is prepared to be presented to others.

10. **Develop findings/conclusions**
    The result of the analysis is interpreted and findings are formulated. The findings are then connected to the hypothesis and the theory that it was based on.

11. **Write up findings/conclusions**
    A research paper is written so that the research can be made public and convince others that it is important.

3.1.2 Approach

The 11 steps in the previous subchapter outline a deductive approach to research. This is an approach that proves or disproves a hypothesis to create new research, which is done by taking general information and applying it to a specific scenario (Bell et al., 2019). However, the steps did not fit this project exactly. For example, a hypothesis was not used, which was because the project focused on improving the situation at NOVO, not on proving or disproving that what they are doing now is correct. Instead, research questions were used, which is more typical for an inductive approach and qualitative research. That is an approach where the researcher gathers information through a specific scenario and then applies it to a more general point of view to create theory (Bell et al., 2019). However, the inductive approach did not fit the project in other aspects, such as it being based on interviews and written information. In this aspect, the deductive approach research fit the project better. A

result of this was that the project was mostly based on the deductive approach, but also added features of the inductive approach.

The method that was used is called systematic combining, which is a method that combines the deductive and inductive approaches (Dubois & Gadde, 2002). It is based on an abductive approach to the research, which means that the research alternates between the theory and the empirical findings, i.e. not only flowing from one part to the other as the deductive and inductive approaches do. By doing this, researchers are able to gain more knowledge about the research than they would have if they followed a strictly deductive or inductive approach (Dubois & Gadde, 2002). This is due to the nature of the method being iterative, which means more opportunities for learning, as well as seeing the theory and empirical findings from several perspectives.

Systematic combining makes it, for example, possible to write the theoretical framework and carry out the data collection and the data analysis simultaneously (Dubois & Gadde, 2002). This is an important thing to do to achieve the method's goal of matching the theory to the real world, which can be accomplished by comparing the framework with the data and analysis. To achieve the matching, the research needs to be continuously redirected according to the findings and the case that is being studied.

3.1.3 Design

Research design regulates how research is carried out, by guiding how the data is collected and determining how the data analysis is made (Bell et al., 2019). There are five different types of research designs - experimental design, cross-sectional design, longitudinal design, comparative design and case study design. The difference between these is what part of the research that is given the most importance, for example how different variables are related, applying the findings in a bigger context, understanding the importance of behaviour in different social settings, and seeing how social phenomena change over time.

The research design that was chosen for this project was the case study design, which is a design that emphasizes detailed analysis of a single case, such as a single organization, geographical location, person or event (Bell et al., 2019). This was implemented by the project focusing on only one organization and one location - NOVO and their new factory in Gothenburg. The case study design is also suitable for research that answers *how* and *why* questions (Baxter & Jack, 2008). This was demonstrated throughout the project by the research questions, which aimed to uncover why the bottlenecks existed and how they could be mitigated.

3.2 Literature review

To get a better understanding of what the project entailed, relevant literature was reviewed. There are two approaches to a literature review - systematic review and narrative review. The systematic review includes reading texts from numerous sources, which is to get a holistic picture of what research has been done on a specific topic before (Bell et al., 2019). This is to

make sure that the same research is not done twice. The approach ensures that researcher bias is not included in the review, since thorough research of both published and unpublished works should be done objectively. In contrast to the systematic review, the narrative review is less focused on a specific variable and instead has a bigger scope (Bell et al., 2019). It is used to gather information after the research questions have been formulated, unlike the systematic review, which is done in reverse order. The narrative review is the most common approach and is not as time-consuming as the systematic approach, which makes it more appropriate for a thesis and is why it was chosen for this project.

Because of the chosen approach, the literature review was based on the research questions. Documents containing information about battery manufacturing were obtained from the supervisor from NOVO. This was to get general knowledge of the battery industry and to get an insight into how the company operates. More specific information about NOVO and its owner companies was obtained directly from the companies and their websites, along with information from their press releases. Previous course literature on material flows, bottlenecks, root cause analysis and cost-benefit analysis, in the form of books and e-books, were also used in the literature review. Additional relevant information was obtained through scientific articles using the Chalmers Library database. Keywords that were used included, for example: *anode*, *cathode, FMEA* and *abductive research*.

3.3 Data collection

Data collection is one of the biggest and most important parts of a research project (Bell et al., 2019). The types that were used in this project are - documents, on-site visit and technology training.

3.3.1 Documents

To get information about the amount of samples that are taken from the raw material, the semi-finished products from each process step and the finished products from the end of production, different internal documents were analyzed. They also included, among other things, the production speed for the process steps, the amount of raw material that would be used per hour, which instrument that would test the samples, what quality criteria the instruments were testing for, the testing frequency for each of the samples and how many of each equipment type there would be in the quality lab. An overview of the plan for NOVO's factory was also used to understand the path that the samples will be transported.

Since the factory that NOVO is designing is the company's first factory, most of the data about the samples came from Northvolt's factory in Skellefteå, but some of the documents were also updated with NOVO's specific requirements. The data that was specific about the factory and the quality lab for Gothenburg came from NOVO.

3.3.2 On-site visit

To gain an insight into how samples currently are collected from the production and brought to the quality lab, a visit to Northvolt's factory in Västerås was conducted. There, real-time

observations of the material flows in both the production and to and from the lab were made so that the researchers could get first-hand experience of the processes, which was in the form of a walk-through of the entire production and quality labs. This was to understand how the samples will be collected at line, transported to the quality lab and received by the quality technicians in NOVO's new factory. The tour also included how the tests were carried out in the lab and how the waste was transported from the lab.

3.3.3 Technology training

To acquire more hands-on experience with NOVO's production, processes and equipment, the researchers participated in several sessions that were called *technology training* at the company. There, presentations on topics that varied from different manufacturing process steps to what NOVO is doing to ensure safety within the factory, and were held by NOVO employees that are professionals within their respective areas. This was conducted so that the researchers would not only get general information about how batteries are made, but also how it specifically will happen in NOVO's new factory.

3.4 Trustworthiness

This project is primarily quantitative which means that reliability and validity emerge as important concepts. Reliability ensures consistency and reproducibility of the results across different circumstances (Bell et al., 2019). It encompasses various aspects such as stability, internal reliability and inter-rater reliability. To ensure reliability, stability assessments should be conducted to gauge consistency over time. Internal reliability should be assessed by examining indicator consistency within measurement scales. Inter-rater reliability should be evaluated to ensure agreement among raters, particularly for subjective judgments. Validity means that the conclusions from the research are accurate (Bell et al., 2019). This term can be divided into internal and external validity, which covers whether the results are believable and if they can be applied in other studies.

However, these concepts do not fully align with this project, since it is not fully quantitative. Reliability and validity fit projects that are doing tests to prove or disprove a hypothesis, but this project has a mixed approach with research questions leading the research instead. This is a more qualitative aspect, and the term "trustworthiness" is often emphasized for qualitative research instead of reliability and validity (Bell et al., 2019). The trustworthiness of qualitative data has been a subject of debate, yet it has robust support from its supporters. The term includes the criterias credibility, transferability, dependability and confirmability (Bell et al., 2019), which are more suited to assessing the quality of the qualitative research part, considering its focus on understanding phenomena from contexts of the case study.

Ensuring the credibility of qualitative research is related to establishing internal validity in quantitative analysis. Credibility involves providing accurate data about the study, ensuring that the findings truly represent the participants' perspectives and experiences (Bell et al., 2019). Techniques such as triangulation and validation are often used to enhance credibility. In order to enhance credibility in this project, triangulation involved collecting data from

multiple sources, such as databases and observations, to confirm findings. Member validation allowed participants to review the interpretations, ensuring that their perspectives were accurately represented.

Transferability refers to the degree to which research findings can be applied to other contexts, groups, or settings with similar characteristics (Bell et al., 2019). Unlike quantitative research, which often seeks broad generalizability, qualitative research focuses on rich, context-specific insights. Providing detailed descriptions of the research context allows others to determine the applicability of the findings to their own settings. To enhance transferability, this project provided detailed descriptions of the research context.

Dependability concerns the consistency and reliability of the research process. It indicates that the findings are stable and repeatable under similar conditions (Bell et al., 2019). By maintaining an audit trail throughout this project, which documents the research process in detail, the dependability is enhanced by allowing for external scrutiny and verification.

Confirmability ensures that the findings are shaped by the participants' responses rather than researcher bias (Bell et al., 2019). To maintain confirmability in this project, the researchers remained objective throughout the research process, avoiding the inclusion of biases on the data. Regular audits of interpretations were also conducted to identify and mitigate potential biases, which further enhanced confirmability.

4. Current situation

In this chapter, the current situation is described. It includes the plan for how the material will flow from production to the quality lab, as well as inside the lab. There is also a description of the types and amount of samples that will arrive in the lab per week. In addition to this, the time that each test will take, from preparation to getting the result, is presented.

4.1 Material flow of samples in the factory

Within the factory, the flow of samples can be divided into two parts - from the production to the quality lab and within the quality lab. During the first part, the samples are collected, and during the second part, the samples are received and analyzed, and the waste is being generated.

4.1.1 Sample collection

Samples are collected from various points in the production, which is to ensure that the product meets the quality requirements. The samples are taken from both the raw materials before they enter production, which is called Incoming Quality Control (IQC), as well as semi-finished products from all of the process steps and from the finished products at the end of production. Each sample is labeled with relevant information, including the date and time of collection, location, batch and production lot number, before being transported to the quality lab. This labeling ensures proper documentation and traceability of each sample. The traceability is important because if a problem occurs, then the reason for it can be found by looking at the data from each step. It also makes it possible to find all of the affected batches and remove them from production.

After labeling, samples are appropriately packaged to prevent contamination or degradation during transportation. Packaging materials may vary depending on the nature of the sample and any specific handling requirements, for example will the foils be transported in plastic folders to prevent bending and tearing. When the samples have been packaged, the material handling team collects them from the various pick up points and delivers them to the quality lab. Upon arrival outside of the lab, the samples are placed into a two-way cabinet.

4.1.2 Sample reception

On the other side of the two-way cabinet, from inside the lab, a quality technician or operator collects the samples. Then, the samples undergo a reception process where they are logged into the Laboratory Information Management System (LIMS). This step ensures proper tracking and management of all incoming samples. After that, the samples are placed into their respective storage locations to wait for pick-up by the people performing the quality tests. Proper storage conditions are maintained to preserve sample integrity until testing occurs.

4.1.3 Analysis

When the personnel responsible for quality testing are ready to conduct their analyzes, they retrieve the samples from the storage locations based on their testing schedule and priorities.

There will be about 15 people working in the lab per shift, and in total there will be three shifts per day, seven days per week. This is to keep the production running, since it cannot run if the materials aren't tested before they enter production.

There are three different labs within the quality lab, mechanical, chemical and imaging, where different types of tests are being conducted. These areas house various analytical instruments such as titrators, chromatographs and microscopes. The quality tests are conducted on the samples according to the predetermined testing protocols, which are called Standard Operating Procedures (SOP). This may involve various analytical techniques, equipment and methodologies specific to the quality parameters being assessed. The results of the quality tests are recorded accurately and entered into LIMS. Any deviations or abnormalities are noted and further investigation may be conducted if necessary.

4.1.4 Waste

After testing is complete, samples may be disposed of according to the waste management protocol. Work areas and equipment are cleaned and maintained regularly to prevent contamination and ensure optimal performance. This includes routine maintenance of instruments, decontamination of work surfaces and proper disposal of waste. The waste generated during testing may include various types, which are segregated according to their characteristics and potential hazards. This results in four different types of waste - general contaminated waste, glass contaminated waste, contaminated plastic waste and liquid waste.

1. **General contaminated waste**
   Each laboratory will generate around two 50 liter bags of general contaminated waste per shift for each lab. With three shifts per day, this results in 42 bags of waste per lab per week. Since there are three different labs, it makes the total expected general waste to 126 bags per week across all labs. This category encompasses various disposable items such as gloves and wipes.

2. **Glass contaminated waste**
   The generation of glass contamination waste is estimated at two 50 liter bags per week in total for all labs. This includes glass vials and empty chemical bottles.

3. **Contaminated plastic waste**
   Similar to glass waste, contaminated plastic waste is expected to result in two 50 liter bags per week in total for all labs. The category encompasses chemical containers, used bottles and other plastic items that are contaminated during the laboratory procedures.

4. **Liquid waste**
   Liquid waste generation is primarily attributed to the chemical lab with an estimated daily output of 10 liters. Within this liquid stream, approximately 2-3 liters per day

consist of acidic waste, which may include strong or weak acids. This results in a total of 70 liters of liquid waste per week across all laboratories.

4.2 Amount of samples

To get the amount of samples that the quality lab will receive, data from Northvolt's factory in Skellefteå is analyzed together with the updated requirements for NOVO's factory and its production speeds.

The samples that are tested in Northvolt's factory are divided into different documents, called control plans, depending on which process they come from - IQC, mixing, coating, calendering, notching, stacking, cell assembly, and formation and aging. The control plans contain all of the tests that are carried out for each process step, both in line, at line and off line. In line means that the test is done continuously in the production line and that all of the products are tested, for example via cameras. This is the most preferable way to conduct the quality tests, since they are fast and don't require any human interaction. At line means that a sample is collected and that the test is performed next to the production line. This is for tests that are easier and don't need to be carried out by personnel with extra training. It is the second most preferable way to perform the tests, since the samples don't have to be transported to the quality lab. This allows for fast results, enabling production to be stopped quickly if there are any issues. Off line means that the sample needs to be sent to the quality lab, which is because it requires special equipment or personnel. This is the least preferable way, because it takes the longest time to get the test results. The control plans also contain detailed information regarding which quality parameters that have to be checked, how often the materials have to be tested, which person that should test them and what to do if the quality is too low. To know which of the samples that are meant for the quality lab, the samples that are carried out by quality technicians off line were separated out from the rest.

4.2.1 Samples from IQC

Most tests will be done on samples from IQC, which is the raw material that enters the factory. It includes everything that is a part of the battery, from the components of the anode and cathode, to the separators and tapes that keep the components together, and the cans and lids that encapsulates the battery. These tests are very important, since NOVO has to be sure that they are not sending bad or contaminated material into the production. The materials, also called process elements, that will be tested from ICQ, along with the equipment, amount and testing frequency for each process element are shown in *Table 1*.

Process element	Equipment	Amount	Testing frequency
Artificial graphite	BET DSC Halogen heater ICP Karl Fischer titration Particle size distributor Thermal gravimetric analysis	250 ml	2 batches / week

Natural graphite	BET DSC Halogen heater ICP Karl Fischer titration Particle size distributor Thermal gravimetric analysis	250 ml	2 batches / week
Cathode active material A	BET DSC Halogen heater ICP Karl Fischer titration Oven Particle size distributor Thermal gravimetric analysis	250 ml	2 batches / week
Cathode active material B	BET DSC Halogen heater ICP Karl Fischer titration Oven Particle size distributor Thermal gravimetric analysis	250 ml	2 batches / week
CNT	Karl Fischer titration	250 ml	2 batches / week
NMP	Karl Fischer titration	250 ml	Every delivery (8.1 batches / shift)
Refined NMP	ICP	250 ml	2 batches / week
PVDF	Karl Fischer titration	250 ml	2 batches / week
Aluminum foil	Tensile tester	1 m	Every 5 batches (1 batch / shift)
Copper foil	Tensile tester	1 m	Every 5 batches (1.7 batches / shift)
Separator	Gurley tester Karl Fischer titration Oven Puncture tester Tensile tester	1 m	Every 5 batches (42 batches / shift)
Fixing tape	Karl Fischer titration Tensile tester	1 sample	Every batch (1 batch / shift)
Can	CMM Jomesa microscope Profilometer Roughness tester	4 cans	Every batch (8 batches / shift)
Lid	CMM Jomesa microscope Profilometer Roughness tester	4 lids	Every batch (21.6 batches / shift)
Insulators	Karl Fischer titration Tensile tester	1 sample	Every 5 batches (30 batches / shift)
Insulator tape	Karl Fischer titration Tensile tester	1 sample	Every batch (1 batch / shift)

Wrapping tape	Karl Fischer titration Tensile tester	1 sample	Every batch (1 batch / shift)
Electrolyte	Acid titration Gas chromatography Ion chromatography Karl Fischer titration UV/Vis spectrometer	250 ml	Every batch (1 batches / day)
Temporary seal pin	CMM	4 temporary seal pins	Every batch (21.6 batches / shift)
Seal ball	CMM	4 seal balls	Every batch (21.6 batches / shift)
Permanent seal pin	CMM	4 permanent seal pins	Every batch (21.6 batches / shift)

Table 1: Samples from IQC.

4.2.2 Samples from mixing

During mixing, the only thing that will be tested off line is how clean the area is. This will be done with particle traps that test the air for metallic and non-metallic particles, which can contaminate the product. There will be 4 particles traps in the mixing area, which is based on the area's size, and they will be tested every second day. This is shown in *Table 2* below.

Process element	Equipment	Amount	Testing frequency
Particle traps in mixing	Jomesa microscope	4 particle traps	Every second day

Table 2: Samples from mixing.

4.2.3 Samples from coating

For coating, the jumbo rolls will be tested for tensile strength and dimensions, which is to ensure that they meet the standards before entering further stages of production. This will be done for both the anode and cathode parts. The amount of particles in the area will also be tested to make sure that the area is clean, to avoid contamination on the coated foils. The amount of particle traps for coating is bigger than the amount for mixing, which is because the coating area is significantly larger than the mixing area. There are three coating lines each for both anode and cathode, which gives the amount of samples that will be delivered to the quality lab per shift. These are shown in *Table 3*.

Process element	Equipment	Amount	Testing frequency
Anode jumbo roll	VMZ	3 sheets	Every shift
Anode jumbo roll	Tensile gauge	6 sheets	Every shift
Cathode jumbo roll	VMZ	3 sheets	Every shift
Cathode jumbo roll	Tensile gauge	6 sheets	Every shift
Particle traps in anode coating	Jomesa microscope	25 particle traps	Every second day
Particle traps in cathode coating	Jomesa microscope	25 particle traps	Every second day

Table 3: Samples from coating.

4.2.4 Samples from calendering

In calendering, the product will be tested to make sure that it has the correct properties and the amount of particles in the area is tested again. This is also done for both anode and cathode. In this process, the jumbo roll from the previous process step is cut into four smaller rolls, called pancakes. These pancakes are different lengths for anode and cathode, with cathode being the longer one, but the production speed for them is the same. This means that the number of pancakes that need to be tested per shift is larger for anode than cathode. All of the tests are presented in *Table 4* below.

Process element	Equipment	Amount	Testing frequency
Anode pancake	Optical microscope VMZ	2 sheets	Every roll (56.5 rolls / shift)
Anode pancake	Tensile gauge	12 sheets	Every shift
Cathode pancake	Optical microscope VMZ	2 sheets	Every roll (47 rolls / shift)
Cathode pancake	Tensile gauge	12 sheets	Every shift
Particle traps in anode calendering	Jomesa microscope	18 particle traps	Every second day
Particle traps in cathode calendering	Jomesa microscope	18 particle traps	Every second day

Table 4: Samples from calendering.

4.2.5 Samples from stacking

In stacking, only the particle traps that test for metallic and non-metallic particles in the air are sent to the quality lab. The amount adds up to 45 particle traps for the entire stacking area, which is due to the area housing many machines that could produce particles and contaminate the products. This is shown in *Table 5*.

Process element	Equipment	Amount	Testing frequency
Particle traps in stacking	Jomesa microscope	45 particle traps	Every second day

Table 5: Samples from stacking.

4.2.6 Samples from cell assembly

Cell assembly includes many different manufacturing steps, which is why there are many tests from this process. There will, for example, be tests of both the welding qualities of the can and the lid by microscope, as well checking that the electrodes are aligned with a CT scanner. The electrolyte will also be tested again, to make sure that it is not contaminated. Like all of the previous process steps, the air will be tested for particles to make sure that the products stay uncontaminated. All of the tests are shown in *Table 6*.

Process element	Equipment	Amount / line	Testing frequency
Particles in cell stack	Jomesa microscope	2 cell stacks	Every shift
Cans welding quality	Tensile tester	3 cells	Every shift
Particles in cell	Jomesa microscope	1 cell	Every shift
Lid laser welding	CT scan	3 cells	Every day
Weld seam quality	Optical microscope	3 cells	Every shift
Internal cell appearance	CT scan	8 cells	Every day
Electro alignment control	CT scan	16 cells	Every day
Electrolyte filling	Gas chromatography ICP Ion chromatography	250 ml	Every two weeks
Electrolyte filling	HF titration Karl Fischer titration Optical microscope	250 ml	Weekly
Particle traps in cell assembly	Jomesa microscope	30 particle traps	Every second day

Table 6: Samples from cell assembly.

4.2.7 Samples from formation and aging

For the final step of production, formation and aging, the finished cells will be tested. The area for this process step is very big, since it houses storage places for the cells while they are being tested for charging. Although, the products cannot be contaminated here because all of the seams have been closed, so the only area that will be tested for particles in the air is the packaging area. All of the tests are shown in *Table 7* below.

Process element	Equipment	Amount	Testing frequency
Electrolyte filling	HF titration Jomesa microscope Karl Fischer titration	250 ml	Daily
Welding	Optical microscope	1 cell	Every two weeks
Particles at the surface of cells	Jomesa microscope	1 particle stamp	Daily
Particles in packaging	Jomesa microscope	12 particle traps	Every second day

Table 7: Samples from formation and aging.

4.3 Test equipment

Since the materials and products that are being tested are very different, various tests are needed, and therefore many types of equipment will be used. To find which tests are the bottlenecks, i.e. which takes the longest times, the lead times for the different equipment are needed. The lead times include time for preparation of the sample, calibration of the instrument, testing the sample and cleaning the instrument. The equipment, along with which

properties they test, their corresponding lead times and how many machines that are planned to be installed in the lab, are presented in *Table 8*.

Equipment	Tested property	Lead time per sample	Number of instruments
BET	Surface area	215 min for graphites 185 min for cathode active materials	2
CMM	Dimensions	30 min for cans and lids 7.5 min for seal pins and seal balls	2
CT scan	Alignment Appearance	46 min	2
DSC	Thermal stability Impurities	40 min	1
Gas chromatography	Composition	220 min	2
Gurley tester	Permeability	10 min	1
Halogen heater	Moisture	30 min	1
ICP	Elemental analysis	230 min	1
Ion chromatography	LiPF6 content MP1 content	260 min	1
Jomesa microscope	Particle contamination	55 min (for 6 samples at once)	4
Karl Fischer titration	Moisture	36 min	2
Optical microscope	Appearance	35 min	4
Oven	Solid content	20 min for cathode active material A 40 min for cathode active material B 30 min for separator	3
Profilometer	Surface smoothness	5 min	1
Particle size distributor	Particle size	20 min	2
Puncture tester	Puncture resistance	15 min	1
Roughness tester	Roughness	7.5 min	1
Tensile tester	Adhesion Tensile strength	10 min for cans 20 min for the rest of the materials	5
Thermal gravimetric analysis	Thermal stability Impurities	25 min	1
Titrator	Free acid HF	30 min	2
UV/Vis spectrometer	Color	45 min	1
VMZ	Alignment Dimensions	33 min	4

Table 8: Lead times for the different test equipment.

4.4 FMEA for the quality lab

To gain insight into which risks there are in the lab, an FMEA was made. This included, among other things, failure modes, failure effects, failure causes, current detection controls and measures for every risk that were identified for each of the process steps in the quality lab - sample reception, performing analysis and environment.

The specific data cannot be included in this report, due to confidentiality, but a few examples can be explained briefly:

1. One risk is that there would not be enough operators to perform the tests, which would be mitigated by relocating the work staff from other areas.
2. Another risk is that tests would be performed wrong, and the measures that would be implemented were to provide the correct training for the operators and to ensure that every test has the correct SOP.

5. Analysis

This chapter conducts an examination of the data collected during the study to uncover the bottlenecks. It also provides an assessment of the factors impacting the efficiency of the quality lab, by presenting a root cause analysis with Five Whys and Fishbone Diagram.

5.1 Bottleneck identification

The lead times and possible run times per equipment are presented to show the bottlenecks.

5.1.1 Lead times per shift and lead times periodically

To get the lead times per equipment, the amount of samples were combined with the respective lead times per material. Firstly, all of the samples that will be carried out per shift were gathered to get the total lead time per shift. This resulted in *Table 9* below.

Equipment	Material	Test frequency	Lead time per shift
CMM	Can Lid Temporary seal pin Seal ball Permanent seal pin	32 samples / shift 86.4 samples / shift 86.4 samples / shift 86.4 samples / shift 86.4 samples / shift	5 496 min / shift
Gurley tester	Separator	42 samples / shift	420 min / shift
Ion chromatography	Electrolyte (IQC)	0.33 samples / shift	87 min / shift
Jomesa microscope	Can Lid Particles in cell stack Particles in cell	32 samples / shift 86.4 samples / shift 2 samples / shift 1 sample / shift	1 113 min / shift
Karl Fischer titration	NMP Separator Fixing tape Insulators Insulator tape Wrapping tape Electrolyte (IQC)	8.1 samples / shift 42 samples / shift 1 sample / shift 30 samples/ shift 1 sample / shift 1 samples / shift 0.33 samples / shift	3 003 min / shift
Optical microscope	Weld seam quality	3 samples / shift	105 min / shift
Oven	Separator	42 samples / shift	1260 min / shift
Profilometer	Can Lid	32 samples / shift 86.4 samples / shift	592 min / shift
Puncture tester	Separator	42 samples / shift	630 min / shift
Roughness tester	Can Lid	32 samples / shift 86.4 samples / shift	888 min / shift
Tensile tester	Aluminum foil Copper foil Separator Fixing tape Insulators Insulator tape	1 sample / shift 1.7 samples / shift 42 samples / shift 1 sample / shift 30 samples / shift 1 sample / shift	2304 min / shift

	Wrapping tape Anode jumbo roll Cathode jumbo roll Anode pancake Cathode pancake Cans welding quality	1 sample / shift 6 samples / shift 6 samples / shift 12 samples / shift 12 samples / shift 3 samples / shift	
Titrator	Electrolyte (IQC)	0.33 samples / shift	10 min / shift
UV/Vis spectrometer	Electrolyte (IQC)	0.33 samples / shift	15 min / shift
VMZ	Anode jumbo roll Cathode jumbo roll Anode pancake Cathode pancake	3 samples / shift 3 samples / shift 56.5 samples / shift 47 samples / shift	3614 min / shift

Table 9: Tests that are done per shift.

Secondly, the tests that will be done periodically, i.e. per day, week or every other week, were gathered. These tests don't have a specified time of day that they have to be carried out on, which means that they can be done in the lab when there is time over or when the quality technicians don't have any tests that are more urgent. The lead times were calculated per week to see the total time that needs to be allocated for the periodical tests every week, and then also calculated per shift to see how much time they will need per shift on average. This resulted in *Table 10*.

Equipment	Material	Test frequency	Lead time per week and shift
BET	Artificial graphite Natural graphite Cathode active material A Cathode active material B	2 samples / week 2 samples / week 2 samples / week 2 samples / week	1600 min / week 76 min / shift
CT scan	Lid laser welding Internal cell appearance check Electro alignment control	3 samples / day 8 samples / day 16 samples / day	8 694 min / week 414 min / shift
DSC	Artificial graphite Natural graphite Cathode active material A Cathode active material B	2 samples / week 2 samples / week 2 samples / week 2 samples / week	320 min / week 15 min / shift
Gas chromatography	Electrolyte (IQC) Electrolyte filling (CA)	1 sample / day 1 sample / 2 weeks	1650 min / week 79 min / shift
Halogen heater	Artificial graphite Natural graphite Cathode active material A Cathode active material B	2 samples / week 2 samples / week 2 samples / week 2 samples / week	240 min / week 11 min / shift
ICP	Artificial graphite Natural graphite Cathode active material A Cathode active material B Refined NMP Electrolyte filling (CA)	2 samples / week 2 samples / week 2 samples / week 2 samples / week 2 samples / week 1 sample / 2 weeks	2 415 min / week 115 min / shift
Ion chromatography	Electrolyte filling (CA)	1 sample / 2 weeks	130 min / week 6 min / shift

Jomesa microscope	Particle traps in mixing Particle traps in anode coating Particle traps in cathode coating Particle traps in anode calendering Particle traps in cathode calendering Particle traps in stacking Particle traps in cell assembly Particles in packaging Electrolyte filling (FA) Particles at the surface of cells	4 samples / 2 days 25 samples / 2 days 25 samples / 2 days 18 samples / 2 days 18 samples / 2 days 45 samples / 2 days 30 samples / 2 days 12 samples / 2 days 1 sample / day 1 sample / day	5 807 min / week 277 min / shift
Karl Fischer titration	Artificial graphite Natural graphite Cathode active material A Cathode active material B CNT PVDF Electrolyte filling (CA) Electrolyte filling (FA)	2 samples / week 2 samples / week 2 samples / week 2 samples / week 2 samples / week 2 samples / week 1 sample / week 1 sample / day	720 min / week 34 min / shift
Optical microscope	Electrolyte filling (CA) Welding	1 sample / week 1 sample / 2 weeks	52.5 min / week 3 min / shift
Oven	Cathode active material A Cathode active material B	2 samples / week 2 samples / week	120 min / week 6 min / shift
Particle size distributor	Artificial graphite Natural graphite Cathode active material A Cathode active material B	2 samples / week 2 samples / week 2 samples / week 2 samples / week	160 min / week 8 min / shift
Thermal gravimetric analysis	Artificial graphite Natural graphite Cathode active material A Cathode active material B	2 samples / week 2 samples / week 2 samples / week 2 samples / week	210 min / week 10 min / shift
Titrator	Electrolyte filling (CA) Electrolyte filling (FA)	1 sample / week 1 sample / day	240 min / week 11 min / shift

Table 10: Tests that are done periodically.

5.1.2 Lead times compared to possible run times

To get the total amount of lead time per equipment, the lead times per shift were added to the lead times periodically, which is shown in *Table 11*. For some equipment, there will only be one type of lead time, which depends on how often the instrument will be used. The possible run times per shift were also included in the table. These describe how many minutes that the equipment is theoretically possible to run during one shift, which depends on the number of instruments that will be in the quality lab. For example, if there are two instruments, then the possible run time is 960 minutes per shift, since the machines can run for 480 minutes each.

Based on the amount of samples and the lead time for each test, the equipment that will be consuming the most time could be pinpointed. When the total lead times per shift were compared to the possible run times per shift for each of the equipment, there were six equipment that were shown to have longer lead times than what is possible. These are CMM, Karl Fischer titration, Profilometer, Puncture tester, Roughness tester and VMZ, which are marked with gray in *Table 11* below. This implies that if the current plan for sample testing

in the quality lab is followed, these instruments will cause delays in the production, as it cannot run if the samples have not been approved. Consequently, these six equipment are the bottlenecks in NOVO's quality lab.

Equipment	Lead time per shift	Lead time periodically per shift	Total lead time per shift	Possible run time per shift
BET		76 min	76 min	960 min
CMM	5 496 min		5 496 min	960 min
CT scan		414 min	414 min	960 min
DSC		15 min	15 min	480 min
Gas chromatography		79 min	79 min	960 min
Gurley tester	420 min		420 min	480 min
Halogen heater		11 min	11 min	480 min
ICP		115 min	115 min	480 min
Ion chromatography	87 min	6 min	93 min	480 min
Jomesa microscope	1 113 min	277 min	1390 min	1 920 min
Karl Fischer titration	3 003 min	34 min	3 037 min	960 min
Optical microscope	105 min	3 min	108 min	1 920 min
Oven	1 260 min	6 min	1 266 min	1 440 min
Profilometer	592 min		592 min	480 min
Particle size distributor		8 min	8 min	960 min
Puncture tester	630 min		630 min	480 min
Roughness tester	888 min		888 min	480 min
Tensile tester	2 304 min		2 304 min	2 400 min
Thermal gravimetric analysis		10 min	10 min	480 min
Titrator (Acid. HF)	10 min	11 min	21 min	960 min
UV/Vis spectrometer	15 min		15 min	480 min
VMZ	3 614 min		3 614 min	1 920 min

Table 11: Summarization and comparison of lead times and possible run times. All of the times are per shift.

The bottlenecks could be ranked based on how much more lead time they will have than the possible run time. This is presented in *Table 12*, and it shows that CMM is the biggest bottleneck with 473% more calculated lead time than the possible run time for the current plan. Karl Fischer titration is also a big bottleneck with 216%, and then VMZ and Roughness tester are around the same amount with 85-88%. Puncture tester and Profilometer are the

lowest with 31% and 23%. Only the three biggest bottlenecks were addressed further, as per the project scope limitations.

Equipment	Total lead time per shift	Possible run time per shift	% of more lead time than possible run time
CMM	5 496 min	960 min	473%
Karl Fischer titration	3 037 min	960 min	216%
VMZ	3 614 min	1 920 min	88%
Roughness tester	888 min	480 min	85%
Puncture tester	630 min	480 min	31%
Profilometer	592 min	480 min	23%

Table 12: Bottlenecks ranked based on the amount of lead time in relation to the possible run time.

5.2 Root cause analysis with Five Whys

To perform the analysis with the Five Whys method, the main problem was stated first (Wolniak & Grebski, 2023). This was that there existed bottlenecks within the quality lab, i.e. that the quality tests were not being approved fast enough in relation to production. Then the question "Why?" was asked, which gave the cause for the main problem. At this step, the Five Whys were split into three different analyses, one for each of the three biggest bottlenecks - CMM, Karl Fischer titration and VMZ. Then, the question "Why?" was asked four more times to uncover the root causes of the bottlenecks (Wolniak & Grebski, 2023).

5.2.1 Five Whys for CMM

For the biggest bottleneck, the CMM, the cause as to why the quality tests will not be approved fast enough in relation to the production is that there will be delays from the instruments. The reason for this is that the samples cannot be tested fast enough, which is due to the total lead time of 5 496 minutes per shift being longer than the possible run time of the two CMM's, which is 960 minutes per shift. By analyzing the data from Northvolt, the total number of samples that need to be tested per shift was found to be large - 377.6 samples. In combination with this, the time to perform the tests will be between 7.5 minutes and 30 minutes per test, with the majority of tests taking the latter amount of time, which results in the long lead time. The causes for this, and also the root causes for the CMM, is that four samples need to be collected from each batch per material and that the instruments are slow when performing the tests. All of the causes for CMM can be seen, in order, in *Figure 5*.

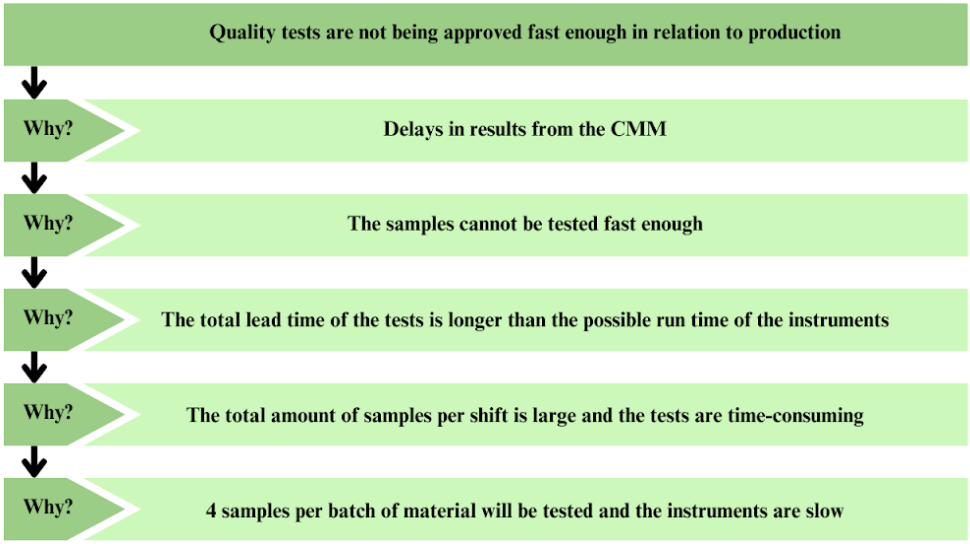

Figure 5: Five Whys for CMM (own illustration).

5.2.2 Five Whys for Karl Fischer titration

Just like the CMM, the reason for the main problem is that the Karl Fischer titration will cause delays because the tests cannot be carried out fast enough. This is also due to the lead time for the instrument being longer than the possible run time, with 3 037 minutes for testing and only 960 possible minutes to do so. The reason for this is also that there is a large number of samples that have to be tested, and that each test will take 36 minutes, which is a long time for the large amount. This is because the equipment is testing the moisture in the components, which is a very important test. Because of this, there are a lot of different materials that need to be tested, and some of them have to be tested frequently, such as the separators that have to be tested 42 times per shift and the insulators that have to be tested 30 times per shift. This, in combination with slow instruments, gives the root cause for the problems with the Karl Fischer titration. The Five Whys for this instrument is shown in *Figure 6* below.

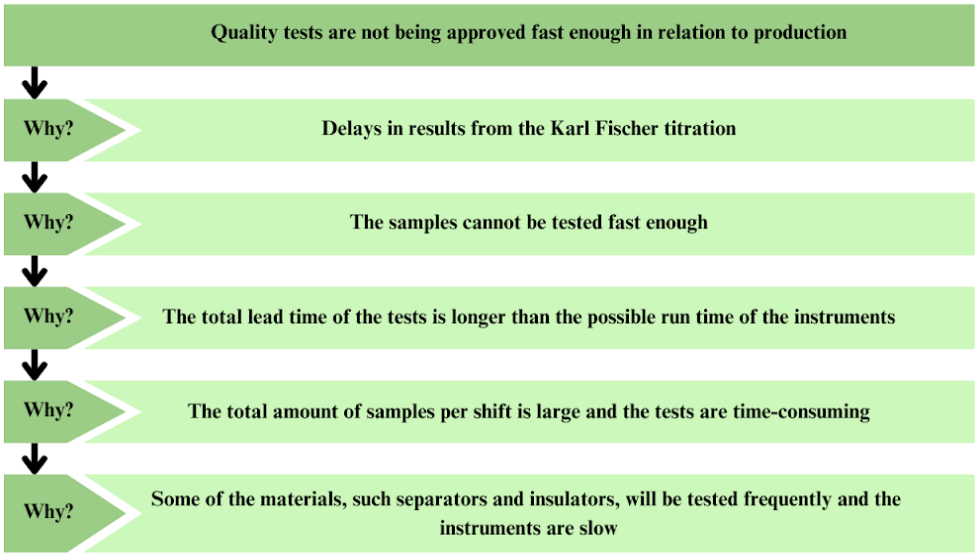

Figure 6: Five Whys for Karl Fischer titration (own illustration).

5.2.3 Five Whys for VMZ

The reason for the main problem when it comes to VMZ is, just like CMM and Karl Fischer titration, that the instrument will be causing delays. This is because the testing is not carried out fast enough. The cause for this is also that the lead time is longer than the possible run time of the instruments, with 3 614 minutes for the lead time and 1 920 minutes for the run time. Although the ratio between the lead time and run time is smaller than the other two bottlenecks, the lead time is still larger and is a big problem, which is due to a large number of samples that need to be tested. The tests are also time-consuming, with 33 minutes per test. The root cause for the problems with VMZ is that the pancakes need to be tested frequently, with 56.5 and 46 tests per shift for anode and cathode respectively, and that the instruments are slow. The Five Whys for VMZ is shown in *Figure 7* below.

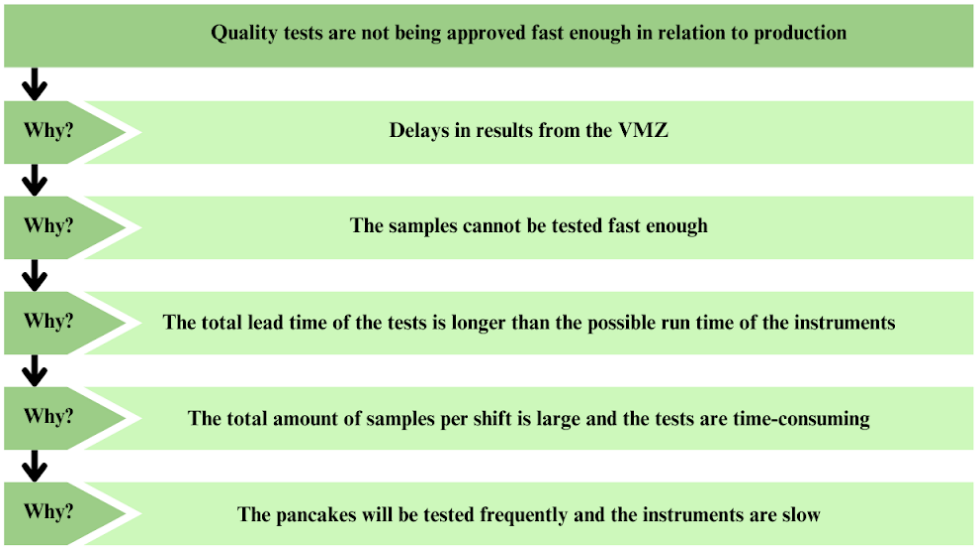

Figure 7: Five Whys for VMZ (own illustration).

5.3 Root cause analysis with Fishbone Diagram

Another, more detailed, method that was used for identifying the root causes was the Fishbone Diagram.

5.3.1 Fishbone Diagram for all three bottlenecks

First the main problem was stated, which was that the test results were delayed (Tarantino, 2022). It was the same problem for all of the three bottlenecks, which is why only one Fishbone Diagram was created. The main problem was placed in a square at the right hand side of the diagram, as the “head of the fish”, and then a main line was drawn out from the square.

After the main problem was formulated, the six following categories were connected to the main line - Environment, Material, People, Method, Machine/Equipment and Measurement. Then, main causes for the problem were stated and filed under the correct category as the “ribs of the fish” (Tarantino, 2022). Further causes were then filled in for each of the main causes, as to explain why they existed.

The Fishbone Diagram is shown in *Figure 8*, and all of the found causes for each of the categories are described in more detail below.

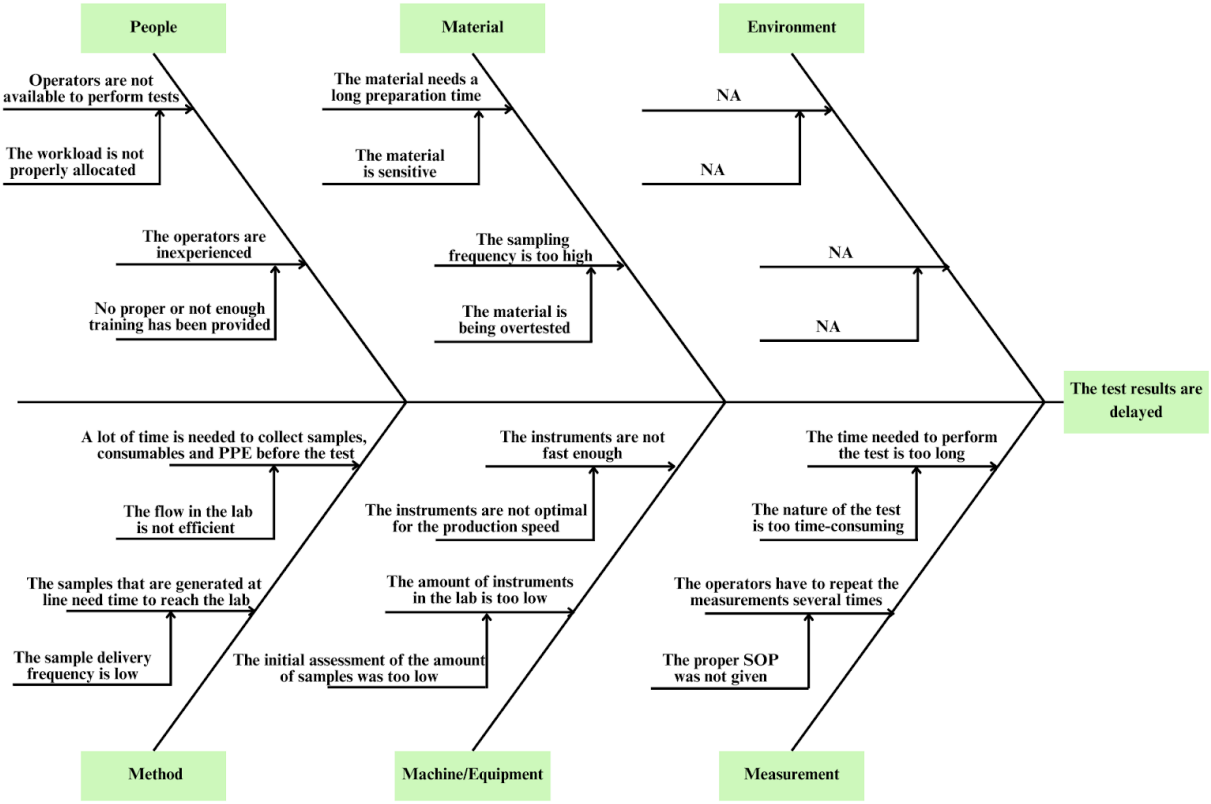

Figure 8: Fishbone Diagram for the bottlenecks (own illustration).

1. **Environment**
   This category doesn't contain any factors that can impact the delivery times for the instruments, so it was marked as "NA" (Not Applicable).

2. **Material**
   The material can impact the sample delivery time in two ways. The first reason is that the material needs a long time to be prepared, which is due to it being sensitive. The second reason is that the sampling frequency is too high, which is a result of overtesting. This means that the material is being tested more frequently than it has to be to ensure the quality.

3. **People**
   If there are no operators available to perform the tests, the results will be delayed. The reason for this is that the workload is not properly allocated, for example if there are not enough operators in the lab or if the operators need to do other tests that are more urgent. The operators can also be inexperienced, which will impact the time needed to perform the tests negatively, by them taking longer than necessary. This is due to the operators not having received any proper training or them not having received enough training to perform the tests in the most efficient way.

4. **Method**
   Regarding the method, it can cause the total lead times of the tests to take longer than necessary if a lot of time is needed to collect samples, consumables and personal protective equipment (PPE) before the test. This is because the operators need time to walk around the lab to collect them if they are far away from each other, which will happen if the flow in the lab is not efficient. Another extra time that will be added to the lead time is the samples transportation time from the production line to the quality lab. For example, if the delivery frequency from the line is low, the samples have to wait there longer than necessary before being sent to the lab.

5. **Machine/Equipment**
   The main causes as to why the delivery time is too long regarding the machines and equipment are that the instruments are not fast enough and that the amount of instruments in the lab is too low. The reason for the first cause is that the instruments are not optimal for the production speed. This means that there might be faster instruments on the market, but that these were not bought due to, for example, lack of awareness of them existing, them being too expensive or them not fitting into the current layout of the quality lab. The reason for the second cause is that the initial assessment of the amount of samples was too low. This could be, for example, due to improper calculations, NOVO having to increase the sampling frequency due to unexpected problems in the factory or them wanting to test more than what has been done in Northvolt's other factories.

6. **Measurement**
   For the measurements, a problem can be that the time needed to perform the test is too long, which would be due to the nature of the test being too time-consuming. This means that the machine that is in the lab is the fastest on the market, but it is still too slow to generate results in time. Another problem could be that the operators have to repeat the measurements several times, which is because they are performing it in the wrong way and therefore getting inaccurate results. This could be due to them not having the correct SOP for the instrument.

5.3.2 Reflections on the Fishbone Diagram

Since the diagram was based on the causes that can lead to the main problem for an instrument in the lab in general, there are several of the causes that don't apply specifically for the three biggest bottlenecks.

When it comes to Material, the first reason is not applicable for the three bottlenecks. This is because there is not a long preparation time for any of the materials that are tested with either CMM, Karl Fischer titration or VMZ. The preparation time is generally only a couple of minutes for these instruments. For the Karl Fischer titration, the second cause about the sampling frequency being too high is not applicable either. This is because the materials

cannot be tested less frequently than they are now, because if they were, the quality could not be ensured.

Both of the causes that are connected to People are legitimate causes for delays with the three different instruments, but they can be overlooked here because of the mitigation that was proposed in the FMEA - that the workload will be redistributed if problems occur. This will also be done by enough operators being hired to carry out the number of tests that are needed for the samples, and the work schedules being planned so that the lab is filled to maximum capacity. It is also assumed that operators are not going to be allowed to work in the lab without the correct education or training, which is a mitigation from the FMEA to ensure safety during tests and to make sure that the tests are carried out correctly, so that the results can be trusted.

For Method, both of the causes can lead to delays, but they are not reasons for the lead times being longer than the possible run times, which means that they don't apply to any of the three bottlenecks. The lead times only include the time to conduct the actual test, and not walking around the lab to gather the necessary tools and material to conduct it or the time that it takes for the sample to arrive from the production line. This means that even if the times for walking and transportation were reduced to 0 minutes, the bottlenecks would still be as big as they are now. Because of this, solutions other than improving the efficiency of the lab and decreasing the waiting times between sample deliveries to the lab are needed.

For Measurement, both of the causes are not applicable. For the first cause, it is assumed that the instruments that will be in NOVO's quality lab are not the fastest on the market, since the instruments that are planned to be in the lab are the same that were bought for Northvolt's quality lab in Skellefteå and there has been innovations with the technology since it was built. This means that it is not the nature of the test that is too time-consuming and causing the bottlenecks. For the second cause, operators can make mistakes while measuring the tests, but the cause of systematic errors can be disregarded because NOVO will ensure that each test has the correct SOP, which is in line with the mitigations from the FMEA. This means that the operators can look up the correct way to perform the test if they are unsure, to avoid making mistakes.

In conclusion, the main causes that are applicable for CMM and VMZ are the second cause for Material, i.e. that the testing frequency is too high, and both of the causes for Machine/Equipment, i.e. that the instruments are too slow and that there are too few instruments in the lab. For Karl Fischer titration, it is only the two causes for Machine/Equipment that apply.

6. Suggestions of solutions

There are three types of general solutions that can be implemented to minimize bottlenecks - increasing the capacity for bottlenecks, moving the workflow to a different area and replacing old technology (Jonsson & Mattsson, 2020). In NOVO's factory, this can be done by buying more instruments, changing the tests from off line to in line and investing in faster instruments.

The order in which these solutions should be prioritized for the factory is:

1. Change test to in line
2. Invest in new technology
3. Buy more instruments

Changing the tests to in line is given the highest priority because the tests require no human interaction. This decreases the risks of personnel related failures, such as performing the test incorrectly or reading the results wrong. It also decreases the personnel costs, since it doesn't need anyone overlooking the tests. In line tests are also faster, since they follow the production speed, and every product has to pass through the tests, which means that every product is tested and any eventual deviations can be found faster. This ensures the quality of all the products.

To invest in new technology is next in the prioritized list because it is still faster than the original equipment, but not as fast as the in line technology. It also doesn't test all of the products as the option above, but it can perform more tests in the same amount of time compared to the original equipment. This increased efficiency frees up personnel to conduct other tests or makes it possible to increase testing for that particular instrument.

Buying more instruments of the original equipment is given the lowest priority because this option leads to significant costs, both in the short term and in the long term. The purchasing and installation costs for additional equipment and the cost for building extra lab space are high one-time costs. The extra space also has to be maintained and additional personnel is needed to run the equipment, which brings higher recurring costs relating to, for example, power, cleaning, maintenance and staffing.

6.1 Solutions for CMM

CMM is an equipment used for collecting dimensional data, crucial for inspection and process control in manufacturing. This equipment has been used for over three decades due to its ability to accurately measure objects of various sizes and shapes (Lin, Damodharan, & Shakarji, 2001). It provides detailed relationships between different features of a workpiece.

To obtain accurate data, the material being tested must remain stationary. CMM cannot measure objects while they are moving and can therefore not be used for inline measurement processes (NOVO Energy, 2024a). There is also no other technology that can perform the

dimension tests faster. This means that the solution for this bottleneck has to be the one that is in last place on the prioritization list - buying more instruments.

Currently, the lab operates with only two instruments, which proves insufficient for conducting all the necessary tests during steady-state production. To address this issue, the following three solutions are proposed:

1. **Invest in more instruments**
   For the first solution, it is essential to calculate the required number of machines to meet the testing demands. Currently, the lead time per shift is 5 496 minutes, while each instrument only can operate for 480 minutes per shift. This means that the total number of instruments needed to perform all of the tests per shift is equivalent to 12 instruments. This results in an increase of 10 instruments in comparison to the current plan.

   However, implementing such a solution is not feasible for several reasons. Firstly, maintaining 12 machines would be prohibitively expensive. The initial capital outlay, along with ongoing maintenance costs, would place a significant financial burden on the organization. Additionally, there is the practical issue of space constraints in the lab. Accommodating 12 instruments would require substantial floor space, which is currently unavailable. This spatial limitation further complicates the implementation of this solution. Another problem is the increase in personnel that is needed to operate the instruments. Since 10 extra instruments need to be bought, 10 extra operators have to be hired and trained, which leads to much higher personnel costs.

2. **Reduce the sampling frequency**
   The second approach is to optimize the use of the two existing CMMs by reducing the testing frequency significantly. This strategy aims to manage the testing workload without the need for additional machines. However, reducing the number of tests will lead to an increased scrap rate, since defects are not detected early if the sampling rate is not high enough. This could result in higher operational expenses due to the cost of scrapped materials and rework, and potentially compromising product quality. On the other hand, by not investing in new equipment, the organization avoids significant capital outlay. While maximizing the capacity of the two existing CMMs by reducing testing frequency could offer a feasible solution in terms of operational and capital expenses, it presents potential risks to product quality.

3. **Hybrid solution**
   A third potential solution involves acquiring 3 additional instruments, while also reducing the testing frequency. This dual approach aims to strike a balance between increasing testing capacity and optimizing resource utilization. By adding 3 more CMM units, the lab can significantly increase its testing capacity. While it won't fully meet the theoretical requirement of 12 machines, it will alleviate the immediate bottleneck and improve throughput. This option also leads to increased personnel

costs, since 3 more operators are needed. With more machines, the lab can afford to reduce the testing frequency to meet the increased testing capacity, while still ensuring a robust quality control process. But in order to do this, the test frequency needs to be carefully managed to avoid compromising quality.

By doing a cost-benefit analysis on the three solutions, the solution that maximises efficiency and capacity, while still being viable, can be determined. First, all of the costs that are associated with the solutions need to be taken into account (Nas, 2016). These are the costs for new machines, new personnel and scrap.

According to NOVO, their initial investment cost for one CMM is 1 616 000 SEK. This includes the installation of the equipment in the quality lab and training for the operators. For the first solution, there will in total be 12 machines, which equals 19 392 000 SEK. There will be 2 machines for the second solution, i.e. 3 232 000 SEK. For the third solution, the number of machines equals 5, which makes the total machine cost 8 080 000 SEK.

The cost for one operator is 50 860 SEK, which is based on the average salary for a laboratory technician being 38 700 SEK (SCB, n.d) and the employer contribution being 31.42% (Skatteverket, n.d.). For every additional CMM, there needs to be an additional operator. This means that the cost for technicians are 610 320 SEK, 101 720 SEK and 254 300 SEK per month for the solutions respectively. This adds up to 7 323 840 SEK, 1 220 640 SEK and 3 051 600 SEK per year.

When it comes to scrap, the cost is counted per battery. NOVO's factory produces batteries with a total capacity of 50 GWh/year and the capacity of one prismatic battery is estimated to be 600-800 Wh. This means that there are 62.5 - 83.3 million batteries produced per year. According to NOVO, the estimated cost per battery that is scrapped is 1 200 SEK and their normal scrap rate is 2%. This gives the total scrap cost of 1.5 bn SEK - 2 bn SEK. When the amount of quality tests are reduced by 60%, for Solution 3, the scrap rate increases to 7% (Bagchi, 2001). This makes the total scrap cost 5.25 bn SEK - 7 bn SEK. When the amount of tests are reduced to fit only 2 instruments, which is a reduction by 83%, the scrap rate increases to 9% and the costs increase to 6.75 bn SEK - 9 bn SEK.

An additional buffer of 15% is added to all of the costs, to account for future increases. All of the costs are presented in *Table 13*, to give a better overview of them for each solution:

	Solution 1 - More instruments	Solution 2 - Less testing	Solution 3 - Hybrid
Number of machines	12	2	5
Total machine cost	22.3 m SEK	3.7 m SEK	9.3 m SEK
Reduced tests	0%	83%	60%
Scrap (SEK/year)	1.7 - 2.3 bn SEK	7.8 - 10.3 bn SEK	6 - 8.1 bn SEK
Number of technicians	12	2	5
Total cost for technicians (SEK/year)	8.4 m SEK	1.4 m SEK	3.5 m SEK

Table 13: Costs for each of the solutions.

Evaluating the three proposed solutions for optimizing the CMM testing process, clear differences in their practicality and costs can be seen. Solution 1 suggests using 12 machines. This solution would ensure high-quality testing since no reduction in tests is needed, but it's impractical due to the high costs and space required. Solution 2 keeps the 2 current machines and reduces the number of tests by 83%. While this is the cheapest option in terms of machine cost, it risks lowering product quality and therefore increasing the scrap cost significantly. Solution 3 proposes increasing the number of machines to 5 and reducing tests by 60%. This approach balances costs and quality, making it a more feasible solution. The estimated scrap cost is substantially higher than Solution 1, but lower than what Solution 2 might imply. In terms of technician costs, Solution 1 is the most expensive at 8.4 m SEK per year, Solution 2 is the cheapest at 1.4 m SEK per year, and Solution 3 is in the middle at 3.5 m SEK per year.

Solution 3 emerges as the most balanced approach. It involves moderate capital expenditure and operational costs, a manageable reduction in test frequency and scalable capacity to meet future demands. This solution ensures a good balance between maintaining quality control and optimizing costs, making it the most viable option for improving CMM operations. It mitigates the risks associated with significantly reduced testing frequency for Solution 2 and, although significantly more expensive, provides a substantial increase in capacity without the prohibitive costs and space requirements of Solution 1. If Solution 1 was chosen, then the plan for the factory had to be changed. This would bring extensive costs, if it even would be possible, which also have to be taken into account.

To improve the efficiency of the CMM testing process, several practical solutions are also proposed. Firstly, responsibility for testing cans could be transferred to the internal contractors that produce the cans in the same building as the battery production. This would involve conducting thorough audits of their processes on-site, to ensure quality and compliance standards are met, while also relieving the workload on internal resources. In terms of reducing test frequency, decisions should be based on thorough analysis. For example, current testing procedures are time-consuming and unsustainable in the long run.

During the initial ramp-up phase, it is recommended to maintain the existing testing frequency, and as the production stabilizes, a gradual reduction in testing frequency can be implemented without compromising quality. To manage increased demand during the ramp-up phase, options include outsourcing additional testing or temporarily increasing internal testing capacity.

6.2 Solutions for Karl Fischer titration

The Karl Fischer moisture measurement method is a used technique for determining the moisture content in various products (Bogart, 2019). The method is highly regarded for its accuracy and precision in measuring trace amounts. Originally, this process was completely manual, but the process has now been automated to improve efficiency and accuracy. Despite advancements in automation, the process remains somewhat time-consuming and requires significant, sophisticated equipment (Bogart, 2019). Because of this, it is not recommended to move the Karl Fischer titration in line, and instead it is recommended to invest in new technology.

An alternative to Karl Fischer titration is Near-Infrared Spectroscopy (NIR). This process is used for analyzing the composition of materials by measuring how they interact with near-infrared light (Bogart, 2019). NIR moisture meters specifically use this technique to assess moisture levels in various substances. By observing how much light is absorbed or reflected by a sample, NIR instruments can accurately determine its moisture content.

Unlike Karl Fischer titration, which consumes samples during testing, NIR moisture meters are non-destructive and non-contact, preserving the integrity of the initial sample (Bogart, 2019). This feature is especially valuable when sample availability is limited or when further analysis is required. NIR moisture meters are also highly versatile, capable of analyzing both solids and liquids in various conditions. They come in handheld, in-line and desktop versions, catering to different needs and environments, unlike the more specialized Karl Fischer titration system (Bogart, 2019).

Hence, NIR is increasingly favored over Karl Fischer titration for moisture measurement due to its non-destructive nature, versatility and adaptability. It is therefore recommended that the Karl Fischer titration is exchanged for NIR. However, maintaining a few Karl Fischer titration setups in the lab is essential for specialized analyses requiring their unmatched precision, as well as validating the new technology. This strategic balance ensures comprehensive analytical capabilities in the laboratory.

6.3 Solutions for VMZ

Video measuring system (VMZ) is an optical technology used to measure the geometric parameters, shape and structure of objects (Levin et al., 2023). These systems are integral to image recognition systems, influencing decision-making processes based on their precise measurements.

VMZ technology benefits from advancements in optical element production, including the creation of aspherical, diffractive and dynamic optical elements. Additionally, the development of advanced image processing and recognition algorithms enables real-time, multidimensional measurement and automated recognition (Levin et al., 2023). VMZ operates on principles of image formation and subsequent processing, serving as the foundation for various measuring instruments across diverse fields of technology.

VMZ offers high spatial resolution and the absence of geometric distortions, ensuring precise measurements. This accuracy is essential for inline quality control and inspection processes where real-time measurements are crucial (Levin et al., 2023). In order to address the needs of VMZ in this project, solutions involving both inline and laboratory-based approaches are proposed. Implementing video technology directly within the production line is critical for VMZ's operational enhancement. This involves seamlessly integrating cameras into various stages of the manufacturing process to monitor and capture real-time footage. By doing so, VMZ gains invaluable insights into its operations, facilitating the swift detection of deviations from the quality standards. The continuous monitoring provided by video integration enables proactive interventions, ensuring timely corrective actions to maintain productivity and uphold quality assurance protocols.

To ensure the accuracy and reliability of the inline video technology, it is wise to maintain a controlled environment for validation purposes. This entails retaining 1-2 cameras within the laboratory setting to serve as benchmarks for comparison. These cameras enable the comparison of data captured in line with results obtained under controlled conditions, ensuring consistency and precision in the monitoring process. By validating the inline video technology through laboratory testing, VMZ can instill confidence in the reliability of its monitoring systems, enhancing overall process integrity.

By combining the benefits of inline video integration with the laboratory validation, VMZ can effectively strengthen its process monitoring capabilities and uphold precise quality control practices. This integrated approach ensures not only operational efficiency but also the continual optimization of quality assurance measures, contributing to sustained excellence in manufacturing operations.

7. Discussion

A discussion regarding the method and the results are provided in this chapter.

7.1 Method discussion

Below, the study's strategy, design, approach and quality criteria are discussed.

7.1.1 Strategy, design and approach

The strategy, design and approach that were chosen for the project were a mixture between quantitative and qualitative research, with a case study design and an abductive approach, that was based on systematic combining. The combination of the two research types fit the project well, with more open research questions being answered by data analysis and root cause analysis. The 11 steps of quantitative research provided a good framework for how the research was conducted, but with research questions instead of a hypothesis. This guided the research in an effective way, even though the use of mixed strategies didn't fit the steps fully.

The case study design was also a good fit for this project, since it focused on improving the material flow for NOVO's quality lab, i.e. for only one part in the factory. Although, some comparisons were made between Northvolt's factories in Skellefteå and Västerås, to gain insights into how the situation will be in NOVO's factory, since it is not built yet. Because of this, the study didn't focus fully on only the factory in Gothenburg, but also drawing conclusions on what the material flows look like in the other factories and applying them to this factory. This means that the caste study design was supplemented by some aspects from the comparative design.

The abductive approach by systematic combining was a good approach for this project, where several parts of the report had to be written at the same time. Since NOVO still is in the design phase of the factory during spring of 2024, not everything was decided in the beginning of the project. For example, some of the sampling amounts and frequencies were changed during the project. This meant that the data and the analysis had to be updated regularly with new numbers, as soon as new specifications were made. The theory also had to be supplemented, for example with FMEA and CBA. This was so that the impact of the risks in the lab and their mitigations could be integrated with the root cause analysis, and so that the solutions for CMM could be compared in an effective way to provide a suggestion for which of the three solutions that was the most viable.

7.1.2 Trustworthiness

Trustworthiness was ensured through various several key practices. Credibility was strengthened by cross-referencing data from different sources. This was done in both quantitative and qualitative research, ensuring that the findings were solid and believable. To ensure the applicability of the findings across different situations, detailed descriptions of the research methodology were provided. This allowed others to assess whether the results might be relevant to their own settings. Since the analysis and results were tailored for NOVO's factory, the results might not be easily applicable to other situations, but a general overview

of the report could be used to assess if the strategy is appropriate for other situations. Dependability was ensured through thorough record-keeping and review by experts within quality control. This process helped to maintain consistency and reliability in the results, regardless of the observer or time frame. This aspect was essential for both quantitative and qualitative research. Lastly, confirmability was highlighted in different ways. In qualitative analysis, focus was placed on reflecting on biases and being clear about how conclusions were reached. In quantitative research, statistical methods and detailed explanations of study conduct were relied upon. These practices ensured that results were solid and trustworthy.

7.2 Results discussion

Below, the results from the analysis and the solutions are discussed.

7.2.1 Analysis

When it comes to the analysis of the data, it is important to note that the results might not be fully accurate compared to what the situation will be in the factory when it is running at a steady state. This is because not all decisions had been made when the study was conducted, meaning that the sample amounts and frequency could change, and tests could be added or removed from each of the manufacturing processes. Additionally, some of the data were also estimations based on the current plan for the factory, such as delivery frequencies and production speed, which are fundamental factors that still could change. This also means that, since the numbers might not be fully accurate for the actual factory, other instruments could be bottlenecks, and the identified bottlenecks could be bigger or smaller than calculated. Because of this, there needs to be a continuous evaluation and analysis of the data, to ensure that there will not emerge any more bottlenecks that NOVO is unaware of.

The analysis with the Five Whys was an easy and quick method to find root causes for potential delays in the results from the instruments. However, since it only follows one line of causation, several perspectives were missed with this method. Because of this, the Fishbone Diagram was a good complement. Although, the root causes that were found with the Five Whys were almost the same as the root causes that were found with the Fishbone Diagram, which means that it still was a good method for the purpose of finding the root causes that could be applied to the bottlenecks and that had big impacts on them. For the analysis with the Fishbone Diagram, there could be more causes for why the results can be delayed than the causes that are stated in the diagram, but they are not likely to have as big impacts as the ones that were found. Some of the causes that were eliminated when narrowing down which ones that were applicable for the CMM, Karl Fischer titration and VMZ can still have big impacts on the time for the results, such as the causes relating to People and Method. To make sure that this is not the case, they have to be carefully mitigated with the reasons stated in the reflection, which were based on the FMEA. Otherwise, the solutions for the bottlenecks will not be as effective. Just like the Five Whys method, the Fishbone Diagram was a good tool to find the root causes for the bottlenecks. Although, in contrast to the Five Whys, the Fishbone Diagram resulted in more root causes from different areas, which gave a wider perspective on the reasons for the delayed results.

7.2.2 Solutions

The solution for CMM could be changed according to how much the sampling could be reduced to ensure that the quality is still maintained, although it is still recommended to use a mixture of reduced testing and investing in new machines. If the sampling cannot be reduced enough for 3 additional instruments, 4 instruments could be invested in. Or if the testing could be reduced more, only 2 could be bought. This depends on further research regarding the sample amounts and frequencies. Additionally, when the testing amount for the cans, lids, seal pins and seal balls are reduced, the bottlenecks for Roughness tester and Profilometer could also be solved. This is because these three instruments test the same materials at the same amount and frequency. When the evaluation for how much the testing should be reduced for CMM, the other two instruments could also be assessed. This will determine if their lead times are reduced enough to not be bottlenecks anymore, or if measures need to be implemented.

The proposed shift from Karl Fischer titration to NIR for moisture measurement is a strategic and beneficial move. NIR offers significant advantages, including non-destructive testing, versatility and adaptability for various conditions. These features make NIR a more practical and efficient choice for moisture measurement needs. Although the initial investment in NIR may be substantial, it is expected to pay off in the long run. NIR is testing faster than Karl Fischer titration, which reduces the time required for each test and, consequently, the labor costs associated with them. This efficiency gain translates to significant savings over time. Maintaining a few Karl Fischer titration setups in the lab for specialized analyses ensures that the unmatched precision of Karl Fischer titration is still available when necessary. This dual approach provides a comprehensive solution, balancing efficiency and precision. Overall, the transition to NIR is well-justified and likely to be cost-effective, though starting with a pilot program could help mitigate initial costs and validate the expected benefits.

The implementation of VMZ as described has clear advantages, particularly in enhancing process monitoring and maintaining stringent quality control through advanced technology. This approach uses high spatial resolution and precise measurements, crucial for real-time quality assurance. However, while the benefits are evident, the initial cost of installation could be a drawback. Although the system reduces the need for manual labor, which offsets costs in the long run, the upfront investment may be substantial. An alternative approach could involve starting with a smaller-scale pilot program to assess the effectiveness and gradually scaling up based on results. Additionally, integrating automated self-calibration systems could further reduce maintenance costs and enhance system reliability without the need for continuous laboratory validation. Overall, the proposed VMZ implementation is robust and beneficial, but considering cost-effective strategies for gradual implementation and maintenance could improve feasibility and reduce initial financial burden.

Another thing to note is that the bottleneck for the Puncture tester has not been addressed at all, which means that it is important to focus on its root causes and possible solutions when conducting further research.

8. Conclusion and recommendations

In this chapter, a conclusion to the study will be presented and the research questions will be answered. Additionally, recommendations for further studies will be provided.

8.1 Conclusion

The purpose of the study was to identify bottlenecks in the material flow of samples within NOVO Energy's quality lab and propose solutions for how they could be minimized. To do this, three research questions were formulated. The questions guided the study in a sequential manner, ensuring that each one could be thoroughly addressed. Answers to the research questions are provided below.

What bottlenecks exist in the material flow within the quality lab, as per the current plan for NOVO's first gigafactory?

The plan for the factory was analyzed, which included the materials that will be tested, which tests that will be performed and how many of each equipment there will be in the quality lab. Data on sample amounts and equipment lead times from Northvolt's production in Skellefteå supplemented the information from NOVO.

This resulted in the following bottlenecks:

1. CMM
2. Karl Fischer titration
3. VMZ
4. Roughness tester
5. Puncture tester
6. Profilometer

The CMM checks the dimensions of the cans, lids, seal balls and seal pins and is the largest bottleneck with 473% more lead time than possible run time. The Karl Fischer titration tests several types of materials for moisture, and is the second largest with 216% more lead time. The VMZ measures the jumbo rolls and pancakes alignment and dimensions, and is the third bottleneck with 88%. The roughness tester tests the surface roughness on the cans and lids, and it has 85% more lead time than possible run time. The puncture tester checks the puncture resistance of the separators and has 31% more. The profilometer measures the surface smoothness of the cans and lids, and is the smallest bottleneck with 23%. As per the project scope limitations, only the three largest bottlenecks were studied further.

What factors contribute to the bottlenecks that are found?

To find the root causes for the bottlenecks, the two methods Five Whys and Fishbone Diagram were used. The Five Whys was used as a quicker method, to get a general idea for what the root causes could be.

The Five Whys method gave the following root causes for the three largest bottlenecks:

1. CMM - 4 samples per batch of material will be tested and the instruments are slow.

2. Karl Fischer titration - Some of the materials, such as separators and insulators, will be tested frequently and the instruments are slow.
3. VMZ - The pancakes will be tested frequently and the instruments are slow.

The Fishbone Diagram was used as another method to get more detailed information about the factors contributing to the delays in results from the testing. The same diagram was used for all three bottlenecks since the main problem was the same, but there was a small difference in which causes were not applicable for each of the bottlenecks, resulting in different root causes.

The Fishbone Diagram gave the following root causes for the three largest bottlenecks:

1. CMM - The sampling frequency is high, the instruments are not fast enough and the amount of instruments in the lab is low.
2. Karl Fischer titration - The instruments are not fast enough and the amount of instruments in the lab is low.
3. VMZ - The sampling frequency is high, the instruments are not fast enough and the amount of instruments in the lab is low.

What measures can be implemented to minimize the bottlenecks?

For CMM, the amount of testing and instruments need to be evaluated. The number of instruments are proposed to increase by 3 and the testing should be reduced, to strike a balance between testing capacity and optimizing resource utilization. With more machines, the lab can afford to reduce the testing frequency to meet the increased testing capacity, while still ensuring a robust quality control process. But in order to do this, the test frequency needs to be carefully managed to avoid compromising quality. Another important measure is delegating testing responsibilities to internal contractors, which can help alleviate the workload on internal resources. Comprehensive audits of their processes should be conducted to ensure adherence to quality and compliance standards. During the initial ramp-up phase of the factory, it is advisable to maintain the existing testing frequency. Options such as outsourcing additional testing or temporarily increasing internal testing capacity should be explored. As the production process stabilizes, the frequency can gradually be reduced without compromising quality.

One effective strategy to minimize the bottleneck in the Karl Fischer titration process is to incorporate Near-Infrared Spectroscopy (NIR) for moisture analysis in the lab. Alongside this, Karl Fischer titration should be kept for validation. Once validated, the NIR technology can be integrated in line, reducing testing time and enhancing overall efficiency. This combination of thorough laboratory evaluation and strategic implementation of advanced technology will help alleviate the bottleneck, ensuring a smoother and more efficient moisture analysis process.

A measure that can be implemented to minimize bottlenecks in the VMZ is integrating in line video technology for real-time monitoring of the production processes. This involves embedding cameras at various stages of manufacturing to promptly detect any anomalies,

allowing for immediate corrective actions. Additionally, conducting laboratory validation with 1-2 cameras is essential to ensure the accuracy of the technology. Synergizing the benefits of inline video integration with laboratory validation enhances overall process monitoring. This approach not only upholds strict quality control practices, but also facilitates continual optimization of manufacturing operations.

8.2 Recommendations for further studies

A recommended continuation of the study is to further investigate the suggested solutions. This includes how much the number of samples collected for the CMM should be reduced, so that the lead time becomes smaller than the possible run time, while still testing enough samples so that the quality and safety of the products are ensured. For the Karl Fischer titration and NIR, the suggestion is to calculate how many NIR are needed and how many Karl Fischer titrators that should be kept to validate the new instruments. The number of VMZ that are needed in line and how many that should be kept off line should also be investigated.

Another recommendation is to investigate mitigations for the remaining three bottlenecks - Roughness tester, Puncture tester and Profilometer. For them, the root causes also need to be found and solutions proposed, so that they don’t cause delays in production. This is recommended to do with the same strategies used in this study.

The study could also be updated with new information about the instruments, amount of samples and if the tests are done at line, in line or off line as the development of the plan for NOVO’s factory progresses, since this study was conducted on information that was not yet decided at the time.

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