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Flexible layout design for the battery cell manufacturing industry to optimize for the unknown future

A comparative analysis of how different project models increases flexibility in layout design

Master's thesis in Production Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The worlds transition towards a more sustainable society is a driver for the demand in electrical batteries for vehicles. To be able to meet the demand new battery cell factories needs to be build, and start their production as fast as possible.

This master thesis has therefore investigated how the factory layout design can increase its flexibility by using different project models as a basis. The results shows that the flexibility can be increased, but the investment cost is in most of the cases higher than if flexibility in the layout is disregarded. The highest level of flexibility would be reached with help of the agile methodology where the generated layout is based on smaller modules. The set-based method could lead to an increase in flexibility depending on the scenario, but has several other advantages. The waterfall methodology would on the other hand not increase the flexibility of the layouts if not re-configurable manufacturing systems (RMS) are included.

Therefore the battery cell manufacturers needs to make a choice between saving investment cost and instead face the risk of re-layout costs or if they want to create a flexible factory that can change its production together with the changing customer demands.

Keywords: Battery Cell, Factory Layout, Project Models, Flexibility, Production Processes, Li-Ion battery.

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This is the final project of our Civil Engineer education after five long years at Chalmers University of Technology and therefore we would also like to thank everyone that has been a part of our journey to this day.

Pontus Axelsson & Maja Jansson, Gothenburg, 2024-06-05

Declaration of AI technologies in the thesis work and writing process

This thesis have been using different AI technologies in order to improve the writing process. However, all the information and provided text have been written and formulated in advance by the thesis workers.

Chat GPT - To improve and formulate different sentences and sections to provide an clear and understandable text for the reader.

Grammarly - To correct spelling errors and bad structure in the text.

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1

Introduction

This chapter aims to provide a brief background for NOVO Energys problem statement and why the master thesis is relevant for both the company and the academic world. The chapter also includes the aim, limitations as well as the research questions for the project which provide insight into the intended direction and boundaries of the thesis.

1.1 Background

The demand for electrical batteries is increasing due to the increase in electrical vehicles (EV's) and more battery cell factories are needed to meet the demand (Duffner, Mauler, Wentker, Leker, & Winter, 2021). In 2021 the production of battery cells was around 1100 GWh/year globally (Bhutada, 2021). However, the battery cell production within Europe was only 30 GWh/year (Breiter, Horetsky, Linder, & Rettig, 2022; ees Europe, 2021). Therefore the building of new factories in Europe needs to speed up and increase from the current capacity. Currently, the largest production of battery cells is occurring in Asia, but the European Union launched the European Battery Alliance in 2017 to build up the battery technology and the production capacity within the EU to reach the climate goals (European Battery Alliance, n.d; Bhutada, 2021).

This master thesis is written in cooperation with NOVO Energy AB - a joint venture between Northvolt and Volvo Cars which is a Swedish company that is currently building a gigafactory in Gothenburg with a potential of producing up to 50 GWh per year when the factory is completed (NOVO Energy AB, n.d). To be able to reach the demand, new battery cell factories have to be built and according to NOVO Energy when creating a battery cell factory, many parameters need to be considered and the four most important are:

1. The product
2. The capacity
3. The process/technology
4. The enablers

Given the urgency to meet the escalating demand for battery cells in Europe, traditional project models present challenges. Due to lengthy lead times inherent in these models, there is a risk of rendering initial customer needs and product designs obsolete by the time production starts. Therefore, exploring alternative project models becomes imperative to ensure adaptability to evolving customer needs, product designs, and process requirements throughout the project lifecycle.

In traditional project models, the customer needs are first clearly defined before the product design phase can begin. Then when the product is defined the factory layout can be designed to be able to produce the product that meets the customer's demand (Thesing, Feldmann, & Burchardt, 2021).

The problem with this traditional project model occurs when companies have to start building the factory X years before the product design and production phase due to long lead times. This results in the customer needs and product design becoming obsolete concerning the factory layout once the production phase is initiated. Therefore, NOVO Energy requires new ways to create a more iterative process that is more prone to handle changes and disturbances in customer needs and product design as well as process design to have a factory layout design that will meet the requirements that is expected by the previous steps.

1.1.1 Problem formulation

The core-problem for this thesis is therefore to investigate if the use of project-models could enhance the layout generation when the uncertainty in capacity, process, and product design is high. And therefore provide a structural way in order to increase the flexibility and robustness of the factory layout design. It should also guide the company in the decision making process when determining the factory layout.

1.2 Aim

This Master Thesis aims to find a solution to optimize the layout of battery cell factories for the so-called unknown future where the customer need and product design isn't clearly defined in advance before the building of the production to help improve future factories. The project aims to help pace up the industry and the time it takes to build each factory to enhance the transition to a more sustainable society.

1.3 Research question

To achieve the project's aims, the research questions that are being investigated is:

1. How can the use of project-models increase the flexibility of battery cell factory layout design in order to handle fluctuations in customer needs, product, and process design?
2. What is the value for the company and industry to increase the flexibility of the factory layout design?

By answering these research questions the project will help NOVO Energy to optimize future gigafactories and help pace up the battery cell industry.

1.4 Delimitation's

The project is scoped to focus on prismatic lithium-ion (Li-Ion) batteries and investigate how the production can become more flexible in regards to changes of the customer need, product and process designs. The focus was therefore on the process steps regarding Li-Ion batteries and focused on how the factory layout could be designed to increase flexibility to cope with changes in the product and process design. In regards to the timeframe the production capacity was not be the primary focus and therefore was disregarded.

Since the master thesis was limited by time the project's scope was limited to the main process steps of battery cell production and scoped down to one of the major steps. The project step that was investigated was Cell Finishing due to its nonlinearity and was therefore seen as the most suitable for flexible layouts. Cell Assembly and Electrode Manufacturing, however, are more linear and were therefore excluded due to the limited time.

Another limitation of the thesis is that it focuses on the manufacturing part of the processes, not the research and development (R&D) which involves the chemical design of the product. The main focus was also on European and North American battery cell production due to easier access to research papers and other information. As battery development & manufacturing is an emerging and competitive market, the relevant research literature on the subject is in short supply with many domestic resources, especially from Asia.

In this thesis, the term "optimize" is used with a focus on refining processes for generating flexible layouts suitable for various battery cell manufacturing, rather than solely pursuing an ultimate, singularly mathematical optimal layout. Therefore, the reader should acknowledge this throughout the thesis.

2

Theoretical Framework

The world is currently in a transition to become more sustainable and one of the movements is the shift from combustion engines to electrical motors. As the demand for batteries for EV are increasing, the production of battery cells needs to increase. Different manufacturers around the world focus on speeding up the production pace and invest in new factories. In traditional industries the project follows a logical order where the project is defined first, then the product, then the production system and lastly the layout of the production system. The battery cell industry on the other hand is expanding quickly and the way of working can instead look like that the project is firstly defined, then the production system and then the layout before the product is defined.

In this chapter the theoretical framework is presented and regards production systems, Li-ion batteries, project models and factory layouts.

2.1 Production Systems

The traditional definition of production is "the transformation of raw materials into products by a series of energy applications, each of which affects well defined changes in the physical or chemical characteristics of the materials" (Danø, 1966). Today manufacturing and production has a broader definition compared to the original definition. Today, "manufacturing" encompasses a series of interrelated activitiesfrom design and materials selection to production, quality assurance, and marketinghighlighting the integration of design within the manufacturing process (Hitomi, 2017).

A production system comprises a number of elements between which there are reciprocal relations (Bellgran & Säfsten, 2010). This could for instance be buildings, humans, equipment or software. However, a production system could also involve dimensions of the decision-making process and therefore include, capital management, business management and production management to the system (Bellgran & Säfsten, 2010) Each component is an important system resource, but are also potential sources for variation and disturbances which can be difficult to predict (Bellgran & Säfsten, 2010).

Traditionally production systems have been created to suit a specific product or product family under a long time period (Rösiö et al., 2020). As the competitive environment and market is changing this production system isn't longer suitable as new products need to be introduced into the system which requires changes within it (Rösiö et al., 2020). Therefore the new production systems need to become more flexible and reconfigurable (Rösiö et al., 2020).

2.1.1 Decision Areas

In order to create a functional production system there are areas where companies need to make decisions, which are called decision areas and can be seen in Table 1 (Bellgran & Säfsten, 2010). These areas comprise a number of issues and questions which a company has to deal with and make decisions on (Bellgran & Säfsten, 2010).This thesis will focus on the first decision area (production processes) but as stated before there are interdependencies between several areas which will affect the production processes like capacity, facility and product design.

Table 1: Decision areas and related examples

Decision areas	**Examples of decision questions**
Production process	Process type, layout, technical level
Capacity	Amount, acquisition point
Facility	Localisation, focus
Vertical integration	Direction degree, relation
Quality	Definition, role, responsibility, control

The production process involves converting resources into products, and decisions related to the production process includes considerations of process type, layout, and technological level. Process type relate to the organization of various processes and activities, with direct connections to production volume and the number of variants (Bellgran & Säfsten, 2010). A fundamental principle for categorizing production is frequency, which is how a certain product family is run in production. These are categorized in terms of single unit process, intermittent process and continuous process where intermittent process implies a production is run with a certain interval in production (Bellgran & Säfsten, 2010). Another dimension of intermittent process can also be based on decoupled or coupled flow of products. The classical product-process matrix, depicted in Figure 1, identifies the optimal process type for managing product volumes. The diagonal line in Figure 1 represents the standard position, and any deviation from this line heightens the risk of elevated costs to offset flexibility or suboptimal utilization of process flexibility (Bellgran & Säfsten, 2010).

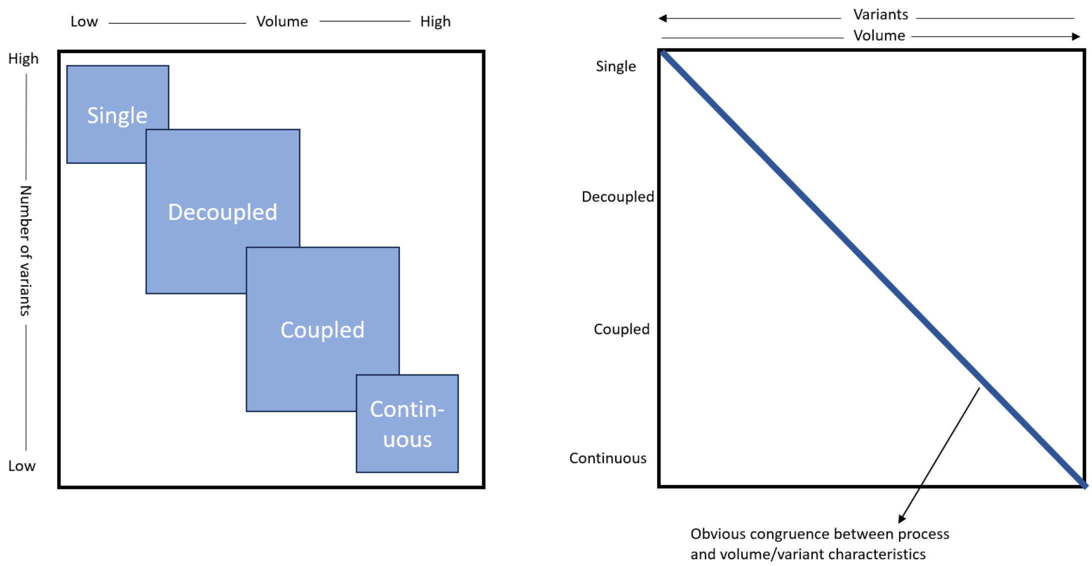

Figure 1: Product-process matrix between volume and production variants/process based on Bellgran & Säfsten (2010).

The next decision area concerning the production process is about the layout design, which handles the physical arrangement of different equipment in the factory. Aspects influencing the different layout options are production volume, number of variants and relevant competitive factors (flexibility, cost, etc.). A division can be based on several different layout options and are discussed more in section 2.5.

2.1.2 Production Development

When developing and introducing new products within a manufacturing context most often new assembly systems need to be developed (Bellgran & Säfsten, 2010). The reason for introducing new products differs between companies and industries and the old production system might not be suitable for the new product (Bellgran & Säfsten, 2010).

Production development can be considered as a natural part of the production realization process where product realization refers to the process from product planning to the completed product (Bellgran & Säfsten, 2010). Product realization concerns development and production of products attractive to customers and therefore comprises all activities necessary to develop solutions satisfying and identified customer needs, and all activities required to realize these solutions in terms of physical products and services (Bellgran & Säfsten, 2010). In this thesis product realization is therefore considered to be a concept where product and production development are integrated processes with dependencies over each other for efficient development. The product realization process also consists of required supporting functions like production engineering, quality, IT, engineering material and process development for instance. The production realization process is illustrated in Figure 2 with the different parameters (Bellgran & Säfsten, 2010).

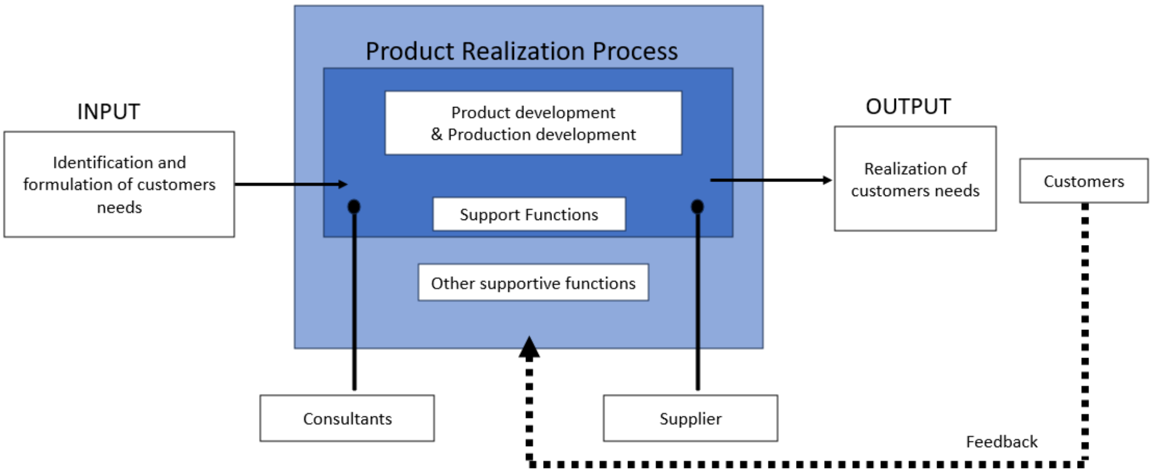

Figure 2: The product realization process based on Bellgran & Säfsten (2010).

The production realization process is part of the innovation process which in turn comprises all the necessary activities to make a new product available for use in the market, from research and design, process and production planning to the use and service phase (Bellgran & Säfsten, 2010). The innovation process is part of the product life-cycle which involves end-of-life treatment of worn and scrapped products. These activities are illustrated in Figure 3, and are necessary to consider before, during and after the product realization process (Bellgran & Säfsten, 2010).

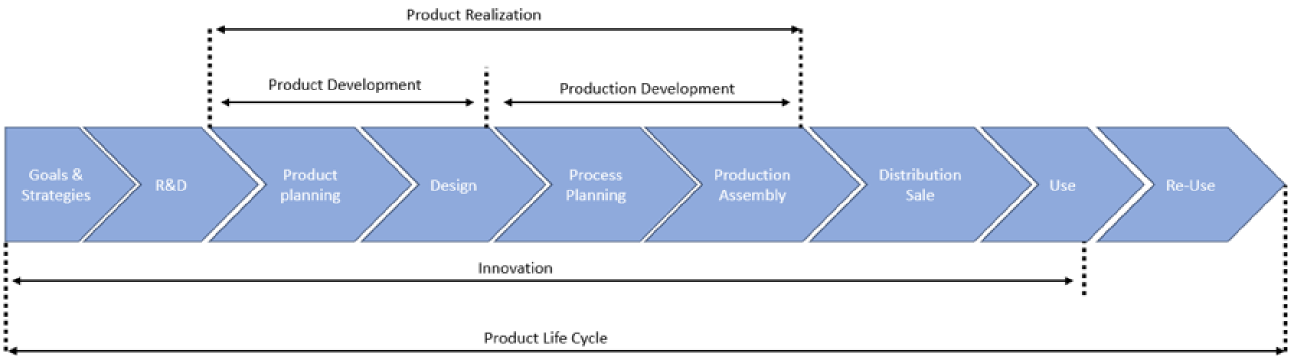

Figure 3: The production realization process, part of the innovation process and the product life-cycle based on Bellgran & Säfsten (2010).

2.1.3 Reconfigurable Manufacturing Systems

Reconfigurable manufacturing systems (RMS) is a class of manufacturing system which are capable of efficiently and quickly adapt to changes in the market, such as changes in demand, product mix or variants (Brunoe, Soerensen, & Nielsen, 2021).

The need for RMS arises from unpredictable market changes, such as increasing frequency of introducing new products, changes in existing products, and shifts in process technology (Koren et al., 1999), driven by escalating economic competition and rapid technological advancements (Koren et al., 1999). RMS encompasses both hardware and software adaptable to changes, optimizing resource utilization as production requirements evolve (Rösiö et al., 2020), designed for upgradability and flexibility to ensure optimal functionality and capacity alignment over time (Rösiö et al., 2020). The overarching objective of RMS is to establish responsive production systems capable of navigating rapid shifts in product and process technologies resulting from fluctuations in customer demand (Koren & Shpitalni, 2010), distinguishing it from flexible production systems (FMS) which address product changes but lack adaptability for structural shifts, thus proving unsuitable for abrupt market fluctuations. FMS also grapples with high throughput and relies on costly equipment compared to RMS and dedicated manufacturing lines (DML) (Koren & Shpitalni, 2010).

RMS are marked by six core reconfigurable characteristics for the system which are mentioned in (Koren & Shpitalni, 2010). These characteristics are customization, where the system is designed by allowing flexibility for a specific product family. It should also boast convertibility enabling easy adaptation of existing systems and machines to meet new production needs. Another characteristic is scalability permitting adjustments to production capacity by adding or removing manufacturing resources or system components. Modularity which divides operational functions into units, which can be manipulated to optimize the production arrangements. Integrability, which ensures rapid and precise module integration through mechanical, informational and control interfaces. And, lastly, diagnosability which enables automatic assessment of system states to detect and address root causes of product defects efficiently.

The first three characteristics are critical for RMS, while the last three allow rapid configuration and do not guarantee modifications in capacity or functionality (Koren & Shpitalni, 2010).

Moreover, RMS are designed according to reconfiguration principles. These principles are intended to improve reconfiguration speed and speed of responsiveness to (i) unpredictable external resources (market changes), (ii) planned product model changes, and, (iii) unexpected intrinsic events system events.

As described in (Koren & Shpitalni, 2010) these principles results in that:

1. A RMS system provides adjustable production resources to respond to unpredictable market changes and intrinsic system events.
   - RMS capacity can be rapidly scalable in small increments.
   - RMS functionality can be rapidly adapted to new products.
   - RMS built in adjustment capabilities facilitate rapid response to unexpected equipment failures.

2. An RMS system is designed around a product family, with just enough customized flexibility to produce all members of that family.

3. The RMS core characteristics should be embedded in the system as a whole, as well as in its components.

2.2 Li-Ion Batteries

The development of Li-Ion batteries started in the 1980s and in 1991 they reached the commercial market (Pistoia, 2013). The major parts in Li-Ion batteries are cathode which is the positive electrode, anode which is the negative electrode, a separator and an electrolyte (Duffner et al., 2021; Pistoia, 2013). For Li-Ion batteries it is important that the battery specifications are properly designed to meet the requirements that are set upon the system as the system utilizes chemical reactions to be able to provide energy to the system the battery is connected to (Pistoia, 2013). Recently the major focus has been on increasing the energy density of the Li-Ion batteries by improving anode and cathode materials for higher voltage and energy density.

2.2.1 Different Recipies

The production of prismatic Li-Ion cells can differ within the chosen recipe which in turn can lead to differences within the production processes. During the development of a new battery cell there are different samples being produced. The A samples, which are the first samples of a battery design, are produced in small sample volumes on a pilot line and undergo simple function and performance tests (Örüm Aydin et al., 2023). The B samples are manufactured on larger test lines and undergo customer tests and verification of the required product properties with the aim of freezing the product design (Örüm Aydin et al., 2023). The C samples are produced on the series production line, and checked in detail to the customers specification (Örüm Aydin et al., 2023). In the C sample phase only small adjustments are made to the product as the process design is freezed at the end of the phase and the process release occurs (Örüm Aydin et al., 2023).

The problem that can occur is that if the factory has to be built before the C-sample is created, changes could be made to the product design and therefore changes in the production processes may occur. This is also possible if new batteries are developed after the factory is built.

2.2.2 Different Products and Future Batteries

There are different kinds of batteries that can be used for EVs. Other than Li-Ion there are Lead-Acid batteries which are the cheapest in regards to the raw material but they also have low energy density and therefore are usually used when the operating distance and weight are low (Manzetti & Mariasiu, 2015). Another battery type is the Nickel-Metal Hydride battery which for example Toyota, Honda and Lexus uses in their hybrid EVs but no one uses them for fully electrical vehicles due to its high material cost (Manzetti & Mariasiu, 2015).

Looking at future batteries for EVs one possibility is the solid state batteries (SSB). In comparison to Li-Ion batteries with liquid electrolyte and a separator SSBs would instead contain a solid electrolyte which is impenetrable to Li-metal dendrites which would therefore allow Li-metal as the anode which would result in increased energy density of the batteries (Ulvestad, 2018).

There are three types of battery cells formats which are commonly used in electric vehicles, these are cylindrical cells, pouch cells and prismatic cells. These different cell types have different types of advantages and drawbacks which need to be considered as well as different manufacturing processes. The battery cell is the smallest unit of the battery packs or the single unit of battery packs used in electric vehicles (Halimah, Rahardian, & Budiman, 2019).

Cylindrical cells' most distinguished advantages is that it needs no additional mechanism to control the pressure change during charging and discharging due to its cylindrical metal casing that helps maintain the cell (Halimah et al., 2019). Another advantage is that it can be conveniently densely packed due to its slender cylindrical shape and fitted in the vehicle space. Some disadvantages include high weight per energy storage (Halimah et al., 2019).

The pouch cell however offers the advantage of low weight per energy storage compared to the cylindrical cell. It is mostly used for lighter products such as electronic devices or drones (Halimah et al., 2019). A big disadvantage with this cell is that the casing is not designed to protect the battery from heavy loading (Halimah et al., 2019).

The prismatic cell offers very high energy density compared to other battery types and provides a compact packing. It is very suitable for heavy-weight electric vehicles, a big disadvantage is that the battery cell is more costly to produce than the cylindrical and pouch cell (Halimah et al., 2019).

2.3 Production of Prismatic Li-Ion Batteries

The production of Li-Ion batteries can be divided into three main steps which contains more processes within each step. The first main step is the Electrode Manufacturing which contains slurry mixing, coating, calendering and slitting. The second step is Cell Assembly which contains stacking, cell assembly and packaging and the last step is Cell Finishing which contains electrolyte filling, soaking, pre-charging, degassing, sealing and ageing. the formation steps as well as the aging process. Different manufacturers divided the processes in different ways depending on their situation. In this thesis the chosen division of processes can be seen in Figure 4. There are other processes that can be included in the battery manufacturing but they have been disregarded due to lack of published information.

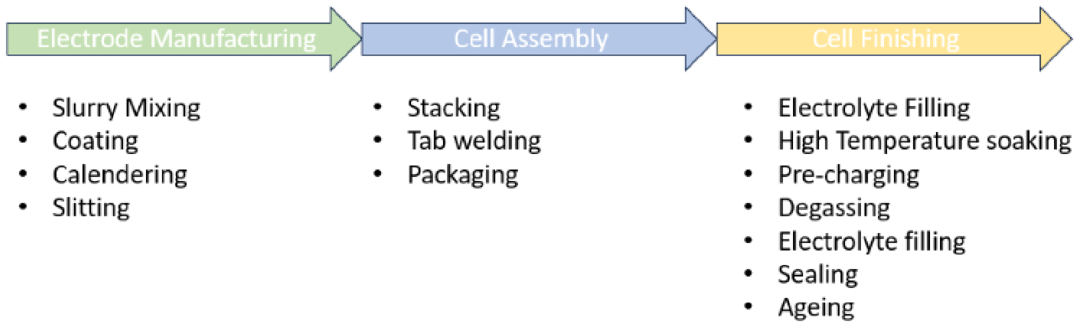

Figure 4: The production processes at NOVO Energy

The complex part of battery manufacturing is that the electrode production belongs to process engineering, cell assembly to assembly technology and Cell finishing to electrical engineering and therefore the three different disciplines need to work together to make the production work (Örüm Aydin et al., 2023).

2.3.1 Environment

Another aspect that makes the battery production complex is the environment that is needed. Some processes must take place in clean and dry rooms where the particles, temperature, and humidity are strictly controlled due to the high moisture sensitivity of different materials (Lechner, Mothwurf, Nohe, & Daub, 2023; Plocher et al., 2023). The need of clean and dry rooms are a contributor to the cost and energy consumption regarding the Li-Ion battery production and as the cost for the rooms depends on their volumes it is important to regard this aspect in the designing phase of the factories (Lechner et al., 2023).

2.3.2 Electrode Manufacturing

The first main process is electrode manufacturing where the electrode for anode and cathode is produced separately, due to the risk of cross-contamination. The processes within electrode manufacturing can be seen in Figure 5.

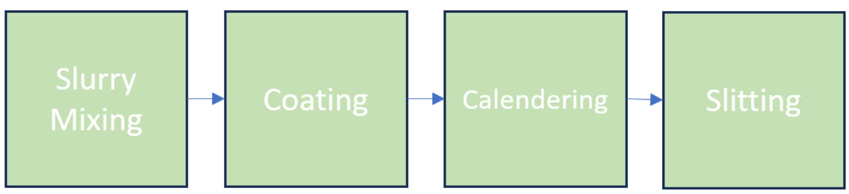

Figure 5: The production processes for electrode manufacturing

2.3.2.1 Slurry Mixing

The first step in manufacturing Li-Ion batteries is the slurry mixing where the active material (most commonly graphite for anode and lithium nickel manganese cobalt oxide for cathode), conductive additives and solvent binders are mixed to create a slurry together with a solvent (Günther et al., 2016; Y. Liu, Zhang, Wang, & Wang, 2021). The active materials as well as the conductive additives are in a solid powder form and bound together with the binder which is either an organic solvent or an aqueous, in a mixer (Duffner et al., 2021; D. Liu et al., 2014). The aim of the process is to achieve the right homogeneity and viscosity of the slurry (Duffner et al., 2021). The slurry mixing process is crucial for the performance and quality of the batteries and therefore the selection of mixing devices as well as procedures are an important step (D. Liu et al., 2014).

2.3.2.2 Coating

In the coating process the slurry is coated on both sides of the current collector which for anode is copper foil and for cathode aluminium foil, and then dried with hot air or thermal radiation throughout the coating machine where the solvent is evaporated and the slurry solidified to the right porosity (Duffner et al., 2021; Günther et al., 2016; Y. Liu et al., 2021). As mentioned in section 2.3.2.1 it is therefore important that the slurry has the right properties so that adhesion occurs with the foil (Duffner et al., 2021).

Depending on the manufacturer and the used coating machine an additional step of drying may be required. In that case the drying is occurring in drying chambers with either air heating, infra-red or laser heating and consists of different temperature zones ranging from 50-180 degrees Celsius (Jinasena, Burheim, & Strømman, 2021).

For both drying within the coating machine and the additional step the drying rate is important as too high rates can lead to binder migration and accumulation to the surface of the electrode which in turn could lead to poor adhesion properties and in worst case crack formations in the electrode (Jinasena et al., 2021).

Depending on if the manufacturer wants to use stacking or winding the coating process differs as the two processes require different types of electrode sheets.

2.3.2.3 Calendering

When the foil has been coated and dried the next step is calendering which adjusts the physical properties of the electrodes, for instance bonding, conductivity and the thickness (Y. Liu et al., 2021). The electrode thickness affects both the cell properties and the cost, if the thickness is increased it results in higher energy density but it decreases the power density and increases the cost (Duffner et al., 2021).

2.3.2.4 Slitting

The last step of the electrode manufacturing is slitting which cuts the electrode to reach the required dimensions to fit the cell's design (Y. Liu et al., 2021). The working width of the coater is usually up to 1500mm which is wider than commonly used electrodes, so the foil has to be cut to the right size in the slitting process (Duffner et al., 2021). The sheets are then vacuum dried to remove any solvent that may remind on the roll (Jinasena et al., 2021).

The electrode rolls are then, if the cell design includes stacking, cut into separate electrodes sheets by shear cutting or laser cutting (Jinasena et al., 2021)

2.3.3 Cell Assembly

The assembly process accounts for a large contribution of the production costs of batteries, including factors like equipment depreciation, labor costs, and plant floor space expenses (Nelson, Ahmed, Gallagher, & Dees, 2019). According to (Nelson et al., 2019) that different stages of the assembly process contribute to the overall costs in varying degrees. Typically, stacking, welding, and enclosing operations are among the primary cost drivers. However, the specific contribution of each stage can vary depending on factors like the type of cell design being produced and the throughput of the plant. To maintain high-quality outcomes, these processes are often conducted in controlled environments, like dry rooms. In cases where such conditions cannot be maintained, additional steps, such as vacuum drying for 12-24 hours, may be necessary to remove moisture from the cells (Tagawa & Brodd, 2009). The production processes for Cell Assembly can be seen in Figure 6

Figure 6: The production processes for Cell Assembly

2.3.3.1 Stacking and Winding

The first step within cell assembly is to either stack or wind the electrodes together with a separator. Different manufacturers uses different processes and they have different advantages and disadvantages.

In the winding process the anode and cathode electrode are together with a separator wrapped to create an endless band (Duffner et al., 2021). The winding process is very productive and precise but cause stress on the electrodes which in turn limits the energy density that can be produced within a cell (Duffner et al., 2021).

Stacking on the other hand involves cutting the electrode rolls created in the calendering process into appropriately sized sheets, both anode and cathode by either die-based punching or with laser cutters (Y. Liu et al., 2021). The edge quality of the cutting process affects the batteries quality and safety (Y. Liu et al., 2021). These sheets are subsequently arranged in a precise alternating sequence of anode and cathode layers, separated by insulating material known as a separator, to achieve required tightness (Jinasena et al., 2021; Wu, 2015). The number of layers is contingent upon the specific requirements of the battery cell type and size. This assembly results in what is known as a 'jelly roll' structure. The process of stacking ensures that the requisite number of layers is achieved (Y. Liu et al., 2021). Stacking has the advantage over winding by applying uniform mechanical load to the sheets which results in higher energy density (Kwade et al., 2018).

2.3.3.2 Welding

The process initiates with the pre-welding of aluminium and copper tabs onto the anode and cathode current collectors, respectively. This step is crucial for ensuring a continuous electrical connection throughout the jelly roll. Typically, ultrasonic welding is employed for this purpose, although resistance welding may be utilized in certain cell designs (Y. Liu et al., 2021). Subsequently, the tabs on each side are collectively connected to a current collector, along with the cell lid. This sequence of actions ensures the establishment of robust electrical pathways within the cell (Michaelis et al., 2018).

2.3.3.3 Packaging

In the packaging process the jelly-roll is inserted in a robust metal housing, while being insulated in insulation foil which protects the jelly roll during the insertion into the metal can (Michaelis et al., 2018). For the prismatic cell the edges of the jelly roll are typically compressed, fixed and then ultrasonically welded to contact the terminals attached to the lid of the battery (Michaelis et al., 2018).The housing is then typically sealed using an additional laser welding process (Michaelis et al., 2018).

2.3.4 Cell Finishing

The cell finishing process is the final stage in the production of the battery cell (Kampker et al., 2023). Depending on the manufacturer's protocol the cells pass through the process steps and measurements in different order (Plumeyer, Kokozinski, & Kampker, 2023). Therefore the process sequence that can be seen in Figure 7 is literature based and can differ between manufacturers.

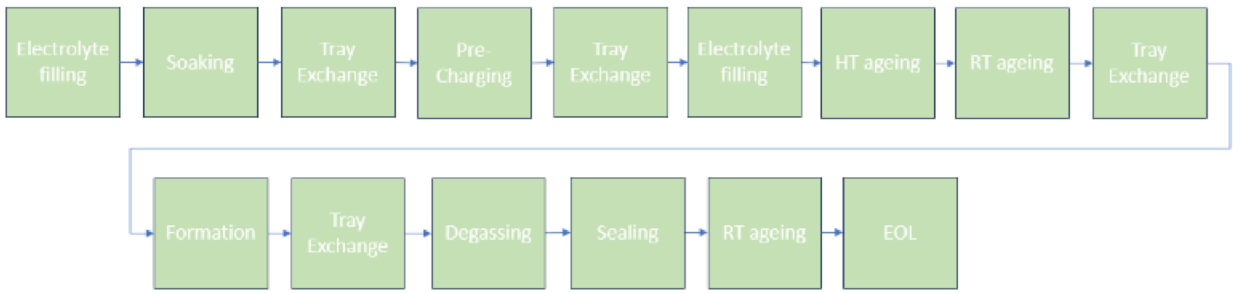

Figure 7: Cell Finishing Process Sequence

The formation part is the most expensive process and accounts for about 6% of the total battery cost. The process is also time-consuming and can range between 1,5-4 weeks where the batteries are undergoing different charging voltages, rest steps and degassing stages depending on cell chemistry and format (Pathan, Rashid, Walker, Widanage, & Kendrick, 2019). As cell finishing requires a large amount of equipment it can can account for 25% of the factories floor space as each individual cell must pass through the processes (Örüm Aydin et al., 2023). Due to the high cost different manufacturers are investigating new formation processes that decrease the total time within cell finishing by having rapid charge-discharge cycles and optimized temperatures etc. (Weng et al., 2021).

2.3.4.1 Electrolyte Filling

Depending on manufacturer the first electrolyte filling can be placed within the cell assembly or within cell finishing. In the first electrolyte filling process the cell is filled with electrolyte in dry conditions with controlled temperatures under weak vacuum (Kwade et al., 2018). Several quality controls are usually in procedure like weighing the cell before and after filling in order to ensure that the correct amount is filled in each cell before the cells are sealed (Kwade et al., 2018).

2.3.4.2 Soaking

After the cells are filled with electrolyte they are typically temporarily sealed and packed in a compression tray in order to be transported into a high-temperature room (around 40-60 degrees) for soaking (Wood, Li, & An, 2019). The soaking step is typically done in multiple steps in order for complete solid electrode interface and cathode electrolyte interface to occur. This is done by allowing the electrolyte to evenly distribute within the layers of the cell, and after they are sent for cooling (Wood et al., 2019). The duration of the soaking process at a given temperature depends on the size and the format of the cell as well as the cell chemistry and the electrolyte-filling process (Plumeyer et al., 2023).

The soaking process usually occurs more than one time during the formation cycle to ensure that the process is successful (Wood et al., 2019).

2.3.4.3 Pre-Charge

Next the cells are typically pre-charged after being inspected for any electrolyte leakage. This is done by a precisely controlled charging cycle in order to activate the cell. The cells are monitored in order to address any non-conformities. During the first charging when electrolyte is accessible to electrons at the electrode while at the same time the electrolyte is experiencing an unstable voltage range the anode solid electrolyte interphase (SEI) and the cathode electrolyte interphase (CEI) are formed (An, Li, Du, Daniel, & Wood III, 2017; Brodd & Tagawa, 2002). The most electrolyte interphase forms during the first charge and discharge cycle due to that the anode and cathode have not formed any passivation layers that electronically insulates the electrode from electrolyte before (An et al., 2017).

The SEI layer that forms on the anode is there to protect it from reacting with the electrolyte spontaneously during the cell's normal operation (Brodd & Tagawa, 2002). The SEI layer is essential to the performance of the battery as it has an impact on its initial capacity loss, the self-discharge characteristics, the batteries cycle life, and safety (An et al., 2016).

During the pre-charge process the cells are placed in a compression tray which is placed in the pre-charge chamber that can only fit one tray at a time (Ulfsparre, 2020). The compression tray compresses the cells into a certain dimension which is necessary due to the fact that during the charging process the cells have a tendency to swell (Rai, personal communication 13th of February 2024).

2.3.4.4 Tray Exchange

For the precharge process as well as formation there is a need to have compression trays that keeps the cells dimension as mentioned in section 2.3.4.3. The compression trays are very expensive and therefore in many cases there isn't an option to only use them for all the processes and therefore aging trays are also used during the other processes.

There are also other trays such as electrolyte filling trays and degassing trays but this thesis is focused on just aging and compression trays due to simplification and limited published information on the subject.

2.3.4.5 Electrolyte Filling

After this stage, the battery is typically filled with electrolyte again to compensate for any fluid that has been evaporated into gas in order to adjust to the correct amount. The same process as described in section 2.3.4.1 is occurring but a smaller amount of electrolyte is filled.

2.3.4.6 Soaking

After the second electrolyte filling the cells are then soaked again as mentioned in the previous soaking step which can be seen in section 2.3.4.2.

2.3.4.7 High and Room Temperature Ageing

In the aging process the cells enter the first cycle of aging where they are stored in a high temperature room for a period of time. After this they are typically kept in room-temperature to cool down followed by the first formation where the cell is exposed to a charge-discharge cycle (Wood et al., 2019).

2.3.4.8 Formation

The formation process consists of charging and discharging steps that are completed at slow rates to ensure that the properties of the SEI and CEI are optimized for minimum capacity fade over cycle life of the battery (Wood et al., 2019). The cells are placed in compression trays and placed in a formation chamber where the charging and discharging is occuring.

2.3.4.9 Degassing

During the soaking and pre-charge some of the components of the electrolyte are reduced which results in gasses forming inside the battery cell which increases the pressure (Plumeyer et al., 2023). For both quality and safety reasons the gas is extracted from the cell during the degassing process which in the case of prismatic cells is done through a port (Plumeyer et al., 2023).

2.3.4.10 Sealing

The next step is to seal the battery. The sealing process ensures that the battery cell is air and liquid tight as it is closed (Kampker et al., 2023).

2.3.4.11 Room Temperature Ageing

The previous processes are usually followed by an aging step which usually takes an additional of 1-2 weeks to complete (Wood et al., 2019). This stage is necessary to check leak currents, which range from 20-50 uA/cm2 after formation to <1 uA/cm2 after the aging stages (Wood et al., 2019). The aging process also requires many electrochemical cyclers, environmental chambers and requires a large amount of factory floor space up to around 25% of the plant capacity (Wood et al., 2019).

2.3.4.12 End Of Line

The last process in the manufacturing of Li-Ion cells is the end of line where the cell's electrical characteristics are tested before the product is finished and can be placed in a battery pack (Wolter, Fauser, Bretthauer, & Roscher, 2012).

2.4 Project Models

A project model is a structure of how a project should be executed and different projects requires different models to succeed (Thesing et al., 2021). The way a project is managed is influenced by many different factors, for example the rising of new technologies and shorter time-to-market cycles (Thesing et al., 2021). There are many different kinds of project models that are being used in different industries and projects but it is important to remember that there is no model that works for all projects as all of the different models are suited for certain projects with specific defined criteria (Thesing et al., 2021).

2.4.1 Waterfall Method

In traditional project models, the customer needs are first clearly defined before the product design phase can begin. Then when the product is defined the factory layout can be created to be able to produce the product that meets the customer's demand (Thesing et al., 2021). Within the traditional project models the processes are usually carried out in a linear manner where the next step cannot begin before the previous one is finished (Putnik & Putnik, 2019).

One example of a traditional project model is the waterfall method which contains five different phases that are conducted in a linear manner and where each of the phases requires a deliverable from the previous phase (Model, 2015). The five phases are Requirements, Design, Implementation, Verification and Maintenance which gives the user a good understanding of how to work with the project. Within each phase a list of tasks containing details of each step is prepared as well as the requirements and the success criteria (Leong, May Yee, Baitsegi, Palanisamy, & Ramasamy, 2023). The methodology can be seen in Figure 8.

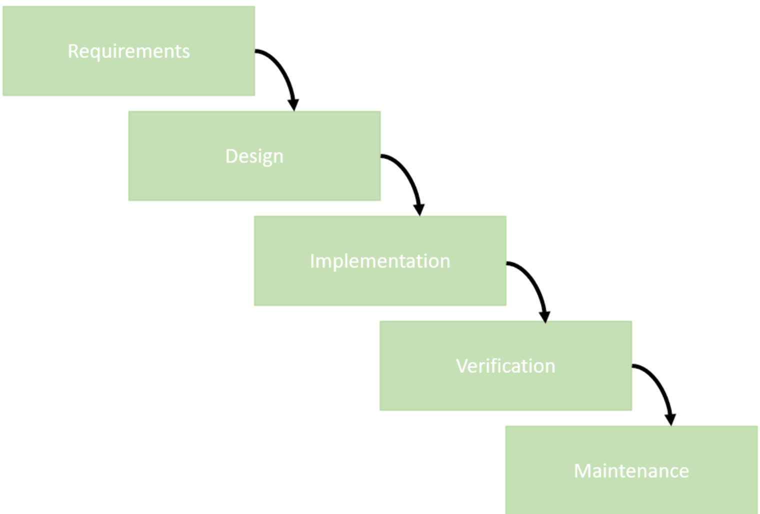

Figure 8: The Waterfall methods phases and order based on Model (2015).

2.4.1.1 Requirements phase

The requirements that are created within the first phase regards the purpose, scope, perspective and functionalities etc. of the project (Senarath, 2021). The purpose of the phase is to outline the big picture of the project's requirements that could be implemented in different ways (Hoory & Bottorff, 2022).

2.4.1.2 Design phase

When the requirements for the project are outlined and delivered the next phase is the design phase. Within this phase the goal is to design different solutions that can reach the requirements of the previous phase (Hoory & Bottorff, 2022).

2.4.1.3 Implementation phase

During the third phase a single solution is chosen to be implemented with the help of technology and then inspect whether the designed solution is able to support the stated requirements from phase one (Hoory & Bottorff, 2022).

2.4.1.4 Verification phase

In the verification phase the implementation is tested to see if it validates the requirements and if the solution is suitable for the project (Hoory & Bottorff, 2022).

2.4.1.5 Maintenance phase

The last phase of the waterfall method is the maintenance phase in which the system created needs to be maintained (Hoory & Bottorff, 2022). The phase involves testing for errors and fixing them if they occur as well as maintaining the solution as a whole (Hoory & Bottorff, 2022).

One of the negative aspects of the traditional model is that it doesn't cope well with late changes and can produce high costs and efforts during the project (Petersen, Wohlin, & Baca, 2009). A consequence of this is that the customers current needs in the beginning of the project aren't met at the end of it (Petersen et al., 2009). As the phases are conducted in a linear manner and each step needs to be finished before moving to the next it can also be a costly method to use if changes are needed.

2.4.2 Concurrent Engineering

Concurrent engineering (CE) is a comprehensive, systematic approach to the integrated, concurrent design and development of complex products and the related process e.g. manufacturing and logistics.The goal of CE is to achieve higher productivity, lower costs and a shorter time-to-market by taking to account downstream requirements and constraint in the design phase (Stjepandi, Wognum, & Verhagen, 2015).The adoption to CE was a reaction from manufacturing companies from traditional sequential engineering in order to handle reduced product life cycles and to meet new market and customer demands (Stjepandi et al., 2015).

CE consists of three basic elements according to Stjepandi et al., 2015 which incorporates different functions e.g. product engineering, process engineering, manufacturing planning and sourcing:

- Early involvement of participants
- The team approach

- Simultaneous work on different phases of product development

2.4.2.1 Set Based Concurrent Engineering

Toyotas Set-Based Concurrent Engineering (SBCE) is a product development method where the developers consider a set of solutions in parallel instead of just a single solution (Sobek, Ward, & Liker, 1999). Toyotas set-based Concurrent Engineering frequently bypasses numerous practices typically regarded as crucial for the effectiveness of concurrent engineering (Sobek et al., 1999).

Historically, design practice focused on quickly arriving at a single solution while then iterating the solution until it meets the design objectives. Subsequent iterations can however be very time consuming if the single solution requires substantial change and can also lead to suboptimal design both in terms of product design and manufacturing system design (Sobek et al., 1999). During the learning cycles the solutions are narrowed down with help of additional information such as customers and tests until the best solution from all aspects are found (Silvestre De Oliveira, Fidelis Peixer, Forcellini, Riso Barbosa Jr, & Lozano Cadena, 2023; Sobek et al., 1999). One of the main parts of the SBCE is the continuous communication between different parts of the development team, such as the design engineers and manufacturing engineers which leads to the final idea being suitable for all teams involved (Sobek et al., 1999). Most of the projects where SBCE is used have a solid knowledge background and well established technologies and the model is supported by continuous development (Silvestre De Oliveira et al., 2023).

The SCBE is performed with various principles identified by (Sobek et al., 1999), with different approaches to attain convergence in the product design and manufacturing design process. This creates a framework in order to work in parallel in order to create flexible system design. This is illustrated in Figure 9.

2.4.2.2 Principles for set-based Concurrent Engineering

This step is done in order to develop and characterize different alternatives used within the convergence process. Furthermore, this is done on two levels. First on individual projects to explore and communicate many alternatives in order to map out possibilities within the cross-functional teams. Secondly, the engineers try to capture insights and experience from previous projects on an ongoing basis in order to improve current projects. These principles are shown in Table 1, and each principle is discussed more thoroughly in the next section. The principles for set-based concurrent engineering are based on (Sobek et al., 1999).

Principle 1 - Map the design space
The first step in the process is to Define Feasible Regions which consist of each functional development team for instance for product engineering or production engineering defining feasible regions for the project from their perspective. This is done by independently determining the primary design constraints on each subsystem - what can and what should not be done. Typically this is based on experience, analysis, experimentation, and testing. The functional teams then create checklists

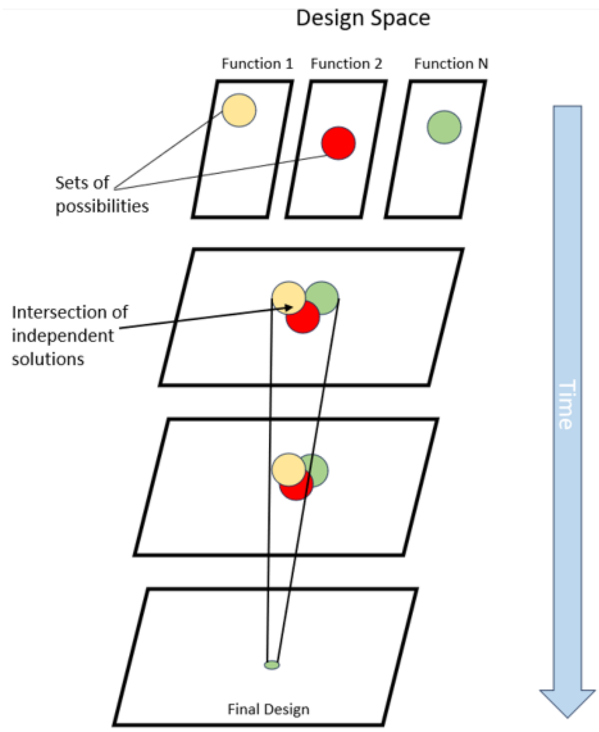

Figure 9: Principles of SBCE based on (Raudberget, 2010).

that have detailed guidelines for the design in relevant areas such as functionality, manufacturability, reliability, and so on. It can also outline what is economically feasible as well as new emerging technologies and production methods that can suggest enhancement in quality, cost etc. These checklists are then passed along functions in order to update other departments on what is feasible and what problems have been solved previously.

The next step in principle one is to explore trade-offs by designing multiple alternatives since merely identifying alternatives is insufficient. This is done by intelligently deciding alternatives by exploring trade-offs by designing, prototyping, and simulating alternative systems and subsystems.

The third and last step in principle one is to communicate sets of possibilities. This is done through the sets of possibilities, trade-offs, and implications of choosing an alternative over another then trying to communicate and understand feasible regions of other functions. This is done in order to avoid sub-optimal system solutions where one alternative is excellent for one functional team but poor for another. In order to evaluate this one option is to create a sample matrix with design alternatives along with different criteria for different options which can be seen illustrated in Figure 4. The evaluation criteria can be determined by absolutes (acceptable/unacceptable) or in terms of bounded intervals from (optimal to unacceptable) in order to find convergence. An example of the evaluation matrix can be seen in Figure 10.

Table 2: Principles for Set-based concurrent engineering (Sobek, Ward, & Liker, 1999).

Principle 1:	Map the design space • Define Feasible Regions • Explore trade-offs by designing multiple alternatives • Communicate sets of possibilities.
Principle 2:	Integrate by intersection • Look for intersections of feasible sets • Impose Minimum Constraint • Seek Conceptual Robustness
Principle 3:	Establish Feasibility before commitment • Narrow Sets Gradually While Increasing Detail • Stay within Sets Once Committed • Control by Managing Uncertainty at Process Gates

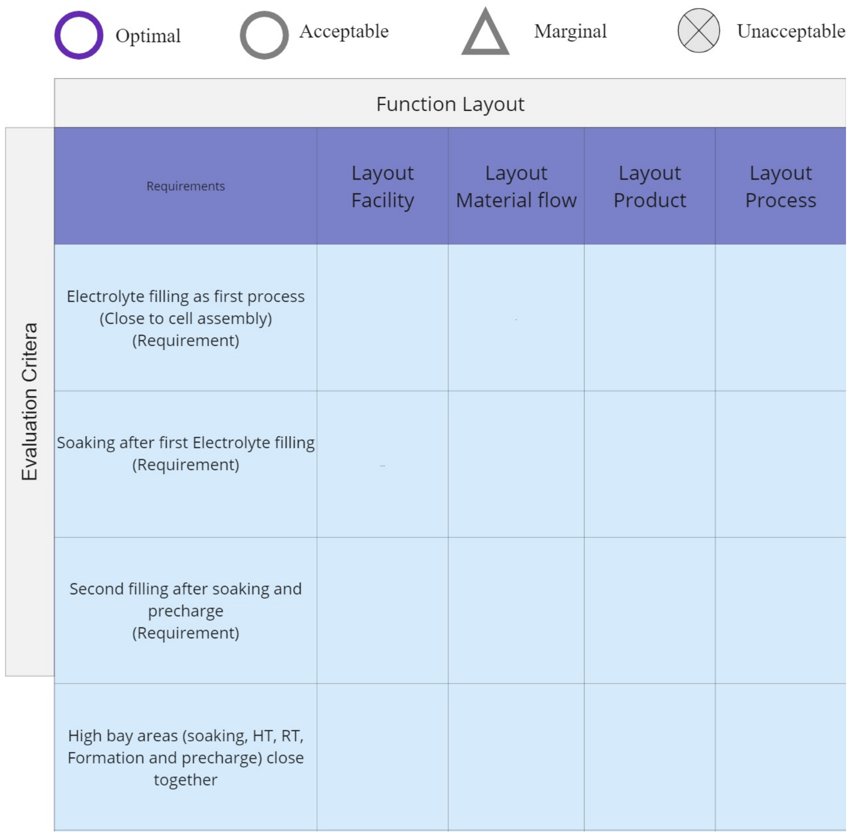

Figure 10: Evaluation matrix based on Sobek et al., (1999)

Principle 2 - Integrate by Intersection
After the steps for principle one is done it begins with principle two as the cross-functional teams now understand the considerations from the different perspectives and try to integrate sub-systems that identify solutions suited for every area. This step begins with looking for intersections of feasible sets.

After communicating the different possibilities teams should look for intersections for different functions i.e. where the feasible regions overlap. This is done in order to avoid integrating independently optimized components in order to optimize the total system performance. Communication in this step is crucial and its optimal to have several cross-functional meetings in order to argue for different solutions and find solutions for the intersection of the feasible regions to find the best solution for the overall system.

The next step of principle two is to Impose Minimum Constraint, in traditional engineering key decisions are made early on in order to simplify interactions among subsystems. Traditional engineering therefore aims to maximally constrain design in order to achieve the desired effect (early freeze on hard points like vehicle dimensions) in order to avoid confusion for the different functions. Set-based concurrent engineering however tries to in contrast impose minimum constraints needed at the time ensuring flexibility for further exploration or adjustments that can help improve the integration.

The third step of principle two is to seek conceptual robustness that applies both to product design, but also robustness in market variation. This applies to creating strategies in shorter development cycles, manufacturing flexibility, and standardization in order to decrease design susceptibility to changes in market demand or competition. For instance, both suppliers and the manufacturer need to make projections on product-design improvements for next-generation products in order to create the manufacturing system.

Principle 3 - Establish Feasibility before commitment
The last principle emphasizes a flexible approach to product and production development in order to enable overall system optimization and to seek an understanding of all possibilities and interactions before committing to a particular design. This is done by exploring multiple designs in parallel, and gradually converging instead of making late changes to the design.

The first step of principle three is Narrow Sets Gradually While Increasing Detail which emphasizes gradually eliminating possibilities until a final solution remains instead of picking the best solution from a set. As the set grows smaller the detail in the design is increased and enables functional prototyping and simulations. This ensures full understanding the relevant considerations before committing to a specific design. This ensures that each function narrows the respective sets with communication with the other functions in order to converge to a solution that integrates with the whole system. Narrowing the options down also enables the possibility to consider the most important alternatives to a larger extent while allowing flexibility in the development.

The second step of principle three is to **Stay within Sets Once Committed** which means that the functional teams have to stay within the narrowing funnel when continuing to improve the current alternatives. This means that changes that cause rework to the whole system cannot be made.

The third step of principle three is to Control by Managing Uncertainty at Process Gates as the need to make decisions is vital in order to progress with the design set-based concurrent engineering aims to remove certain uncertainty along with each gate. The gates represent an integrating event like a prototype of the design. This differs from traditional engineering where typically system functions hand off partial solutions to each other knowing changes result later on. Instead, set-based concurrent engineering obliges the functions to report in effect of each gate knowing that a good solution lies between the set of possibilities defined at each gate.

2.4.3 Agile Method

One of the newer methods is the agile method . The agile methodology arised from the software development industry and was developed by software developers in 2001 (Rigby, Sutherland, & Takeuchi, 2016). The method is based on iterative and incremental development and has been proven to be able to solve complex issues and adapt fast to new changes (Kaur & Jajoo, 2015; Marnada, Raharjo, Hardian, & Prasetyo, 2022). The method is most suitable when the project is surrounded by changes as it is more flexible than traditional methods such as the waterfall method (Chovanova, Husovic, Babcanova, & Makysova, 2020).

Within the software industry,the need of operating in dynamic and competitive environments where speed, quality and cost are important the method has been seen as successful within all three areas due to the methods focus on customer demand, the responsiveness to change and the continuous iterative processes (Stavru, 2014). Since the rise of agile methodology within the software industry it has been spreading to different industries such as automotive, machine development and marketing (Rigby et al., 2016). But as most of the agile frameworks have been developed from software development they might not always be easily replicated in other areas (Heimicke, Dühr, Krüger, Ng, & Albers, 2021). One big difference from other methods is that within the agile method documentation and planning is kept to a minimum so that flexibility and fast response to the changing environment is possible (Tena., Gosar, Kuar, & Berlec, 2020). This goes in hand with the four values that the agile methodology is built upon are (1) individuals and interactions over processes and tools; (2) working software over comprehensive documentation; (3) customer collaboration over contract negotiation; and (4) responding to change over following a plan (Beck et al., 2001).

As the agile methodology is about innovation it is less suitable for routine processes but as many industries are operating within dynamic environments there is a need for continuous innovation in functional processes (Rigby et al., 2016). The agile methodology is most effective if it is used where the problem that needs to be solved is complex, the possible solutions are unknown, the product requirements are unknown and where close collaboration with both customers and within the team is possible (Rigby et al., 2016).

There are different frameworks that are included within the agile methodology, the most popular is Scrum which is an iterative framework that focuses on flexibility and a holistic product development strategy (Kaur & Jajoo, 2015). The Scrum framework consists of iterative phases of planning, requirements analysis, design, execution, tests, and delivery to customers and stakeholders until the project is released (Salameh, 2014). A visualization of the method can be seen in Figure 11.

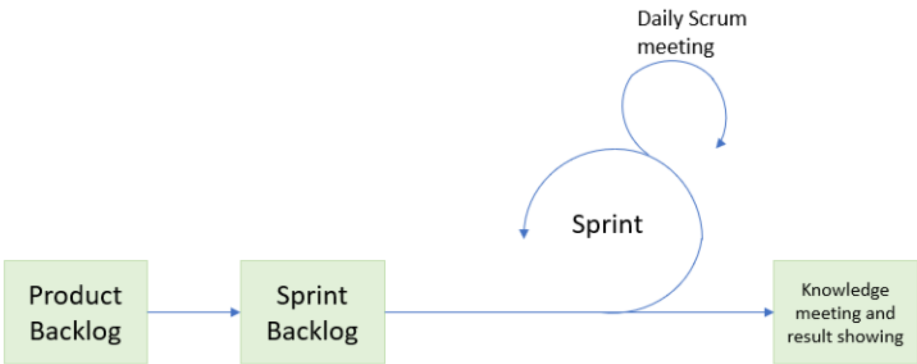

Figure 11: Scrum method based on Rösiö et al., (2020).

Scrum is structured in iterative cycles that are called sprints which are never longer than a certain time period and all of the sprints take place without any break in between until the final date (Deemer, Benefield, Larman, & Vodde, 2010). The people involved in the Sprint should be a cross-functional team that works together during the scrum process. The first step of a sprint is to select a number of customer requirements from a prioritized list which will be completed until the end of the sprint and they should not be changed during the period (Deemer et al., 2010). After the first sprint the people involved review the work with stakeholders and get feedback for the next sprint which then is executed in the same way as the last one (Deemer et al., 2010). The method emphasizes on using short cycles of development and continues to develop the solution (Deemer et al., 2010).

Changes and modifications of the project are allowed within the agile method as the requirements are evaluated in each interaction (Salameh, 2014). The method also focuses on defining the project's scope and requirements based on the value it brings to the customers and market share and it is therefore important to involve the customers in the iterative processes to make sure that the project is heading in the right direction (Salameh, 2014). On the other hand a disadvantage of the agile methodology is that in many cases there are low levels of documentation as short and face to face communication is preferred (Dzanic, Toroman, & Dzanic, 2022). This can lead to that information being lost and that it can create a problem of how to maintain the project later (Dzanic et al., 2022).

2.4.4 Other Project Models

As mentioned, there are many different project models that can be used for different projects. As this master thesis is time limited the three models that have been presented are the ones that will be used during this project but there are other models such as Platform Based Product and Production Development and Product Evolution Process and which are both two project models often used in the automotive industry that could have been applied within this thesis (Göpfert & Schulz, 2013).

2.5 Factory Layout

The project of planning a factory's layout is of importance for the future performance of the manufacturing system but it is a complex process due to the large variety of possible solutions (Klar, Glatt, Ravani, & Aurich, 2023). The most important objectives within factory layout planning is the flexibility and changeability in companies where changes are occurring frequently (Burggräf, Dannapfel, Hahn, & Preutenborbeck, 2021; Pérez-Gosende, Mula, & Díaz-Madroñero, 2021). Therefore having a sufficiently flexible layout is of high importance as by having an effective facility layout the manufacturing expenses can be reduced by 10-30% (Pérez-Gosende et al., 2021; Yang & Peters, 1998).

Layouts are usually designed for the initial conditions of the factory but when internal or external changes such as changes in production volumes, changes in processes and technology and changes in the product re-layouts are usually necessary (Monga & Khurana, 2015).

2.5.1 Traditional Layouts

Different processes can be realized by using different arrangements of machinery and equipment and the physical positioning of the production systems components is called layout (Bellgran & Säfsten, 2010). There are four traditional layouts that are further described in the following sections.

2.5.1.1 Fixed Position Layout

In the fixed position layout all of the value-adding activities are performed at the same place (Bellgran & Säfsten, 2010). The layout is suitable for very large products that are produced in a small quantity where the material and personnel are transported to the product instead of having the product travel between different stations (Bellgran & Säfsten, 2010). In Figure 12 an example of the fixed position layout is shown.

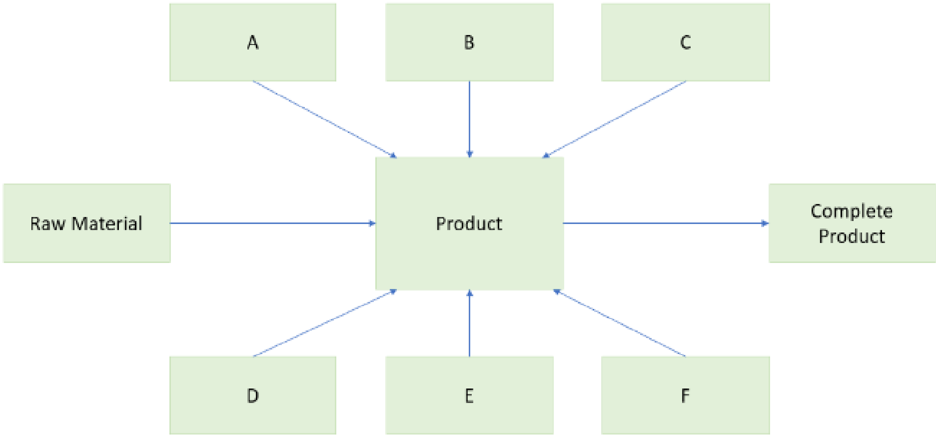

Figure 12: Example of Fixed Position Layout

2.5.1.2 Functional Layout

In the functional layout all equipment of the same type are located at the same place (Bellgran & Säfsten, 2010). It is usually used when there is a large number of products produced in small volumes (Bellgran & Säfsten, 2010). The flow between the functional areas depends on which operations are needed for making a certain product which leads to flexibility as it is possible to choose the machine in the specific area that is available at that particular time (Bellgran & Säfsten, 2010). On the other hand the layout can lead to high throughput times and waiting times due to the transportations between machine groups which also increases the need of planning (Bellgran & Säfsten, 2010). In Figure 13 an example of the functional layout is shown.

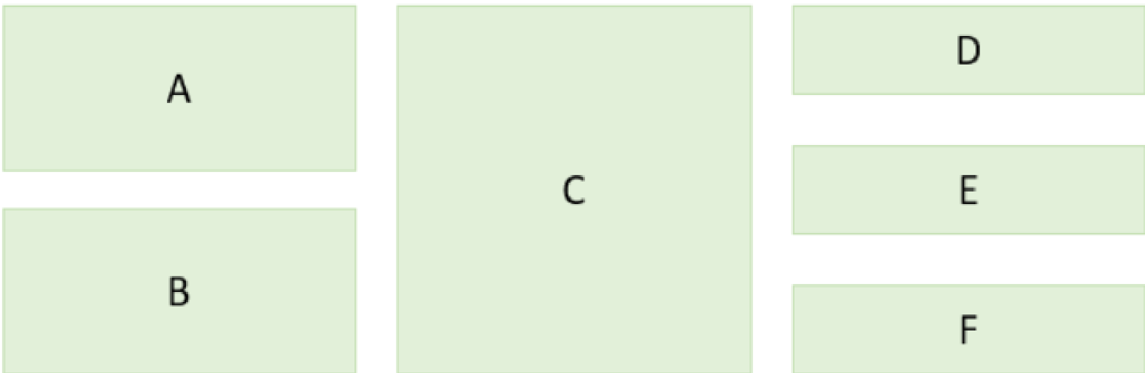

Figure 13: Example of Functional Layout

2.5.1.3 Cell Layout

In the cell layout the different equipment and processes that are needed for making a product are located at the same place (Bellgran & Säfsten, 2010). The layout is usually used when products are produced in large volumes and to some extent in many variants (Bellgran & Säfsten, 2010). The machines are placed in the direction of the flow instead of the functional similarity between them which leads to a product-oriented layout which can lead to short throughput times (Bellgran & Säfsten, 2010). The aim of using the cell layout is to create a sequential flow for as many products/parts as possible while having short set-up times to increase the flexibility (Bellgran & Säfsten, 2010). In Figure 14 an example of a cell layout is shown.

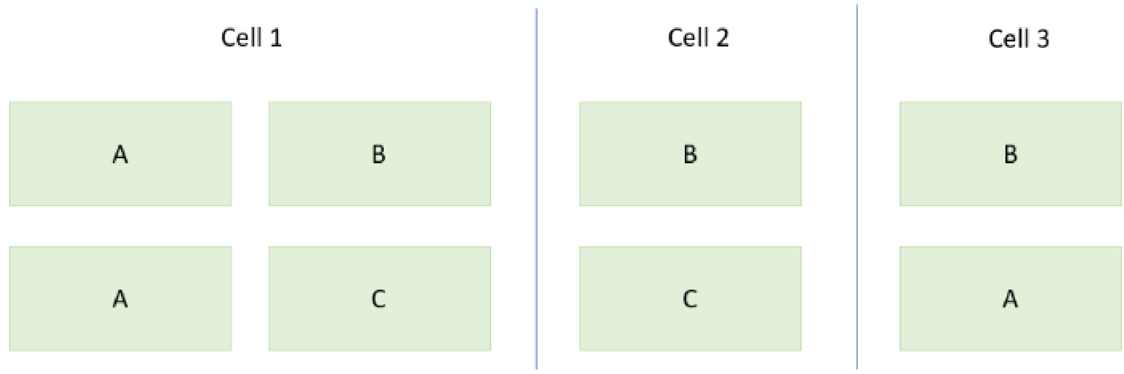

Figure 14: Example of Cell Layout

2.5.1.4 Line Flow Layout

In a line flow layout the machines are placed in the operation sequence for the product produced (Singh & Khanduja, 2019). The line flow layout is optimal to use when the production volume is large as it is efficient and reduces the cost per each item to produce (Singh & Khanduja, 2019). If more than one product is produced within the layout the sequence of the operations might differ which means that an alternative routing must be in place (Singh & Khanduja, 2019).

The traditional assembly line can be categorized into different groups depending on their shape and number of products that are produced on that line (Kara, Gökçen, & Atasagun, 2010). The different shapes can be the traditional straight line or a U-shaped line where the traditional straight line has been most common for mass production industries while the U-shaped is a newer shape that has provided more flexibility, productivity and quality as well as it has been proven to adapt to demanded changes quickly in comparison to the traditional shape (Kara et al., 2010). In Figure 15 an example of a line flow layout is shown.

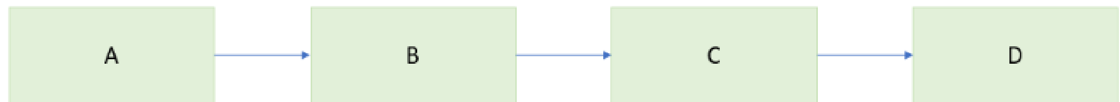

Figure 15: Example of Line Flow Layout

The number of products that are produced on the line depends on if the assembly line is a single-model or a mixed-model (Kara et al., 2010). The single-model assembly line is arranged to only produce one product type while the mixed-model produces different models of a certain product type (Kara et al., 2010).

The advantages with line flow layout is the short throughput times, the simple material flow, high degree of exchangeability as well as high resource utilization (Bellgran & Säfsten, 2010). On the other hand the line flow layout is sensitive to disturbances, is inflexible as well as hard to balance (Bellgran & Säfsten, 2010).

2.5.2 Dynamic Layout Problem

Manufacturing companies needs to be able to respond to changes in the requirements in order to meet the cost, time and quality and therefore the factory layout need to be planned from the beginning in a way that uncertain but significantly influential factors can be included within the system (Rogalski, 2012). Therefore there is a need of factory layouts that are flexible, modular and easy to rearrange to be able to avoid having to redesign the layout when the production requirements and system changes (Benjaafar, Heragu, & Irani, 2002).

In environments where the product demand and mix are varying the layout must either be easily re-configurable or robust enough to be able to meet the demand (Lahmar & Benjaafar, 2005). According to Pillai, Hunagund, and Krishnan, 2011 there are two major ways of solving the Dynamic Layout Problem, either by using an re-configurable approach or by using an robust approach.

In industries where the re-layout costs are high it can be preferable to have a layout which is robust under multiple scenarios, and even though it might not be optimal for any, it is still suitable for all of them (Benjaafar et al., 2002). The re-configurable approach is more suitable when the re-layout costs are low but the uncertainty high (Benjaafar et al., 2002).

2.5.2.1 Re-configurable approach

The re-configurable approach regards the increase of flexibility, modularity or re-configurability in the layouts with the aim of reducing the cost of relayouts when the production requirements are changed (Benjaafar et al., 2002). The re-configurable approach assumes that the layout will have to be reconfigured after each time period with minimized cost while at the same time guarantee good material handling for the new time period (Benjaafar et al., 2002).

Modular Layout
Modular layouts can be seen as hybrid layouts that include a complex material flow that isn't similar to one of the traditional layouts etc. functional or line flow (Benjaafar et al., 2002). Within modular layouts there are modules that consist of a group of machines that are connected to the material flow illustrated in Figure 16 (Benjaafar et al., 2002).

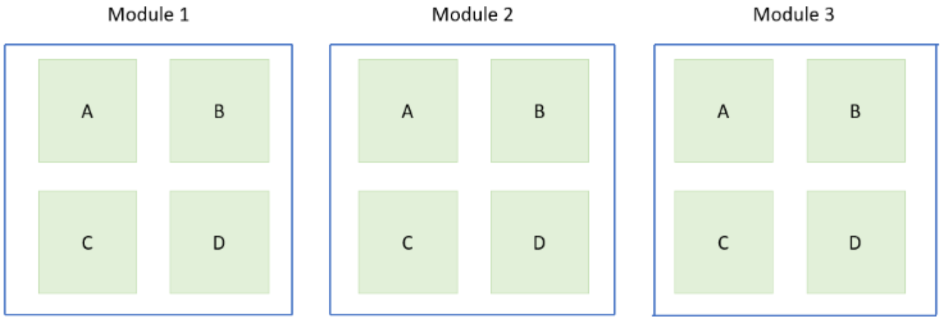

Figure 16: Example of a Modular Layout Design

For the re-configurable approach the modular layout is a suitable choice as modularity can be seen as one of the most important aspects for changeability due to that if there is a need for change the modular structure will allow existing modules to be expanded or exchanged which leads to easy and cost efficient changes (Burggräf et al., 2021).

Modularity in production process and layout design is characterized by organizing production processes into standardized groups that have a few or multiple strong organizational ties, permitting the sequencing of machines and tooling with little loss in functionality due to each production module working as a fairly autonomous unit. Thus, if each production operation is independent of prior operations, the process can be viewed as modular (Kubota, Hsuan, & Cauchick-Miguel, 2017). Modularity is a determining factor in creating re-configurable manufacturing systems. By developing a modular production system design parts of the production system can be exchanged or added without a negative effect on the whole system. This means that defined modules can be developed relatively independently of the additional system and be used at different locations or be reused in other systems like in a sister factory (Rösiö et al., 2020).

As stated in Rösiö et al., (2020) there are several benefits in developing modular production systems which allows for added agility:

- Increased re-configurability: The modules of the production system can rapidly be configured and modified to meet altered manufacturing requirements.
- Handling complexity in the system: The technical equipment is broken down in smaller parts which allow an increased transparency and reduces the complexity. The modules can be developed, produced, tested and validated relatively independent from each other.
- Reduces the risk of unwanted modifications: Since parts of the production-system are more independent of each other in a modular system the risk of changes in one part of the system does not alter the other modules.
- Improved maintainability: The system becomes easier to diagnose, maintain and repair.

- Economical scalability: The modular system can be scaled since the development and modification can be added gradually per module.
- Increased control and organization: Parallel development since multiple modules can be developed simultaneously which decreases lead-time for development.

The challenges with modularity is that it initially requires a large effort and capital in building the module system and developing standardized interfaces like facility planning, information system and material handling between the modules (Rösiö et al., 2020).

In addition, to create a production system that is re-configurable in nature there are other aspects except modularity that is important. Other important factors include integrability, diagnosability and mobility. Integrability includes standardized interfaces so modules can be easily and cost efficiently integrated in the system. Diagnoseability which handles quality and equipment status in order to achieve a low variation of quality and an efficient setup of the machine or module. Mobility however handles in that equipment and tools are able to be transferred in a preferred process layout to optimize production or to handle new product variants (Rösiö et al., 2020).

Purpose of reconfigurable approach
Through the specified properties reconfigurable manufacturing system aims to contribute to a number of benefits in order to handle disturbances and changes in the production system according to Rösiö et al., (2020):

- Capacity changes: This handles the scalability of the system in order to adjust for the capacity of changes in production volume.
- Product variant changes: Re-configurable manufacturing system aims to adapt the production system and its subsystems to new variants or products. This through utilizing and re-configuring existing equipment and integrating new equipment in the system in an efficient and cost effective way.
- Automation variation: A re-configurable manufacturing system can handle the degree of automation in the system by replacing manual stations to automated cells if needed or removing automation to increase flexibility.
- Handling transport of equipment between departments and factories: Through modular and mobile solutions production equipment can be transported to different departments and factories.

2.5.2.2 Robust Approach

When using a robust layout the assumption is that re-layouts will lead to too high costs and therefore the aim is to minimise the total material handling cost that can occur in all different periods with a single layout (Pillai et al., 2011). The layout is therefore developed with multiple scenarios in aspect when creating the layout that will be suitable for all of them (Pillai et al., 2011).

For the robust approach production data for multiple periods are needed at the initial design stage so that the layout can be confirmed to be robust over multiple periods which can be impossible in dynamic environments (Benjaafar et al., 2002). Instead the layout can include inherent features that will lead to reasonable material handling efficiency throughout all of the time periods (Benjaafar et al., 2002).

The advantage of using a robust layout is that there is no need for interruptions if there are changes within the production system as it has already been accounted for.

Robust Functional Layout
As the aim of the robust layout is to be able fulfil a wide range of product requirements the most common robust layout is the functional layout (Lahmar & Benjaafar, 2005). Within the functional layout resources of the same time are grouped together into functional departments and then placed depending on the material flow cost for all future planning periods within a specific planning period (Lahmar & Benjaafar, 2005).

The benefits of using a functional layout is the limited commitment to having a strict flow pattern as well as providing a capacity pooling for each of the resource types (Lahmar & Benjaafar, 2005). On the other hand the material flow often becomes inefficient and the scheduling within the layout becomes complicated due to the fact that the layout is not optimized for a particular product (Lahmar & Benjaafar, 2005).

In comparison to the traditional functional layout the robust layout is constructed for multiple planning periods, while the traditional is created for a certain time-frame.

Distributed layout
A distributed layout consists of functional departments that are divided into smaller sub departments that are distributed in strategic places (Lahmar & Benjaafar, 2005). The aim of the division and distribution is to be able to meet future changes in the product mix, the product routing and the demanded volume (Lahmar & Benjaafar, 2005). As the distribution of the sub departments into different places throughout the plant could lead to increased accessibility to the different departments and that could result in more efficient flows which in turn leads to that need of re-layout could be extinguished even if production requirements change (Lahmar & Benjaafar, 2005). In Figure 17 two different distributed layouts are shown.

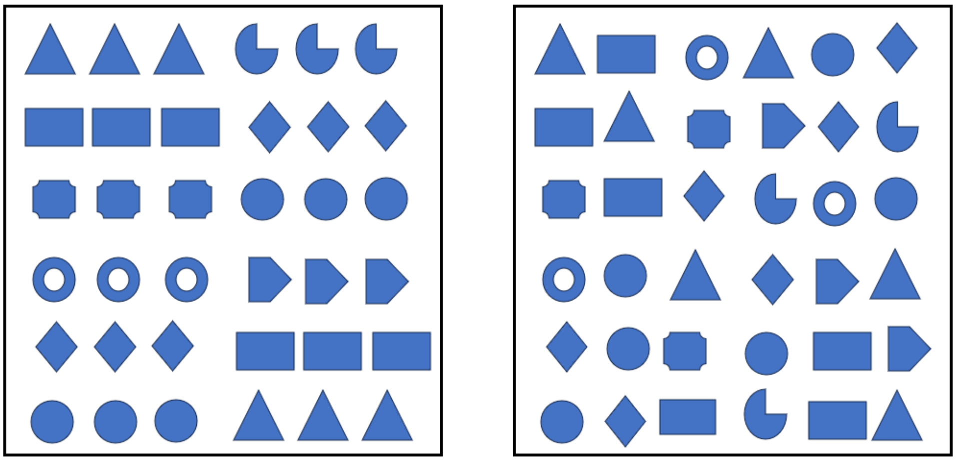

Figure 17: Distributed layouts based on Lahmar & Benjaafar (2005).

The use of distributed layouts are most suitable in production systems where the demand variability is high or where the product variety is low (Lahmar & Benjaafar, 2005).

One of the problems when creating a distributed layout is how the sub departments should be created and how many of each that are needed (Benjaafar et al., 2002). The duplication of departments might lead to increased flexibility within the layout but it comes with the cost of needing duplications of operators and auxiliary resources (Benjaafar et al., 2002).

3

Methodology

This chapter regards the project's structure and the methodology that has been used in order to conduct this project. Further, it aimed to justify the research method that was used and why it was suitable for this project.

3.1 Research Design

The research was designed to be able to fulfill the aim of the study, which was to find an optimized factory layout for battery cell factories and help pace up the industry. The research was carried out with an inductive work process where the research had its basis in developing a general standardized workflow in enabling battery factor cell design for unknown parameters (Patel & Davidson, 2019). As the research questions were explorative, the research process needed to be iterative as shown in Figure 18. Furthermore, the structure of the project was a combination of five different phases as illustrated in Figure 18 at the next page.

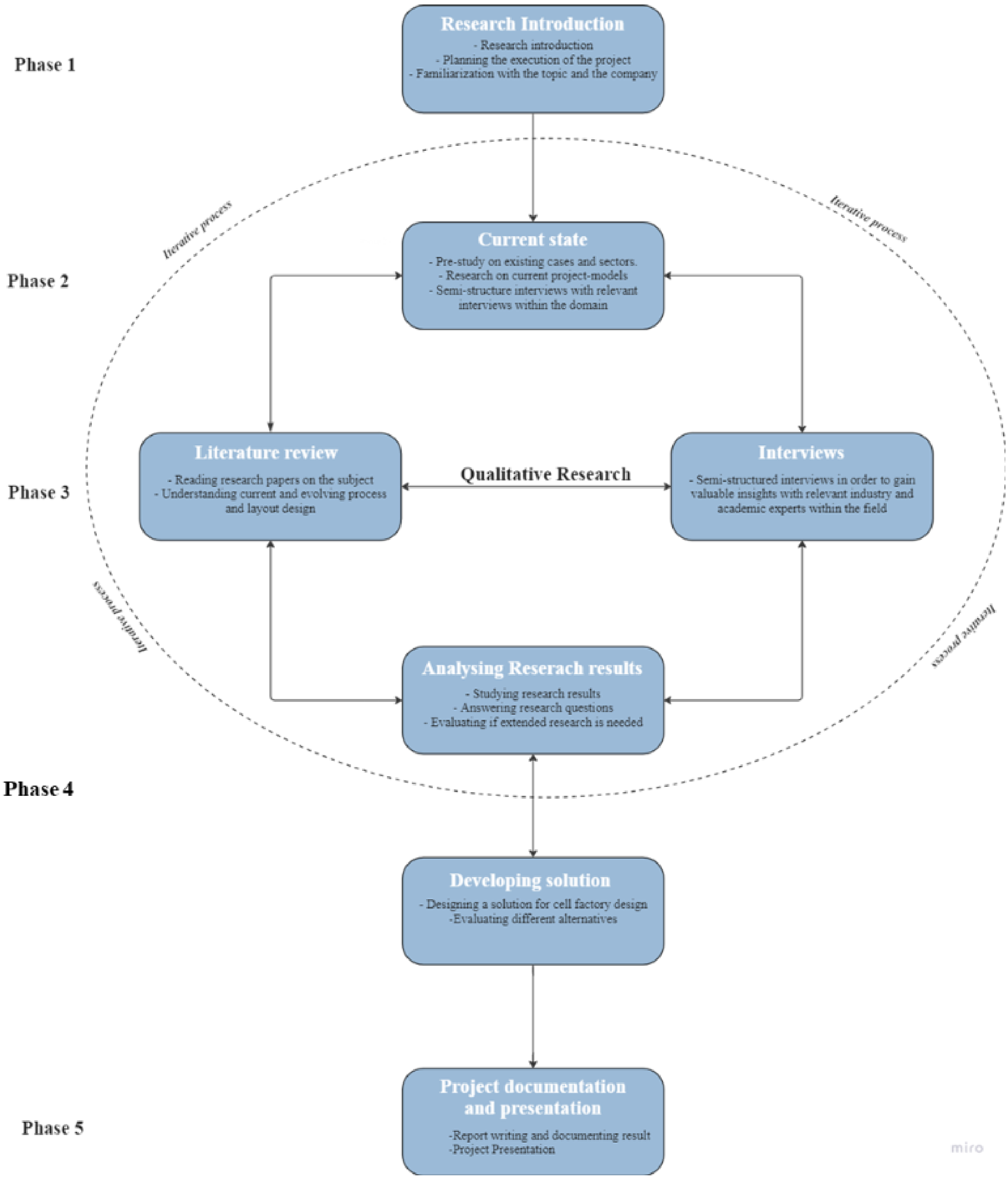

Figure 18: Research Design

3.2 Research tools

The research tools that were used in this thesis was a qualitative study based on interviews with relevant people within the field and literature studies. A qualitative approach was chosen as it provides a deep insight to the subject which helped to answer the research question (Tenny, Brannan, & Brannan, 2023; Venkatesh, Brown, & Sullivan, 2023). The decision to use a qualitative study was further supported by the consideration of the amount of available numerical data. Given that the battery cell industry is relatively new, there was a limited amount of published numerical data. This scarcity of quantitative data and the lack of measurable phenomena made a qualitative approach more appropriate (Patel & Davidson, 2019).

3.2.1 Interviews

As the study was to an extent relying on interviews the main access to interviewees were through NOVO Energy, either employees of the company or other contacts they had. The decision to have interviews rather than surveys was because the project aims to solve a complex problem and a detailed understanding of the collected data were necessary which surveys could not support (Denscombe, 2014).

The interviews were in most cases semi-structured to let the interviewee speak more widely and develop new ideas (Denscombe, 2014). Therefore the interviews were conducted with a low level of standardization and semi-level of structure (Patel & Davidson, 2019). The use of semi-structured interviews also let the interviews develop as more knowledge was gained and to continuously develop the data collection to become more detailed. In some cases an in depth interview was used when there was a specific topic that needed further investigation (Kvale & Brinkmann, 2014).

The transcribed interviews were also checked with the interviewee to make sure that he or she was comfortable with his or her answers.

The data that was gathered from the interviews were used as the base for the project and helped with the idea generation part. As the industry is relatively new and published information was limited, the knowledge of the interviewees was of crucial importance to gain a deeper understanding to be able to solve the complex problem.

3.2.2 Literature review

In addition, a literature review was carried out in advance and alongside with the interviews in order to gain valuable knowledge and provide validation for the interviews. The main purpose of the literature review was to gain a general understanding of different project models, and different processes as well as how flexibility can be increased in factory layout design within battery cell production. The gained information from the literature review was used to form a theoretical framework and support the creation of interview questions. The data gained from the literature was also used to make sure that the data that was gathered from the interviews were reliable by using triangulation with other interviews and the collected data

(Denscombe, 2014). In order to ensure a high standard of the literature review the researched papers had to be peer-reviewed (Patel & Davidson, 2019).

The literature review was carried out by searching academic databases (Google Scholar, Chalmers Library and Scopus) in order to find relevant articles, publications, industry journals, and case studies on topics related to the scope. Printed books were also used in cases where it was deemed necessary. The main literature that was searched for regarded the different production processes, factory layouts, project models, and battery production. Keywords that were used in the search was *Li-Ion battery production*, *Gigafactory*, *Factory layout*, *Cell Finishing*, *Project models* etc.

3.2.3 Qualitative analysis

Further, a qualitative analysis was performed in order to evaluate results of the research design. An important aspect of the literature review as well as the interviews was to analyze the gathered data ongoingly, since it provided useful insights that were important for further steps (Patel & Davidson, 2019). The main idea was that the iterative qualitative analysis of the material would provide a pathway for further investigation and ideas and in extent enrich the iterative process in order to design the solution. The qualitative analysis also aimed to problematize variations and homogeneity in the collected data as well as the relations between the parts in the material that is aimed to constitute the entirety of the project (Patel & Davidson, 2019).

3.3 Phase 1

The first phase regarded the research introduction, and the main focus was on the planning report as well as onboarding within the company and a basic understanding of the processes and the product.

3.4 Phase 2

The second phase was a pre-study of other mature industries and investigated how their project models looked. This was done by a literature study that regarded project models as a general topic and then focusing on how they work in different industries. After the literature study, interviews were conducted with employees at NOVO Energy that had previously been working at other companies and had experiences with different project models. The interviews took place during a 30 minute period and recorded on Microsoft Teams to ensure that the results could be transcribed and validated after the interviews. The interviewees and their previous work industry is presented in Table 3 but due to confidentially their real names are masked. The interview questions can be seen in Appendix A.

This phase was a way to understand how other industries had been working with projects and helped generate ideas for the battery industry. The generated results

Table 3: interviewee in the Pre-Study

interviewee	Previous Industry
A	Automotive
B	Process
C	Battery
D	Automotive

from the interviews were analyzed and compared to existing literature to make sure that the information was correct and validated.

From this phase, three different project models were discovered and further investigated with the help of a literature study to create three models that could be used to generate factory layouts.

3.5 Phase 3

The third phase regarded the different production processes within Li-ion battery manufacturing and investigated how the different processes worked in-depth and how they could become more flexible. This was done by first doing a literature study as well as reading technical reports regarding the processes before holding semi-structured interviews with process engineers within the specific area. The interviewees are presented in Table 4 together with their current role at NOVO Energy. Due to confidentiality, the interviewees' real names are masked.

Table 4: interviewee in the third phase

interviewee	Current Role
A	Senior Technical Project Manager - Formation and Ageing
B	Process Engineer - Formation and Ageing
C	Manager Engineer - Factory Layout & Simulation
D	Material Flow Engineer

The interviews were conducted during an hour each time and recorded on Microsoft Teams to ensure that the answers could be transcribed and validated after the interviews. The information that was gathered from the interviews were analyzed in comparison to the found literature to make sure that the information was validated. The interview questions can be seen in Appendix B.

3.6 Phase 4

The fourth phase regarded answering the research questions with help from the previous phases. When knowledge of how the different production steps could become more flexible and how other industries were working with projects, the main focus was on how the factory layout could become more flexible and how that would affect the other areas within the project.

As this master thesis aimed at finding a solution to how to optimize the layout of a battery cell factory for the unknown future all of the described methods in section 2.4 were used to find three different solution options for the problem. The methodology that was followed for each of the methods can be seen in Figure 19 with some modifications to suit the project.

Waterfall	Concurrent	Agile
1. Requirements 2. Design 3. Implementation 4. Verification 5. Maintenance	1. Map the design base 2. Integrate by intersection 3. Establish feasibility before commitment	1. Create a vision + Prioritized list 2. Create a smaller list 3. Create a layout from the smaller list 4. Iterative process (2+3) 5. Validation

Figure 19: The used project models and their structure

To make sure that all of the methodologies had the same aim a scenario were created to be used as a starting point which is further described in the next section.

3.6.1 Scenario

The scenario that was used for the layout planning was that there is a battery cell under development and that the physical factory and its processes has to be built before the product is finalized. Therefore process steps and necessary equipment might change from the time that the factory is beginning to be built until it is ready to produce cells.

3.6.2 Requirements and wishes

To be able to find requirements for Cell Finishing interviews were conducted with process, material handling and layout engineers as well as R&D employees in combination with the conducted literature study. The resulting requirements can be seen in Table 6. Wishes from different functions within a battery manufacturing company are also presented in Table 7.

3.6.3 Waterfall Method

To be able to find an optimized layout for the future battery cell factory the first method to be used was the waterfall methodology. The working procedure is described below.

1. Define requirements
The first step was to define all of the requirements for the project. As the building of the factory is occurring before the final sample of the battery cell the requirements

that was defined were based on existing information and could therefore change before the final cell design is completed. Due to the fact that some of the requirements could differ between different prismatic Li-Ion cells a made-up recipe based on the literature study was used in this method and for those requirements which can be seen in Figure 7.

2. Design
The second step within the waterfall method was the design phase in which a layout was created which should be able to reach the requirements that were set in the previous phase. To make sure that the layout could fulfill all of the requirements the process sequence was the first priority of the layouts. The sequence was mapped with help of the literature-based recipe and visualized by drawing lines between the processes depending on the process flow. Then the amount of lines each process had was then calculated and used as the starting point for the layout, and then in the order of most to least lines the different processes were placed. The processes that were included in the recipe were then mapped after the material flow between them and regarding the requirements which can be seen in Figure 20. The amount of lines which indicates the relation between the processes was then calculated which created a list of how important each process was, the ones with the most lines to them were seen as most important and the one with the least as the less important.

Then a layout was created that fulfilled all of the requirements as well as the process sequence in an efficient way before the different wishes were regarded. The different wishes were incorporated in the existing layout which was then changed to suit both material flow and the wishes in combination. The results can be seen in section 4.4.2.

3. Implement
The third step was the implementation phase in which the solutions from the previous phase were studied during a workshop session with relevant employees at NOVO Energy where both the layout that fulfilled all of the requirements and the layout that was modified to meet the wishes was investigated further. The workshop was conducted with process engineers, a layout engineer and a material handling engineer to make sure that as many parameters as possible would be covered, the participating employees can be seen in Table 5 but their names are masked due to confidentiality.

Table 5: Employees participating in the workshop

Participant	Current Role
A	Process Engineer - Formation and Ageing
B	Manager Engineer - Factory Layout & Simulation
C	Material Flow Engineer

During the 20 minute workshop session the workflow of the method were described and the final layout shown and smaller changes that the team came up with was implemented.

4. Verification
The final step that is suitable for this thesis to use is the verification phase in which the process, layout and material handling engineers at NOVO Energy looked at the layout and verified that it was a possible layout to use for the purpose in aspects such as material flow, cost and optimisation. The level of flexibility was also discussed.

3.6.4 Set-based Concurrent Method

In order to establish a factory and process layout design with the (set-based) concurrent engineering the method had to be adapted to the primary view of manufacturing/layout engineering compared to the more product-oriented nature of set-based concurrent engineering. However, concurrent in its nature is defined by constant communication and integration of each of the cross-functional teams involved within the manufacturing company.

1. Map the design base
The first step was to define feasible regions for the different functions affected by the layout design as the first scope. This included communicating by defining what primary design constraints from each department, and determining feasible regions in terms of construction related to minimum/maximum factory space, battery cell type from R&D and economical and capacity related constraints from strategy/management. This was done in order to create checklists by each department for what is feasible for the factory design. Then different alternatives were designed for the factory and process layout in order to explore trade-offs, and communicating different alternatives for the layout for different criterias between the functions in order to develop feasible regions for the alternatives.

The design base in this method originated from the requirements from the interviews gathered in section 3.5.

2. Integrate by intersection
The next step was to try to look for intersection of these feasible sets, for instance where material flow, process design and R&D-estimations and facility design overlap in order to avoid sub-optimization and look at total system performance. This was followed by imposing minimum constraints, e.g only constraining the layout design in terms of what is possible and narrowing the scope from unacceptable solutions. This is done by using an evaluation matrix as seen in Figure 10. But also to seek conceptual robustness in order to look at flexibility and projections for emerging technologies or product changes.

3. Establish feasibility before commitment
Thirdly was narrowing down the set of alternatives while gradually increasing the detail of said alternatives, this meant moving from conceptual design into the creating more detailed layout models of the layout. Moving forward from narrowing the scope it was important to stay with the current sets of alternatives once committed. During these iterations in narrowing the alternatives certain process gates were used in order to control uncertainty by removing non-viable options and arriving at a single solution.

A workshop with relevant employees at NOVO Energy were then conducted, the participating employees can be seen in Table 5. During this step, discussion with employees from different functions in order to establish feasibility was performed.

4. Iteration
In this method, the steps were iterative before proceeding to subsequent steps if certain areas were unsatisfactory, i.e no option fulfilled the specific requirements. Once the steps were satisfied, a final layout was selected to align with overall good performance.

After the iteration stage a more detailed layout was created in order to find limitations with the less detailed layouts and to ensure their performance.

3.6.5 Agile Method

The last method to be used were the agile method. The working procedure is described below.

1. Vision of the layout + prioritized list
The first step of the agile method was to create a vision of the final layout of the factory and from there a prioritized list of what was needed to reach that vision. As the aim of the factory were to be able to produce the final cell type without knowing what that might look like the vision was set to create a factory layout that can produce any recipe of prismatic Li-Ion battery. For Cell Finishing this meant that there wasn't a determined recipe beforehand and that the process sequence could be based on other than the different requirements that are the same for all prismatic Li-Ion batteries.

The prioritized list was then created by looking at the requirements for the processes and focusing on those that could differ between different recipes and put the focus on finding a solution for them. The first base layout was then created based on the requirements that are the same for all prismatic Li-Ion batteries and with the knowledge that the process sequence was not determined which meant that the cell had to be able to go to all of the processes at any given time.

2. Smaller list
From the prioritized list which included all of the requirements that are the same for all Li-Ion battery a smaller list of one requirement at a time was used to start with the layout generation.

3. Create a layout from the smaller list
A layout was then created from the smaller list with the layout created from the requirements that are the same for all prismatic Li-Ion batteries.

4. Smaller list
After the first layout was created the next requirement that could differ was used to try to incorporate it with the previous layout.

This process of looking at the smaller list containing the requirements that could change while still fulfilling the ones that are the same for all prismatic Li-Ion cells and then making a new layout was done until the final requirement could be met. Then the wishes started to be integrated into the method in a similar manner as the previous steps, first by looking at the first wish and creating a layout and then moving on to the next.

When all of the requirements were fulfilled and the wishes were fulfilled to an possible extent the layout was seen as the final one.

5. Validation
The final layout was then evaluated and validated by the employees at NOVO Energy in a workshop session where they could help to further improve the layout in regards to their area of expertise, the participating employees can be seen in Table 5. The workshop session was held during a 20 minutes meeting together with process engineers, a layout engineer and a material handling engineer where the workflow for the agile methodology was described and the layout were analyzed. Smaller changes were conducted and different parameters such as cost and flexibility were discussed.

3.6.6 Further development of the layouts

To make sure that the created layouts were possible solutions they were created in Autodesk AutoCAD 2024 with actual CAD-drawings of the equipment. From that, further development were made to the layouts as the sizes of the equipment of the processes were included. The results can be seen in Figure 22, 30 and 33.

3.6.7 Layout Analysis

All of the generated layouts were then analyzed regarding their flexibility, the estimated cost, amount of material handling and their size. Based on the output from the workshop, the theoretical framework and in collaboration with process, material handling and layout engineers different advantages and disadvantages of each layout were identified and further discussed. The results are presented sections 4.4.2-4.4.4.

3.7 Phase 5

The final phase of the project methodology was to document the previous phases, discuss the results from the previous steps as well as present the overall findings from the thesis.

4
Results

The results from the different phases described in Chapter 3 are presented in the following section.

4.1 Phase 1

The results from the first phase was a planning report as well as getting to know the company, the product and production processes. This was done by attending on-boarding courses as well as planning the general work.

4.2 Phase 2

In the second phase a pre-study of project models in other mature industries were conducted. This resulted in three interesting project models used in various industries which could be altered in order to be used for layout-generation. These project models are presented in section 2.4 where they are described with their intended function as well as in chapter 3 where they are altered in order to fit the purpose of this thesis which is to use the project-models in order to establish different layout-options.

From the interviews with relevant employees at NOVO Energy that had been working in other industries and the overall results were that traditional sequential engineering was mostly used in most industries, and one case of a more agile approach but also that there were cases where there were no general method on how they worked with complexity and uncertainties in the previous organizations.

4.3 Phase 3

During phase three a literature review was carried out which is part of the theoretical framework which can be seen in Chapter 2. This provided general knowledge for the project on batteries, how they are produced, as well as production systems in general, as well as layout design and implementation of layouts.

From the conducted interviews in-depth knowledge about the processes within Cell Finishing was gained as well as requirements and wishes from the process engineers.

The level of flexibility for each of the process steps were also discussed and gave a ground for what would be possible solutions or not.

4.4 Phase 4

In the fourth phase the different methodologies were used to generate layouts for Cell Finishing together withthe requirements and wishes that had been collected. The results can be seen in the following sections.

4.4.1 Requirements and wishes

The requirements that were created from the literature study and in collaboration with process, layout and R&D engineers are presented in Table 6. The different requirements are colour coded depending on if they are the same for all prismatic Li-Ion battery cells or if they differ. In Table 7 the wished that were collected are presented and colour coded in the same way as the requirements.

Table 6: Requirements on layout

Requirement	**Reason**	**Comment**
First electrolyte filling close to Cell Assembly	If transported too long distances sheets may misalign	True for all types of Li-Ion cells
Soaking after first Electrolyte filling	Battery chemistry	True for all types of Li-Ion cells
Second filling after soaking and precharge	Battery Chemistry	True for all types of Li-Ion cells
Electrolyte filling, precharge and degassing in a clean & dry environment	Process requirement	True for all types of Li-Ion cells
HT needs to be a certain temperature	Battery chemistry	Difference between cells
Tray exchange from aging trays to compression trays before formation and precharge	Cells need to be compressed	True for all types of Li-Ion cells
Number of formation cycles	Depends on recipe	Difference between cells
Time of pre-charging	Depends on recipe	Difference between cells
Soaking time	Depends on recipe	Difference between cells
EOL as last process	Process requirement	True for all types of Li-Ion cells

Table 7: Wishes on layout

Wish	Reason	Comment
Clean and dry room next to each-other if possible	Facility wish / Cost	True for all types of Li-Ion cells
High bay areas (soaking, HT, RT, Formation and precharge) close together	Facility wish / Cost	True for all types of Li-Ion cells
Formation areas close to factory wall	Facility wish	True for all types of Li-Ion cells
Minimize number of tray exchange	Material handling	True for all types of Li-Ion cells
Aging trays for HT RT soaking	Aging trays are cheaper than compression trays	True for all types of Li-Ion cells
Minimize number of equipment	Cost	True for all types of Li-Ion cells
Flexible process design to handle different recipes	Process requirement	Difference between cells

4.4.2 Waterfall Layout

The requirements that were used to create the waterfall layout can be seen in Table 6. The used process sequence can be seen in section 2.3.4. To be able to find the relationships between the different processes the sequence was mapped as can be seen in Figure 20

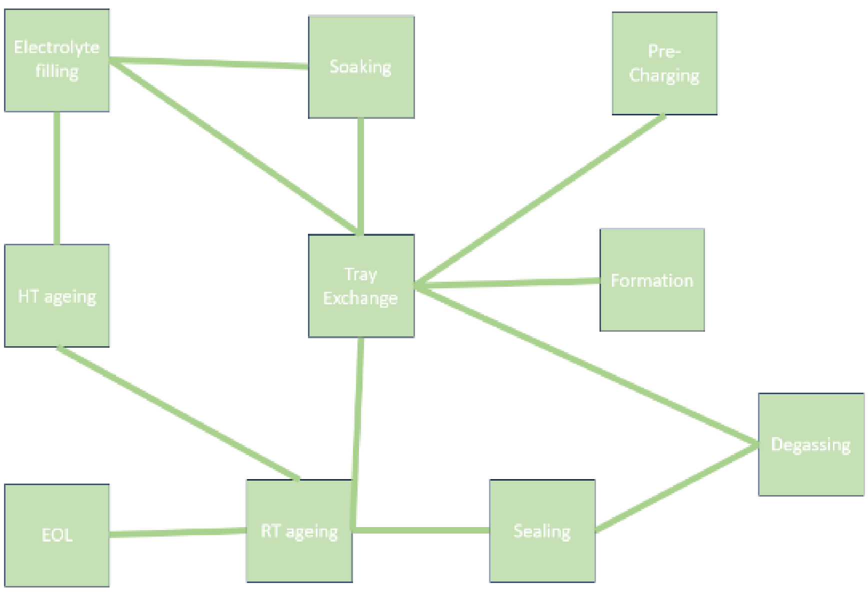

Figure 20: Relationship between the different processes

The final layout from using the waterfall method can be seen in Figure 21 where all of the requirements are fufilled and the wishes of having clean and dry rooms next to each other (visualized with red) and having high bay areas close together (visualized with blue) are included to an extent.

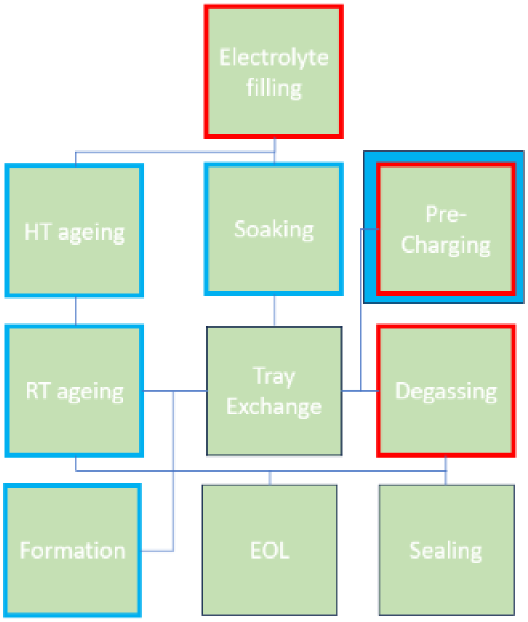

Figure 21: Waterfall Layout

As mentioned in section 3.6.6 the final layout were created in Autodesk AutoCad 2024 to make sure that it was a possible solution. Due to to confidentiality the equipment is covered with colorings blocks. In Figure 22 the changes that had to be made from the layout shown in Figure 21 was to change the position of soaking from the middle to the left side. This was due to that the process equipment were long and if it would have stayed in the middle it would have lead to that more footprint would have been needed. The end-of-line process were also pushed down due to its size to lower the foot-print while still having an optimised flow for one recipe.

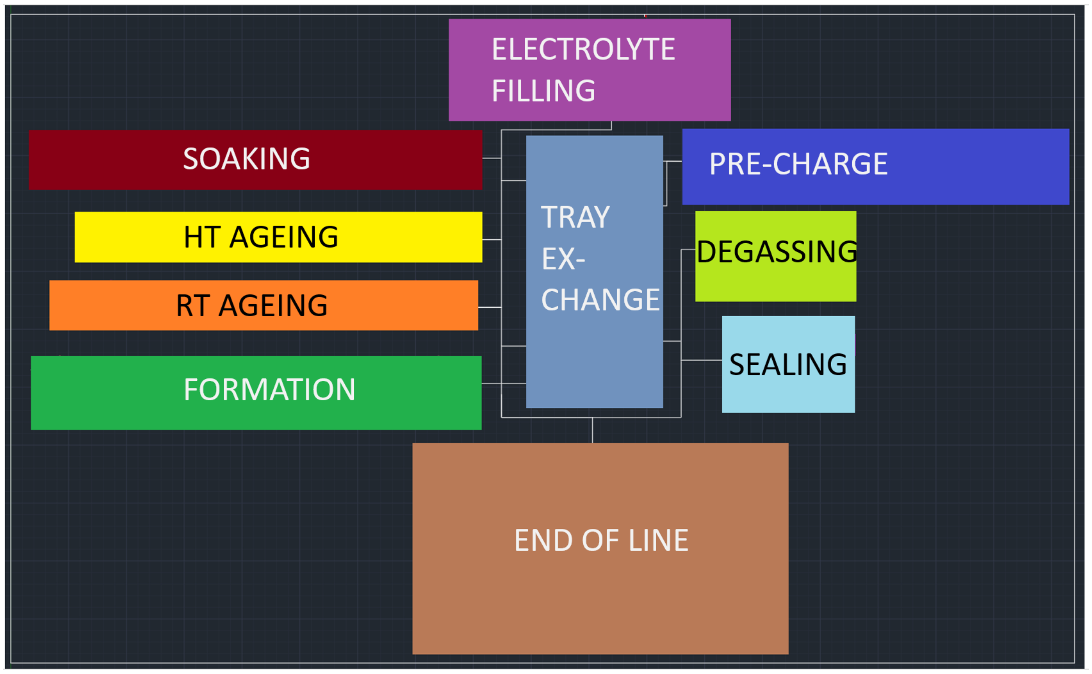

Figure 22: Waterfall Layout with further development

As mentioned in section 3.6.7 the layout were analyzed and the advantages and disadvantages for the layout is presented in Table 8.

Table 8: Advantages and Disadvantages of the Waterfall layout

Advantage	Disadvantage
Cheap	Created for a single recipe
Shorter lead-times	High cost for changes
Optimized (for a single recipe)	Uncertainties if changes are made during the project

4.4.3 Set-based Concurrent Layout

The results from the three different steps with the method are presented in this section.

1. Map the design base

Establishing layout options from the set-based concurrent engineering start with mapping the overall design base for the layout from the different functions. The design base is based on the requirements from the different functions within the company. This is based on interviews and discussions with relevant people within the different functions of the company as well as on the literature study which can be seen in Chapter 2. The different requirements for the different functions can be seen in Table 9-12 based on the original requirements list. The layouts are also based on the process sequence in Figure 7 in order to develop the overall flow of, however since the overall goal is to create a layout that can be able to handle different prismatic Li-Ion batteries the layouts also have to consider a changed process sequence.

Table 9: Process Requirements

Requirement	Reason	Comment
First electrolyte filling close to Cell Assembly	Process requirement If transported too long distances sheets may misalign	True for all types of Li-Ion cells
Electrolyte filling, precharging and degassing in a dry environment	Process requirement	True for all types of Li-Ion cells
EOL as last process	Process requirement - Vital for quality control	True for all types of Li-Ion cells
Second filling after soaking and precharge	Process requirement: Battery chemistry	True for all types of Li-Ion cells
Number of equipment	Depending on product design	Difference between cells
Limited space for more formation chambers	Depending on product design	Difference between cells
Minimize number of equipment	Process wish: Reduce cost	Difference between cells
Flexible process design to handle different recipes	Process requirement	Difference between cells

Table 10: Product requirements

Requirement	Reason	Comment
HT needs to be a certain temperature	Product Design: Battery chemistry	Difference between cells
Second electrolyte filling	Product Design: Battery Chemistry	Difference between cells
Number of formation cycles	Product Design: Battery chemistry	Different numbers of cycles depending on cell
Number of formation and precharge chambers	Product/Process requirement Depends on recipe	Difference between cells
Time of charging	Product/Process requirement Depends on recipe	Difference between cells
Soaking time	Product/Process requirement Depends on recipe	Difference between cells

Table 11: Material Handling Requirements

Requirement	Reason	Comment
Tray exchange from aging trays to compression trays before formation and precharge	Cells need to be compressed	True for all types of Li-Ion cells
Aging trays for HT RT soaking	Aging trays are cheaper than compression trays	True for all types of Li-Ion cells
Minimize number of tray exchange	Material handling	True for all types of Li-Ion cells
Minimize work in progress	Material handling	True for all types of Li-Ion cells
Minimize distances	Material handling	True for all types of Li-Ion cells

Table 12: Facility Layout Design Requirements

Requirement	Reason	Comment
Electrolyte filling, precharging and degassing in a dry environment (close to each other)	Expensive to have too many separate clean and dry rooms.	True for all types of Li-Ion cells
Formation chambers close to the wall	Less expensive to cool	True for all types of Li-Ion cells
High bay areas (soaking, HT, RT, Formation and precharge) close together	Utilize floor space efficiently (cost related)	True for all types of Li-Ion cells

From these requirements an alternative layout was created for each function in order to find an optimal layout design for each department in order to generate sets of possibilities within each area. The layouts are presented in Figure 23-26. The next step in the set-based concurrent project model was to find feasible intersections between the layouts in regions where the independent layouts overlap between the functions for the different requirements. This was done using an evaluation design matrix based on the functions and most important requirements between the functions. This is done to explore trade-offs between the different functions and how interest of the design might intersect between them.

During the first stage simplified layouts were created since the set-based concurrent method aims to handle several different alternatives from the functions. Therefore the level of detail during the first layout-generation is created using blocks with no dimensional considerations and no factory walls. This is also mainly done in order to delay making decisions in early stages to increase the overall flexibility and optimization of the factory when more parameters are known in order to handle complexity and uncertainties as long as possible.

The first generated layout was from the process perspective which listed several types of requirements both based on cell type and process design which can be seen in Figure 23. The red boxes around the processes indicate that the process is occurring in a clean and dry room.

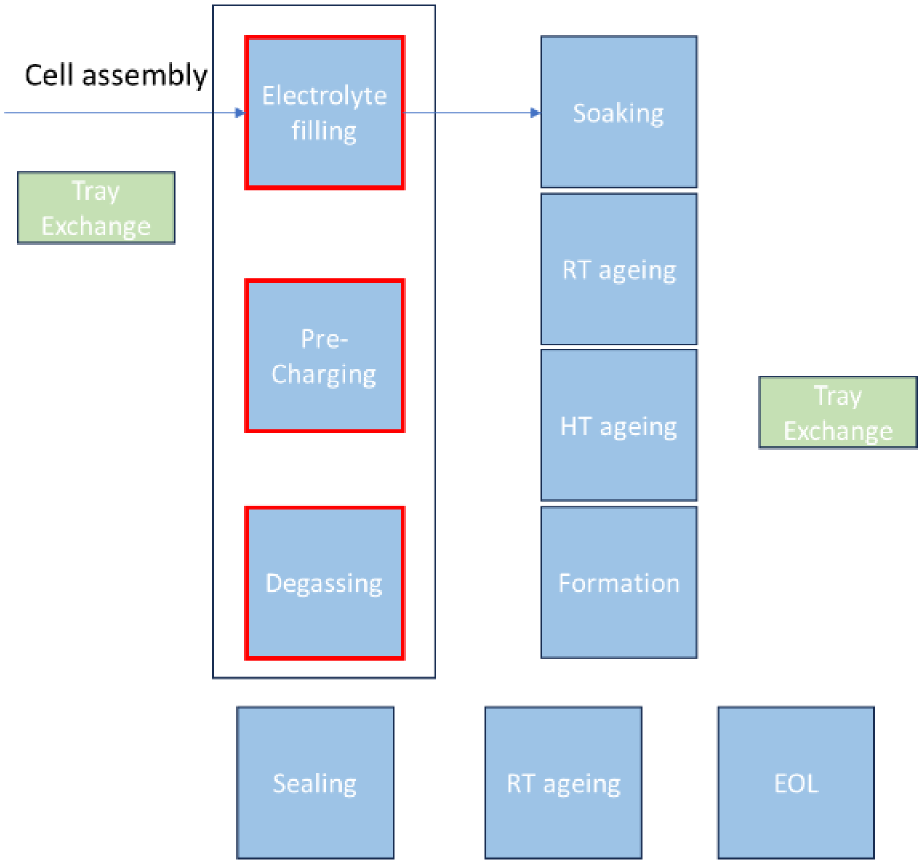

Figure 23: Process Function Layout

The second generated layout was for the facility function requirements which can be seen in Table 12. As can be seen in Figure 24 the generated facility layout meets the requirements for the facility by having modules for the aging and clean and dry-room as well as providing the formation chambers at the outer perimeter. Therefore the layout is optimal for this function's requirements and is used in later stages to find an optimal system solution.

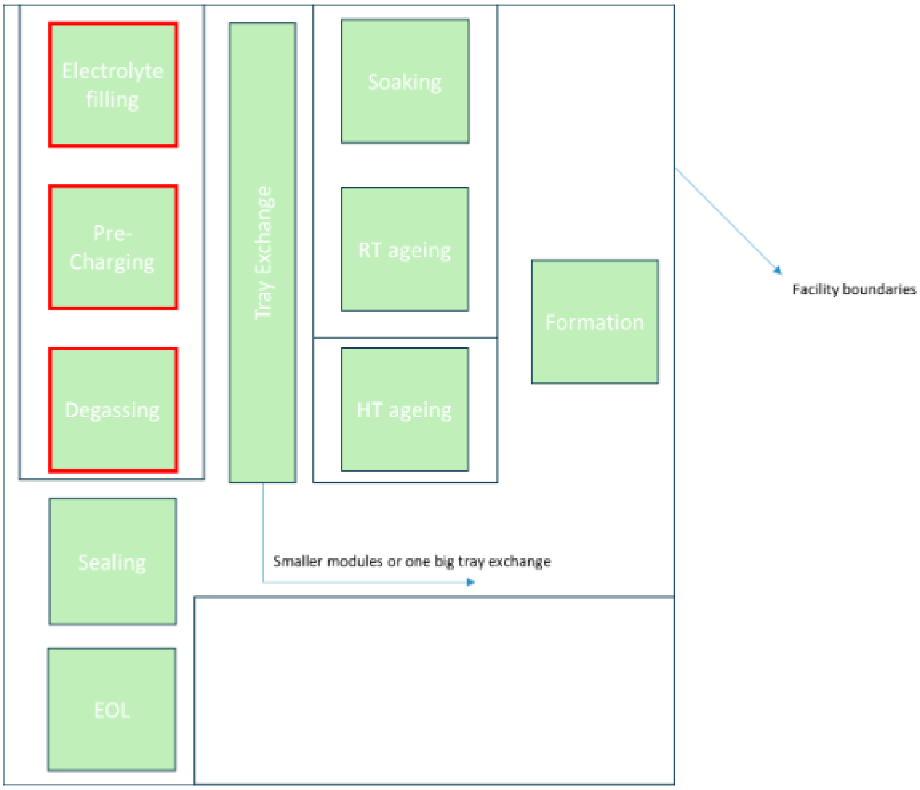

Figure 24: Facility Function Layout

For the R&D or the product function there are several requirements from Table 9 that depend on which type of battery cell type which is produced. Therefore an optimal solution for the product function would be a flow where the process steps can be altered depending on cell type. An optimal solution here would therefore be to use a conveyor system that handles the transportation between the different processes in non-linear steps if necessary in order to create flexibility. The layout generated for the product/R&D function can be seen in Figure 25.

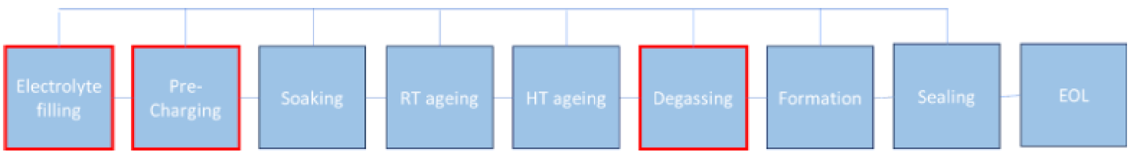

Figure 25: Product Function Layout

The material handling requirements, see Table 11 were less developed in terms of strict requirements and is mainly focused around tray exchange between the different processes and how to optimize them. However, parameters of optimal flow and inbound/outbound logistics were also considered during the layout generation. The material handling function layout can be seen in Figure 26.

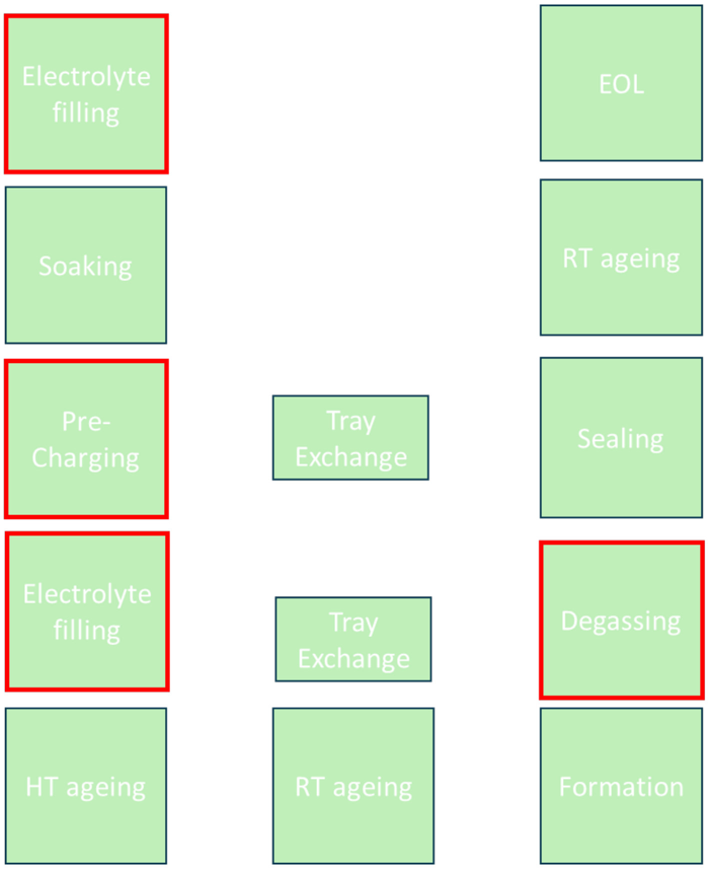

Figure 26: Material Handling Function Layout

2. Integrate by intersection
After the layouts were created for the different functions the next step in the set-based concurrent method was to find synergies and intersections between the different layouts. This was done by using an evaluation matrix in order to determine the different layouts. The matrix consists of each of the specific requirements from Table 6 in the rows, as well as the different layouts from the different functions in the column. They were then evaluated with regard to the requirements in terms of optimal, acceptable, marginal and unacceptable for each different layout. A fraction of the evaluation matrix is illustrated in Figure 27, and the whole evaluation matrix is attached in Appendix C.

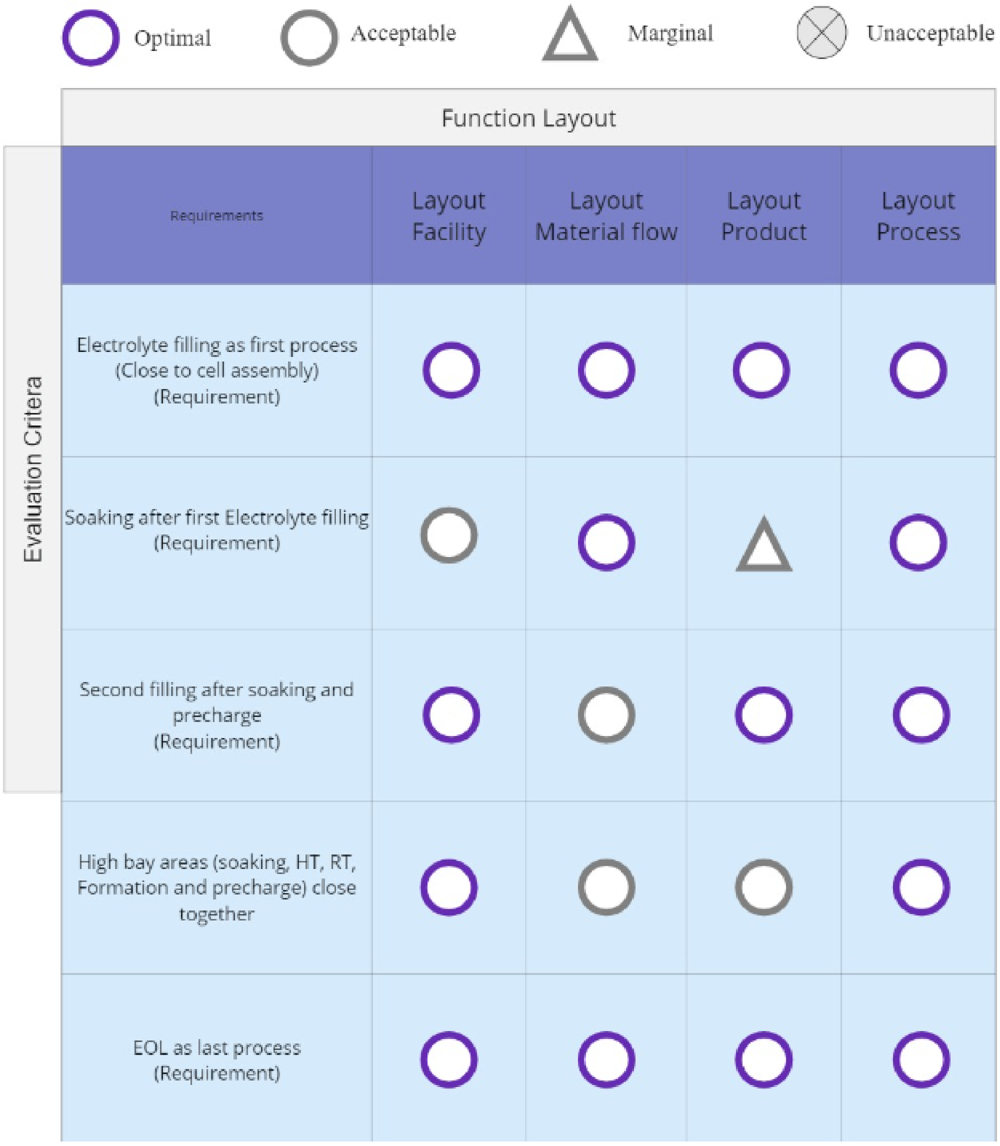

Figure 27: Evaluation matrix for the function layout design

The evaluation matrix was then used in order to find feasibility and intersection between the layouts, for instance, we could see in Figure 27 that all layouts fulfilled the requirements of having electrolyte filling as a first step as well as having the EOL as a last process step in an optimal way. But for other requirements, some layouts had optimal design for that specific requirement. The evaluation matrix was the foundation for finding convergence and optimal layout design for the cell finishing area with the set-based concurrent method. This made sure that an optimal layout could be developed and the set-based concurrent method as a tool to avoid sub-optimization.

By using the results from the evaluation matrix a layout was created by the intersections that were found. This ensured that all the requirements and wishes were discussed and evaluated. The result from this layout can be seen in Figure 28

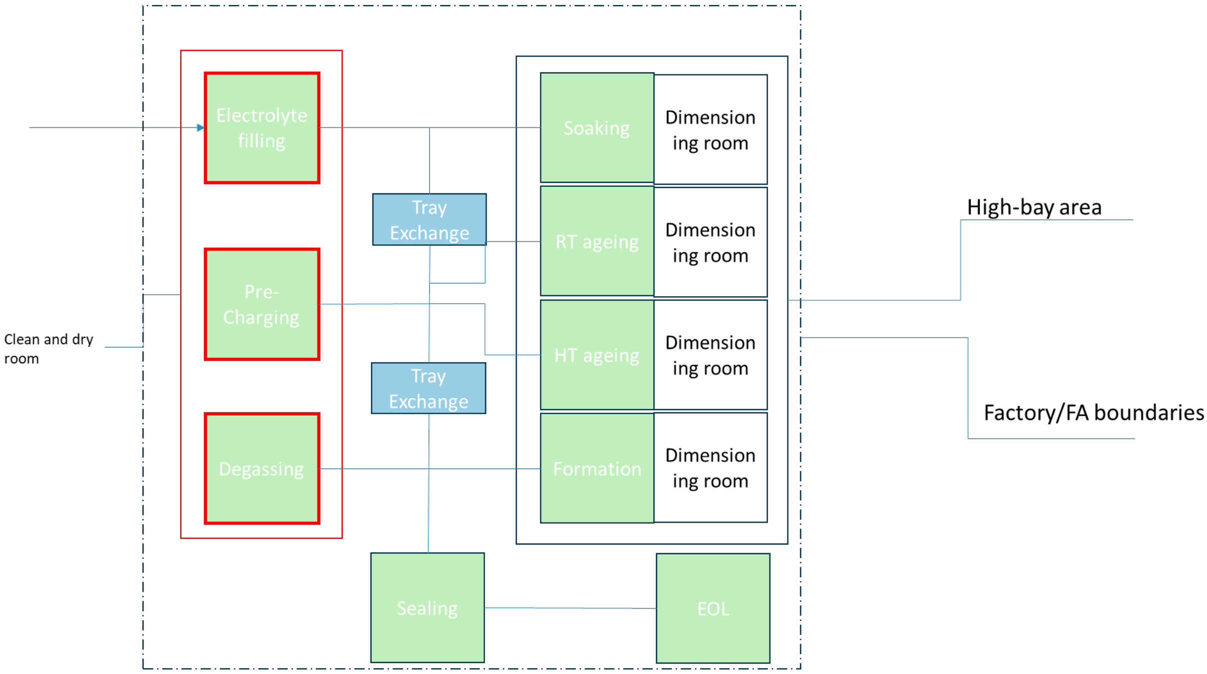

Figure 28: Set-based layout after intersection

3. Establish feasibility before commitment
In order to test the feasibility of the layout generated a workshop was conducted with relevant people at NOVO Energy which consisted of layout, process and material flow engineers with insights within the thesis. During this workshop the project models and the process of generating layouts were presented. Further, the layouts were discussed and analyzed in order to find potential improvements and find a more optimal system solution based on experience between the functions.

After the workshop the set-based layout were modified from the workshop results, in order to improve the layout further. This was done in order to avoid mistakes and factor in previous knowledge and experience from employees. The main difference of the improved layout was that pre-charging occupied more space and needed to be seperated from degassing while electrolyte filling were moved to the top of the layout. The improved layout can be seen in Figure 29.

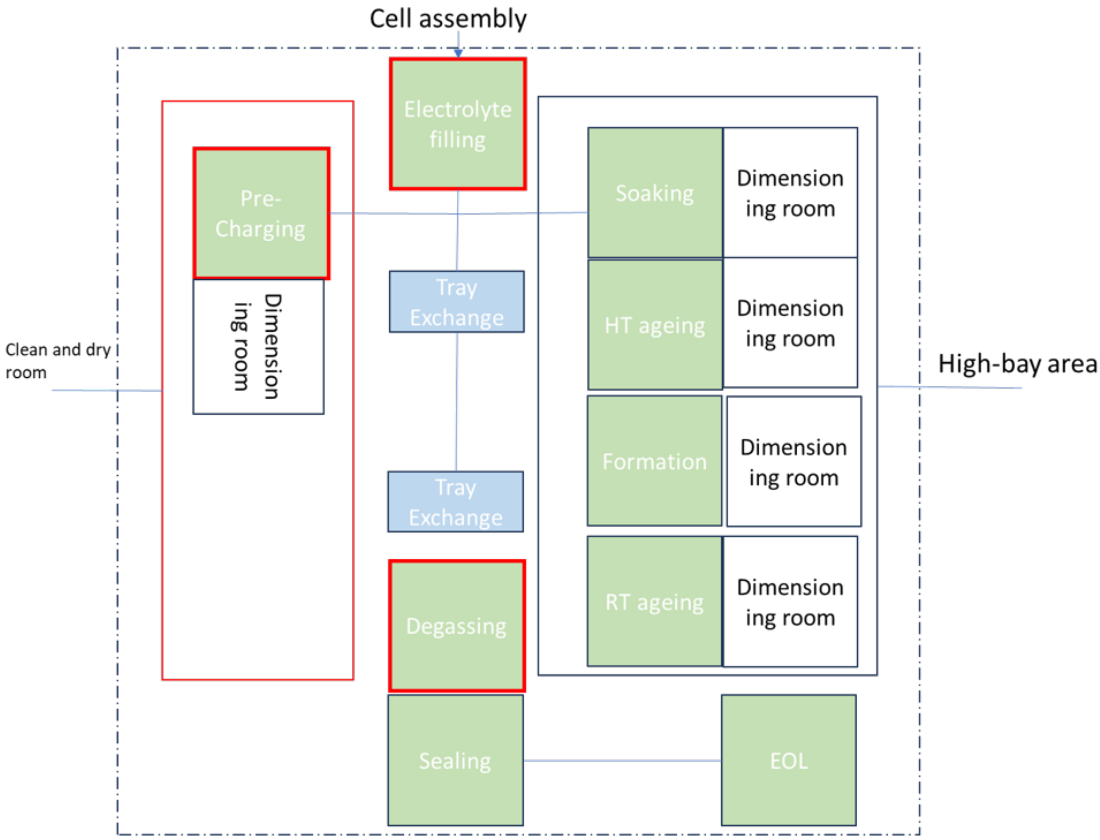

Figure 29: Set-based layout after workshop

After the first layouts where generated with help of the different project models the next step was to increase the detail of the layouts as mentioned in section 3.6.6 which can be seen in Figure 30. Due to confidentiality the equipment is covered with colorings blocks. In Figure 30 several changes has been made compared to the layout in Figure 29. These mostly included adopting the actual dimensions of the machines in order to optimize the layout. Compared to the layout in Figure 29 the pre-charging were to long so it was moved to the other high-bay equipment. Further, electrolyte filling, tray exchange, degassing and sealing are aligned on the left-hand side. This is overruling the wish of electrolyte filling, pre-charging and degassing close to each-other since they are in clean and dry-rooms but enhances the wishes of high-bay areas close together and better material flow.

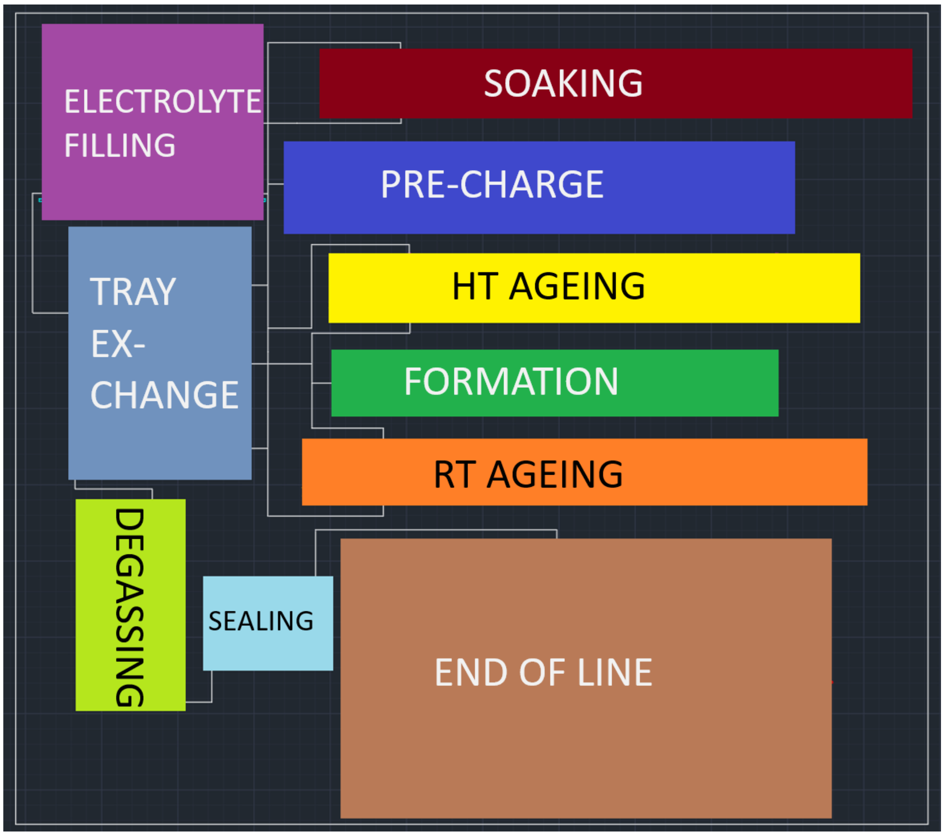

Figure 30: Set-Based Layout with further development

As mentioned in section 3.6.7 the layout were analyzed and the advantages and disadvantages for the layout is presented in Table 13.

Table 13: Advantages and Disadvantages of the Set-based layout

Advantage	Disadvantage
Integrates all functional requirements and needs within the layout	More work in progress depending on recipe
A robust layout which could handle moderate change in product without relayout	Could be longer lead-times to implementation due to the collaboration and longer initial phase
Optimized system performance	Not flexible for all types of product changes

4.4.4 Agile Layout

By using the agile methodology described in section 3.6.5 the first layout that was created based on the requirements that are the same for all prismatic Li-Ion batteries and the fact that the recipe is unknown can be seen in Figure 31. The red boxes around the processes are indications that the process is taking place in a clean and dry room.

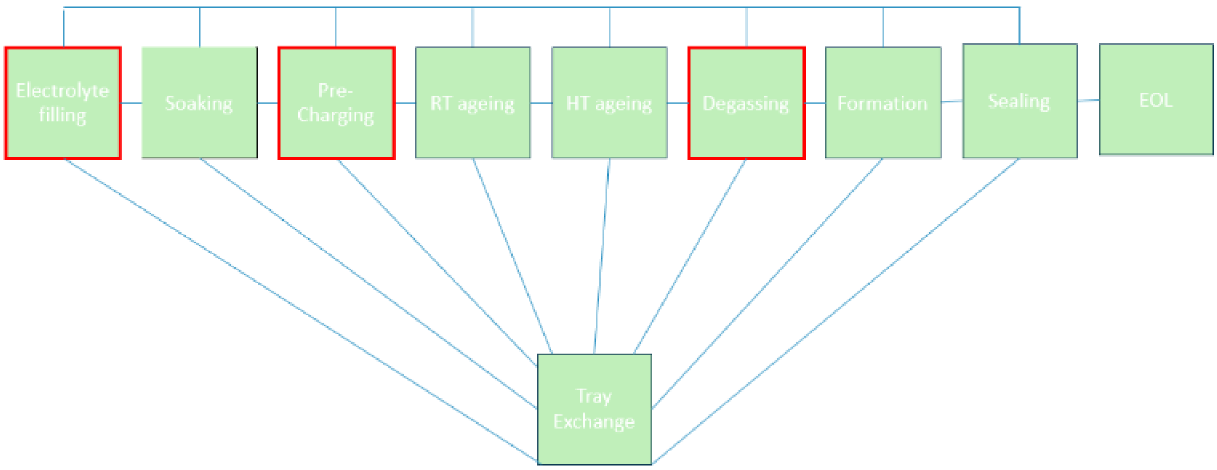

Figure 31: Layout based on the requirements

With the layout shown in Figure 31 as a base, new layouts were iteratively made based on the requirements that differ between different recipes of Li-Ion batteries. All of the layouts that were iteratively made can be seen in Appendix D.

The final agile layout that was created by using the agile methodology can be seen in Figure 32. The blue boxes around the processes indicate that the process is occurring in a high-bay area.

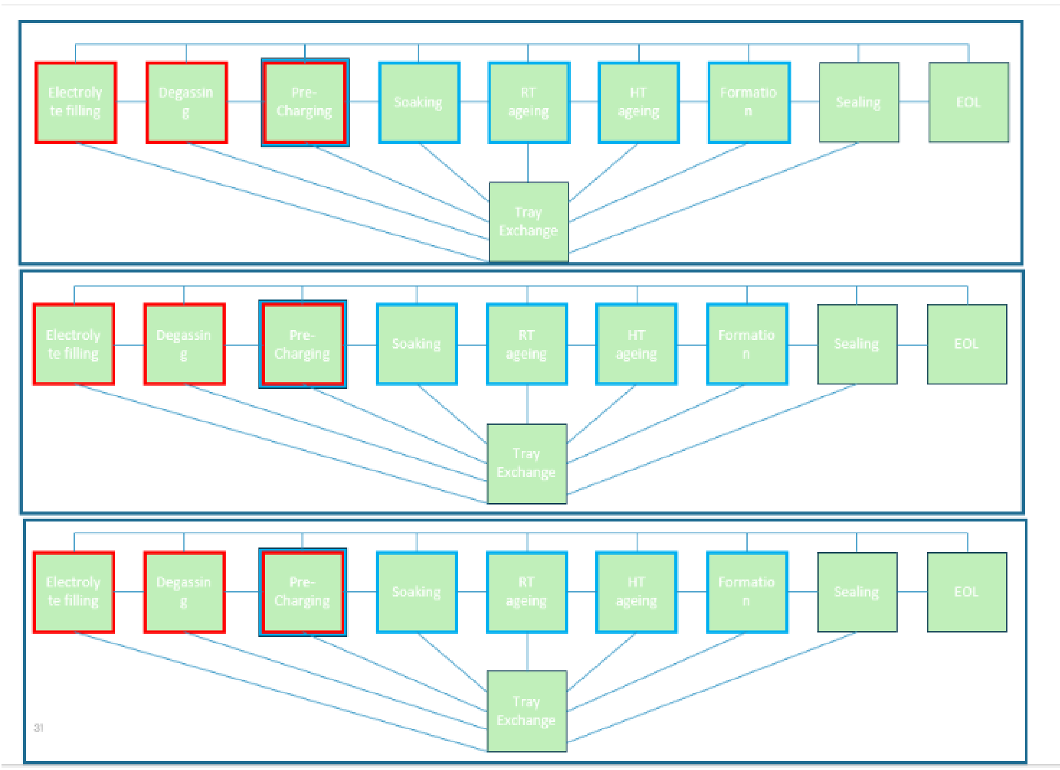

Figure 32: Agile Layout

After that the final agile layout was generated it was created in Autodesk AutoCAD 2024 as mentioned in section 3.6.6. Due to confidentiality the equipment is covered with colorings blocks. In Figure 33 the agile layout is presented, in comparison with the layout in Figure 32 the only change is the position of the modules. The layout in Figure 33 shows that there is more empty space within each module under electrolyte filling, degassing and pre-charing which could for instance be used for maintenance or to expand the processes further in the future.

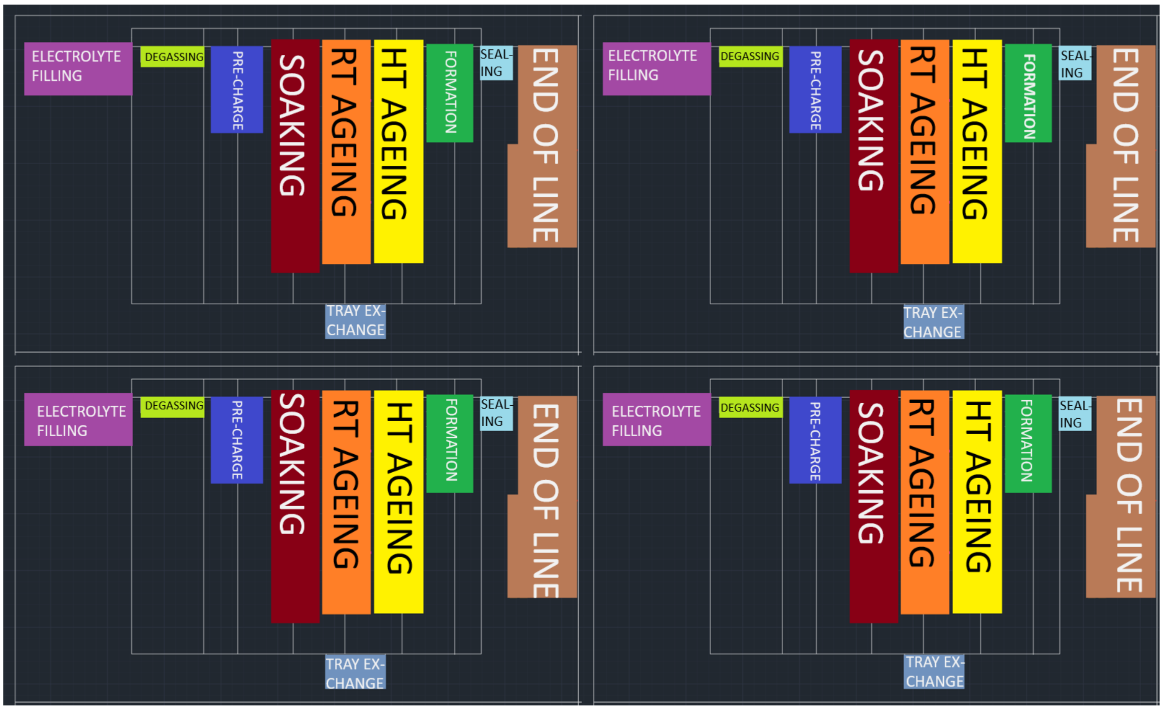

Figure 33: Agile Layout with further development

As mentioned in section 3.6.7 the layout were analyzed and the advantages and disadvantages for the layout is presented in Table 14.

Table 14: Advantages and Disadvantages of the Agile layout

Advantage	Disadvantage
Flexible	High initial cost
Changes could be made to one module at a time	More conveyors which leads to a bigger footprint
No need for re-layout	Increased material handling

4.4.5 Comparison between the methods

The different project models that were used were also analyzed in regards to each other which can be seen in Table 15. The different aspects that were analyzed are all of importance within the battery cell manufacturing industry and as the three models are different in their nature and used in different industries the comparison gives a deeper understanding of why the layouts became different.

Table 15: Method Comparison

Aspect	Waterfall	Set-based	Agile
Cost	Low	High	High
Time demand	Low	Intermediate	High
Flexibility	Low	Intermediate	High
Level of involvement	Low	High	High
Level of collaboration	Low	High	High
Structure	Sequential	Semi-iterative	Iterative
Ability to handle changes	Low	Intermediate	High
Level of documentation	High	High	Low

As seen in Table 15 the methods have different advantages and disadvantages which are further discussed in Chapter 5. Due to the iterative nature of the set-based concurrent and agile project model compared to the more sequential nature of waterfall there are several differences between the methods for layout generation. Iteraiton drives cost, time demand and requires larger level of collaboration and involvment in the process. While in return, it could prove to minimize late changes and consider all relevant requirements before making decisions. Looking at the aspect of flexibility it can be seen that the waterfall method has a low flexibility which is also true for the layout that can be seen in Figure 22. For the set-based and agile method the results shows that they are intermediate and high within the flexibility aspect which is also true for their final layouts. The structure of the different methods are also very different, which can be of value in different situations. As mentioned in section 3.7 the different methods have been modified to suit the purpose of the thesis but their original structure remains the same which shows that different methods can be used for the same situation but that the outcome will become rather different depending on which one that is used. In section 5.2, 5.3 and 5.5 the methods are further discussed. In section 5.7 a further discussion regarding combinations of the models are discussed.

5

Discussion

In this chapter a discussion about the different methods, the generated layouts and other possible solutions are presented as well as answers to the research questions. First the different project methodologies and the generated layouts are discussed and then the research questions are answered. After that a further discussion regarding the research methodology as well as ethical, societal and ecological perspectives. The last section of the chapter regards the future battery cell factories and further research topics that is of interest for the future.

5.1 Waterfall methodology

In the waterfall methodology the customer's needs has to be clearly defined before the product design and factory layout can be created which is a problem in situations when the construction of the factory is occurring before the product design is finished (Thesing et al., 2021). As the scenario for this thesis is that the product and its design is still under development while the factory is being built the layout has to be based on what is known at the time, for example an earlier cell type. As mentioned in section 2.4.1, one of the negative aspects of the method is that it doesn't cope well with late changes and if the customer needs are changed during the project it would lead to high costs (Petersen et al., 2009). In the scenario used there is a high possibility that changes to the product would occur which would mean that the whole project would have to be redone from start as a new recipe would mean that the process sequence would most likely change or that the dimensions of the process equipment would have to change.

As the methodology has five different phases that are carried out in a linear manner a positive aspect is that nothing will be missed during the project, all of the needed processes and equipment will be included etc. as the next phase requires a deliverable from the previous phase (Model, 2015). This can both be an advantage as nothing is missed but it also means that it can be time consuming if information is unknown or if there are uncertainties regarding the project. In an industry such as the battery cell there are a lot of uncertainties as the development of batteries are complex and as the batteries are developed from A-sample to C-sample, changes can be made along the development phases (Örüm Aydin et al., 2023). Therefore the use of the waterfall methodology is better suited for more mature industries and could be a potential method to use when the industry has become more stabilized. As there are many examples of the waterfall methodology used within other industries it should not be disregarded within the battery cell industry, but wait to be used until the industry is mature enough.

5.2 Waterfall Layout

Looking at the generated layout that can be seen in Figure 22, the chosen one has fulfilled all of the requirements as well as some wishes, but it is based on a single prismatic Li-Ion cell recipe that could be changed over time.

One of the positive aspects of the layout is that it is optimised in terms of equipment and material handling which lower the costs for the manufacturing company but on the other hand if the recipe were to change there would be a high cost of remaking the layout. As layouts are usually designed for the initial conditions and the information that is known at the time, it is of value to regard that both internal and external changes may occur and in those situations, a re-layout may be necessary if they haven't been regarded beforehand (Monga & Khurana, 2015). Therefore a robust layout may be more suitable in a situation where the waterfall methodology is used for layout purposes in an uncertain environment as the robust layout is able to fulfill a wide range of product requirements (Lahmar & Benjaafar, 2005). On the other hand, a robust layout approach would lead to higher costs as more equipment is needed but at the same time, costs of rearrangements are reduced (Pillai et al., 2011).

The final waterfall layout also includes some unused space which can be seen in Figure 22 besides electrolyte filling, under formation, and under pre-charge. This space could therefore be used for other areas that are needed within battery cell manufacturing such as maintenance, quality, break-rooms, and packaging, but as this thesis has been focusing on just the processes those further areas have not been included. It could also be used for further expansion of the processes if needed. If on the other hand, those areas would not be used for anything it would be a waste of space and therefore the layout should be re-made to lower the footprint of the cell finishing processes.

As the layout is created for a single recipe the flexibility to change to another recipe is limited, one way this could be increased is by increasing the number of conveyors between the different processes so that the material flow easier can be changed. This would however lead to an increased cost for the company and if changes to the product aren't invested conveyors will be a waste.

5.3 Set-based Concurrent method

One benefit of the set-based concurrent method is that it aims to utilize an extensive planning period of the project in order to minimize and avoid late changes within the project (Sobek et al., 1999). This is a benefit when trying to remove complexity and removing early-decision making in order to handle new requirements and changes associated with the process and layout design and could be more beneficial compared to the waterfall-method to delay decisions (Stjepandi et al., 2015).

Another major benefit of the set-based concurrent method is that it provides a systematic and strategic method in how to generate and create layouts from an early stage. It provokes the different functions to cooperate in order to find an optimal system solution instead of sub-optimizing the layout for different needs and develops a need for constant communication for the different functions (Sobek et al., 1999). This means that new requirements that affect the system can be discussed earlier and late changes can be avoided, which reduces the overall cost of the project.

Concerning layout flexibility the set-based concurrent method does not specifically aim to handle a flexible layout and process design. However, the method is based on keeping alternatives open to a late stage and handling different needs and requirements that occur during the process of building a factory (Sobek et al., 1999). The design process is also determined by which requirements or design base you have, therefore level of flexibility for the layout needs to be considered at an early stage of the factory development to be considered an option. Therefore, there is a need to determine long-term strategies as well when using this project method

The drawback of the set-based concurrent method is that it could potentially increase lead-time compared to more traditional methods as more time is spent on the initial project phase generating sets of alternatives. However, the approach could also reduce lead times during the later stages if there is a reduction in late changes based on a more iterative approach compared to more traditional methods (Sobek et al., 1999). This is however very dependent on the complexity of the project and how well the project can be estimated beforehand.

One main issue with layout generation based on the set-based concurrent method is that the requirements from the different functions can be updated and changed during the long process of building and developing a battery cell manufacturing plant and related production system. The set-based concurrent method can handle part of this complexity by iteration of the steps and to generate good system solutions at an earlier stage compared to traditional methods while still narrowing the solutions as time progresses. However, if new product-specific requirements occur during late stages that are not apparent when considering the flexibility the project model does not support the changes.

5.4 Set-based Concurrent Layout

The final layout that was iterative generated through the set-based concurrent layout method had a good intersection between the different functions' needs and wants while still enabling a great system performance. The layout could take into account every different requirement and wish that was established in section 3.6.2 and generate viable options for each different function while finding the best intersection points between the different layouts. This resulted in that no requirements and wish being left out when generating the full system. Also, several important changes could be made during the iteration phase from both the evaluation matrix as well as the workshop with employees. As the evaluation matrix considered "hard facts" and the workshop could account for previous experience and real-case scenarios the combination of these methods enhanced the overall layout generation and could account for several important aspects that would otherwise be left behind. Therefore, an important aspect when using the set-based methodology is to thoroughly iterate and to have a constant cross-functional discussion in order to establish important requirements and wishes early and also discuss them continuously to generate good alternatives.

It was also important to increase the detail of the finalized layout in real-life scenarios in order to spot issues and improvements that were hard to consider during the initial phase. When creating the layout in Autodesk AutoCAD 2024 several issues and potential improvements were discovered since the layout had to be altered to fit the dimensions and characteristics of the real-life equipment. Compared to the waterfall-layout the end-result was a production system that occupied much less space and could utilize this excess space in order to over-dimension several pieces of equipment if needed but also build exaggerated conveyors if needed if the product recipe would change in the future.

The overall layout also generated a good flow of products while implementing conveyors in order to transport products to different processes if any change occurred to the recipe. This could be further developed and with modular conveyors, the layout performance could probably still be very streamlined while also handling changes.

A negative aspect of the finalized layout was that it could not fully handle the wish of having all processes within the same clean and dry room as it would result in a poorer performance of the system and much more unutilized space. However, every other requirement and wish could be fulfilled with different levels of commitment.

However, since the method required a better system performance rather than fully optimizing specific function needs the wish for flexibility was not exaggerated. This could have been avoided if flexibility had been more important for all the different functions. However, in actual use-cases there is a need to consider factors for all functions and therefore the finalized layout result. However, the final layout is robust and incorporates room for additional processes and capacity of processes. The final layout also incorporates conveyor systems that could potentially be used in order to handle fluctuations in the recipe, both by using modular conveyor systems which is in line with the RMS approach which is seen in section 2.1.3 or by having an automated conveyor hub.

5.5 Agile Method

The agile methodology has been proven to solve complex issues and adapt fast to new changes (Marnada et al., 2022). As the agile methodology is most effective in situations where the problem that needs to be solved is complex and the possible solutions and product requirements are unknown it fits the scenario problem well (Rigby et al., 2016). In the scenario that this master thesis is using the situation is complex due to the fact that the product is not defined before the construction of the factory begins and the factory layout has to be made. But as the agile methodology was developed for the software development industry some modifications were needed to suit this purpose (Heimicke et al., 2021). As the method had to be modified to suit the project's purpose the results should not be seen as fully agile as for example a full Scrum was not conducted as well as certain traditional scrum rolls were excluded.

The agile methodology is known for being flexible and fast to respond to changes which suited the scenario for the thesis (Tena. et al., 2020). As the methodology took in regard all of the requirements that are the same for all prismatic Li-Ion batteries in the beginning and based a layout on that as well as the fact that the recipe is unknown the base layout could be seen as a good start for further iterations of development.

The iteration process regarded the defined requirements that could differ for different types of prismatic Li-Ion batteries, in this case when different processes could change the decision was to duplicate the process, but it is important to notice that the requirement change could also mean that the process could need less space or equipment.

Another aspect of the agile methodology that should be taken into account is that it is usually well-suited for smaller teams, and could potentially lead to problems when the team-size grows. During this project, the team-size has been relativity small, around five to seven people, but in an organisation with over a hundred people involved the methodology might not be as well suited.

5.6 Agile Layout

The final layout that was generated from the method is a modular layout which could accommodate changes in the recipe presented in Figure 5. By using a modular layout where multiple modules can produce the needed cells, changes could be made on only one module at first to try new ideas or recipes before implementing them in all modules. This would then mean that not the whole production would need to be shut down during the changes, but rather that the other could produce as normal until the change is sure to be a good thing to implement in all modules (Burggräf et al., 2021).

A negative aspect of the agile layout is that there is a higher number of equipment which goes against the wish of minimizing the number of equipment. On the other hand the equipment will be smaller in size instead of having bigger machines to be able to produce the wanted capacity. Therefore it could be argued that the only thing that takes up more footprint is the increased number of conveyors that are needed between the equipment.

One of the advantages of the agile layout is that if there is a change in product mix the different modules can be used to produce different cells as it is possible to make changes to only one of the modules. That could strengthen the battery cell manufacturers' competitiveness in the market if there is a need for different recipes of prismatic Li-Ion cells.

5.7 Combination of methods

The planning of a factory layout is a complex process due to the many possible solutions (Klar et al., 2023). As can be seen in Chapter 4 the same part of a battery cell factorys layout can look different depending on the known information and the methodology used. By analyzing the three final layouts none of them are following any of the traditional layouts that are mentioned in section 2.5. In comparison with other parts of a battery cell factory such as Cell Assembly where the process sequences are standardized and performed in a linear manner, a line flow layout is suitable. In Cell Finishing the process sequence can change depending on the product design and therefore a line flow layout would not be a suitable choice as it is inflexible and sensitive to disturbances (Bellgran & Säfsten, 2010).

The choice of project model for the layout creation also affects the budget of the project. The waterfall layout is assumed to be a cheaper layout than the others, but it could also come with high costs for re-layout if changes are made to the cell. However, the set-based concurrent method requires a much larger initial process as it is based on generating a large number of alternatives which could lead to more initial costs but could in theory also reduce rework if more parameters are considered early in the project. The agile layout further increases the iterations and can be more expensive as an initial cost while it is reducing the need for re-layout in case of changes which will lead to a lower cost long term.

The waterfall and agile methods could be seen as opposite each other due to the structured way of the first method and the more flexible way in agile which is illustrated in Table 15. Therefore it is hard to make a combination of them to create a single method. On the other hand, a combination of the waterfall and set-based methods could lead to a structured way of collaborating between different functions which could result in deliverables of high quality being delivered between the different steps. It could also lead to a high level of collaboration between the different functions through the whole project which could lower the risk of misunderstanding but on the other hand could lead to longer project times to make sure everyone has the same understanding.

Using the agile and set-based methods together could mean that the working teams that are collaborating in the set-based method would be smaller and meet more often if they incorporated the agile way of working. This could lead to shorter lead-times and higher productivity.

5.8 Answer to research questions

This thesis has been investigating how different project models can help increase the flexibility of battery cell manufacturers factory layout. With the previous chapters as a base the questions that were stated in section 1.3 are answered below.

RQ1: How can the use of project-models increase the flexibility of battery cell factory layout design in order to handle fluctuations in customer needs, product, and process design?

The flexibility of the factory layout for battery cell manufactures could be increased in different ways depending on which method is chosen.

By using the agile method the flexibility would be increased the most due to the ability of changes within the modules while the set-based on the other hand addresses the set-up requirements in order to find a flexible design. By using the set-based layout the flexibility is mostly handled by a robust-layout which enables the product to be transported to different sections depending on recipe. The layout design also incorporates specific processes where the recipe can be changed close to each-other which decreases the throughput-time if the change occurs.

The waterfall method could also be used to increase the flexibility of the layout, but only if it is done together with RMS so that changes could be made to the manufacturing system rather than the layout. As the waterfall method is sequential and works in a linear manner late changes to the layout would not be possible and therefore isn't a suitable option if flexibility is the aim.

RQ2: What is the value for the company and industry to increase the flexibility of the factory layout design?

Depending on which of the models that are used there are different things that are valuable to the company.

The waterfall methodology would increase the structure within the company and lead to that nothing is missed. On the other hand the flexibility wouldn't be as high as with the other models which argues for that the value in terms of flexibility is low if changes needs to be made but if no changes are needed the value is the lower cost.

If the set-based concurrent method is used the value is that the company is provided a well-established project model that could create a better structure on how to approach large projects. It would also ensure that the company would incorporate the different function needs at an earlier stage ensuring that consistent discussion and establishment of feasibility could be ensured. The value of this would also ensure that the creation of a layout could be created with less emphasise on experience and "guesses" and provide a more data-driven layout. Depending on the overall strategic goals of the company, flexibility could be enhanced and made important during the early steps of layout generation and would ensure to incorporation of this in the layout.

The agile model gives the company the value of being flexible and able to change one module at a time but it is estimated to be a more expensive initial investment. The value of the agile layout arises if there are changes made to the products because then there would be no need for re-layout. If there isn't a need to change the layout the cost of the agile layout could on the other hand be seen as unnecessary due to the bigger investment cost.

5.9 Research Methodology Discussion

The methodology that has been used in this project was based on an inductive work process to be able to answer the explorative research questions. The work-structure was divided into five different phases in which an iterative process was used for phases two, three, and four. The advantage of the methodology was that it provided the thesis with thorough information on batteries, project models, and layouts through different research papers. This information and knowledge could then be evolved with the interviews held with employees at NOVO Energy further enhancing the knowledge. This also resulted in that both academic papers and real-life scenarios and experiences of actual use cases could be utilized. This was useful when using the different project models in order to generate layouts.

The primary aim of this research was to employ triangulation as a methodological approach, ensuring a comprehensive and dependable analysis. To achieve this, various theories were investigated, drawn from diverse sources, and employed multiple methods. This approach enhances the robustness and credibility of the findings, contributing to a more thorough exploration of the subject matter in this thesis. In Chapter 2 several different theories from project models and layout generation from different peered resources were investigated while also using different methods like interviews and workshops in order to validate them. This resulted in a comprehensive understanding of the subject and phenomena.

For the project models that were used to create the three methodologies to generate layouts, some modifications had to be made to suit the purpose. Therefore, the different project models were analyzed in the context of how they could be used for layout generation instead of the intended purpose. This was based on the previous research done in Chapter 2. The overall changes in the project models mostly revolved around contextualizing the different steps by alerting the "product" focus to the layout focus. This made the three project models very suitable for generating different layout options.

A factor to consider when evaluating the different methods is that due to the limited scope of the thesis, not every single requirement was considered when generating the different layouts. It could also be that different employees would have defined different requirements. Another aspect is that typically these kinds of projects are generated over several years, while the thesis project spans over several weeks. This means in a more industrial setting the layout would likely be iterated and developed repeatedly. Therefore, the results of the layouts could have been different under these settings.

One potential improvement in the methodologies would be to also consider how important each requirement is for the finalized layout. One way to implement this would be to provide a score for each requirement in terms of how vital it is for the specific case and could therefore change the outcome of the methods. However, since this thesis aims at exploring flexibility within the layout design these parameters were not included, but would however be suitable in a real-life scenario.

5.10 Ethical, societal and ecological perspectives

As there is an increasing demand for EV's the production of electrical battery cells needs to increase (Duffner et al., 2021). To be able to reach the climate goals more battery cell factories are needed and they need to be built fast. Developing new battery factories plays a crucial role in the transport sector's transition in decarbonization by replacing fossil fuels with battery cells produced and powered by clean electricity (Rinaldi, Syla, Patel, & Parra, 2023). Therefore, enabling better decision-making and a factory design more resilient to process changes will reduce the overall ecological impacts of building new factories by reducing rework and effectively using resources in layout design. This will in advance lead to a lower carbon-footprint.

Further, enabling more flexible and effective layout design will increase the competitiveness of NOVO Energys operations and in extension affect economical and societal benefits. Enabling a better factory layout more prone to avoiding late and unnecessary changes will reduce costs, decrease lead-times and provide a more resilient design which in advance would lead to several benefits in the economical sustainability dimension. This will also affect the competitiveness for NOVO Energy which in advance will lead to more jobs and an overall secure battery industry sector in Sweden.

To make sure that the factories can produce the right product that the customers wants it is important to make sure that the factory is optimised for it. Therefore the battery cell manufacturing companies needs to be able to respond to changes in requirements and be able to handle changes (Rogalski, 2012). For the battery cell manufacturers this could mean that they have to increase the flexibility within their production.

The increase in flexibility, whether it is by factory layout or by RMS, will lower the environmental footprint created by re-layout or new equipment as well as lower the cost for the companies. By planning for change in advance battery cell manufacturers can help speed up the transition from combustion-engine vehicles to EV's and at the same time reduce the need for building new factories when new battery cells are developed.

As the thesis was written in collaboration with NOVO Energy it was important that company information was treated in a secure way. The group members have also signed a contract which regards that critical information cannot be published which will be taken into consideration as the master thesis is owned by Chalmers University of Technology and will be published. Another aspect of the project was that it needs to proceed in an ethical way and therefore anonymity was used regarding the interviews.

5.11 Future battery cell factories and further research

As the battery cell industry is relatively new and expanding at a fast pace there is a need to find a project model that can be used to help pace up the industry. The industry has to make a shift from the traditional production system which is created to suit a specific product to a production system which is more flexible and re-configurable (Rösiö et al., 2020). Looking forward, the industry will continue to grow and further development of battery technology will arise. If the SSBs become the new standard battery the processes might change a lot and therefore none of the generated layouts might be suitable. Of the three final layouts the agile layout is the only one that might be able to produce a totally different product such as SSBs as the modules can be changed. As the production of prismatic Li-Ion battery cells can differ depending on what recipe is used the differences between the A sample and the C sample can be huge (Örüm Aydin et al., 2023). This is due to the product development that is occurring during the development of the cell. The development of the cells should be seen as a natural part in the industry as the product should satisfy the customers changing needs and expectations (Bellgran & Säfsten, 2010). Therefore it is important to keep in mind when making the factory layout for a battery cell factory that the product could change and therefore design for flexibility.

Another aspect that could further improve the battery cell manufacturing industry would be to only use compression trays within Cell Finishing as it reduces the need of tray exchange and decreases the material handling. The reason why this isn't applicable in most cases is due to the cost of compression trays in relation to aging trays, but it would make the factories more efficient. Another solution to the problem would be to include the compression in the process, instead of having the trays, but as this thesis were focused on the factory layout it was disregarded of further investigation.

It could also be of value for the battery manufacturers to think about utilising the factory space by building on different levels if possible. For example the high bay areas could be higher than two normal levels and therefore processes that aren't the same height could be placed on different levels to reduced the amount of space needed on a single level.

For all of the methodologies the use of RMS would increase the level of flexibility of the processes which could increase the flexibility of the factories. As the RMS is capable of quickly adapting to changes in the demand and product mix the use of RMS could further help pace up the battery cell manufacturing industry (Brunoe et al., 2021). As the RMS is designed for upgrades and changes the projects could follow a traditional project model such as waterfall and create a layout for a single recipe if RMS is included because then the changes could be made later to fit a newer recipe (Rösiö et al., 2020). The most flexible solution would therefore be to have an agile factory layout that includes RMS which would mean that different products could be produced in different modules and changed over time to suit newer batteries.

If a battery cell manufacturer wants to build a flexible factory the initial costs rises due to the uncertainties within the industry. Therefore they need to make a decision if the cost of incorporating flexibility is worth it. When building new factories it is important to include flexibility to reduce the need of re-layout and with that higher costs and more equipment. To make sure that new battery cell factories can be used for future generations of cells they must be designed in a way that changes can be made. Otherwise the results will be that they shut down if the customer needs changes and there is no demand left.

Looking into the future further research within the area of this thesis and the industry are important to help pace up the industry to reach the climate goals. In the list below five further research topics are presented.

- Further development of this thesis could incorporate a more thorough cost-analysis for what the different project-models and related layouts would mean for the industry to be able to have stronger discussion about the value for the company.
- Incorporating the capacity parameter in the factory layout design would increase the reliability of the thesis result and could potential lead to other results than is presented. A change from 10PPM to 20PPM could lead to a 100% increase in needed equipment and would lead to new problems that needs to be solved.
- Different electrical vehicles needs different types of battery cells and as mentioned in section 2.2.2 there are different kinds of cells that can be produced. If a battery cell manufacturer wants to be able to supply different cell-types it could be of interest to further investigate how the production of different cells would affect the layout design and what the value for the company would be to produce them.
- It would also be of value to investigate how the industry and factory layout design will have to change to be able to produce SSBs in the future. As the SSBs are a potential solution to increasing the energy density within cells it could become the new Li-Ion battery and further research in how much have to be change to be able to produce it would be of value to the industry and society.
- As the battery cell manufacturing industry for EV's are relativity new it would also be of interest to investigate how much of the equipment that is needed to produce the batteries that can be re-used to produce different recipes and/or different cell types. It would also be of interest to further investigate how much of the equipment that can be recycled to get an understanding for if the industry is sustainable or not. It would also help with the choice of making the factory layout more flexible from the beginning as if there is a low level of recycle-ability or reuse of the equipment it would be of value to have the right equipment from the beginning.

6

Conclusion

The battery cell manufacturing industry for EVs is relatively new in Europe and expanding at a fast pace. As the industry will help with the transition towards a more sustainable society it is of importance to accelerate the pace of the industry to make sure that the transition towards a more sustainable future is possible (Duffner, et al., 2021). To be able to create factories that can produce batteries that the customers wants at any given time the flexibility needs to increase within the factories. By trying out existing project models or by creating a new one that suites the industry's situation the battery cell industry will be able to continue to develop in a high pace.

This thesis has examined the interplay between different project models and the design of flexible factory layouts within the battery cell manufacturing sector. With the increasing demand for electric vehicles there is a corresponding need for a increase in battery production, the research aimed to address the challenges that the industry is facing due to it's rapid evolution and the need for flexibility in the factory design.

Throughout the course of this study, three different project methodologies were investigated, primarily focusing on their ability to increase flexibility within manufacturing process layout. The traditional Waterfall model, while structured and straightforward, showed limitations in its structure, often proving costly when adaptability was required due to evolving market demands. In contrast, Agile and Set-based Concurrent Engineering methodologies demonstrated a higher degree of flexibility and responsiveness, supporting the dynamic needs of battery cell production.

The findings underscore the significant role of incorporating RMS within the production systems to increase the flexibility. The ability of RMS to be quickly reconfigured supports the industry's need to adapt to new technologies and production scales without extensive overhauls or downtime.

The comparative analysis of different project models highlighted that while initial investments in flexibility might be higher, the long-term benefits, including the reduced need for future major re-layouts and the ability to respond to market and technology changes, are substantial. This aligns with the industry's way towards sustainability and efficiency, advocating for an initial higher investment in flexible systems to avoid future costs and production interruptions and the ability to effectively manage complexity.

As battery technology and market demands continue to evolve, the choice of project model and manufacturing system design becomes increasingly critical. This thesis contributes to the field by providing insights that can guide manufacturers in choosing the most appropriate project model and layout design strategy, balancing between upfront costs and long-term flexibility.

In conclusion, the pursuit of flexibility in the battery cell manufacturing industry is not just a response to the uncertainties of future market conditions but a strategic imperative. This study highlights the need for industry stakeholders to adopt more dynamic project models and invest in adaptable manufacturing systems, ensuring that production capabilities can evolve in tandem with technological advancements and market demands, thereby securing a competitive edge in the fast-paced global market. By incorporating flexibility within the factory layout the battery cell manufacturers will be able to reach the customers changing demand and help in the transition towards a more sustainable world, if they are willing to pay the higher initial cost. On the other hand if the higher initial cost isn't paid the risk is that the factory layout becomes outdated and cant produce the batteries that the customers wants, and then there is a risk of either high re-layout cost or bankruptcy. Therefore the battery cell manufacturers needs to make a decision, if they are willing to take a risk or if they want to make sure that they will be able to keep producing batteries and help with the ongoing transition.

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A

Appendix A

Interview Questions for Pre-Study

1. Which industries have you been working in previously?
2. How did projects work at your previous job?
3. How did you work with changes during the project? What kind of changes were there?
4. How did you incorporate flexibility within processes?
5. How did you incorporate flexibility within factory layout?
6. What could have been done differently?
7. What would you say is the biggest difference between the battery industry and other industries?

B

Appendix B

Interview questions of process engineers

1. How do different recipes/products affect the processes?
   Electrolyte Filling?
   Soaking?
   Charging?
   Degassing?
   Aging?
   Which processes has to come in which order? Can that be more flexible?
2. What were the key factors considered in deciding the layout of the factory or its process arrangement, and what were the primary considerations involved?
3. What other decisions would you have made if cost were not a factor? How did you decide which options to go by, especially when there are uncertainties regarding the product?
4. How do you work with flexibility regarding the uncertainty of recipie/product?
5. Is there anything that can be changed after the production line is built?
6. What amount of flexibility is possible to build into the processes?
7. What do you think the biggest challenges will be regarding the production in the area and the change of recipe/product?
8. Is there anything that you can see that could be improved for this factory?
9. Is there anything that you think that should be changed for the next factory?

C

Appendix C

Optimal | Acceptable | Marginal | Unacceptable

Function Layout				
Requirements	Layout Facility	Layout Material flow	Layout Product	Layout Process
Electrolyte filling as first process (Close to cell assembly) (Requirement)	Optimal	Optimal	Optimal	Optimal
Soaking after first Electrolyte filling (Requirement)	Acceptable	Optimal	Marginal	Optimal
Second filling after soaking and precharge (Requirement)	Optimal	Acceptable	Optimal	Optimal
High bay areas (soaking, HT, RT, Formation and precharge) close together	Optimal	Acceptable	Acceptable	Optimal
EOL as last process (Requirement)	Optimal	Optimal	Optimal	Optimal
Flexible process design to handle different recipes (Desire)	Marginal	Marginal	Optimal	Marginal
Formation chambers close to the wall (Desire)	Optimal	Optimal	Acceptable	Marginal
Aging trays for HT RT soaking	Acceptable	Optimal	Unacceptable	Acceptable
Minimize number of tray exchange	Acceptable	Optimal	Optimal	Acceptable
Minimize work in progress	Wait until more detailed layout with conveyers.	Wait until more detailed layout with conveyers.	Wait until more detailed layout with conveyers.	Wait until more detailed layout with conveyers.
Minimize distances	Wait until more detailed layout with conveyers.	Wait until more detailed layout with conveyers.	Wait until more detailed layout with conveyers.	Wait until more detailed layout with conveyers.
Tray exchange from aging trays to compression trays before formation and precharge	Acceptable	Optimal	Unacceptable	Optimal
Clean and dry-rooms close to each other (Desire)	Optimal	Unacceptable	Acceptable	Optimal

Evaluation Critera

D

Appendix D

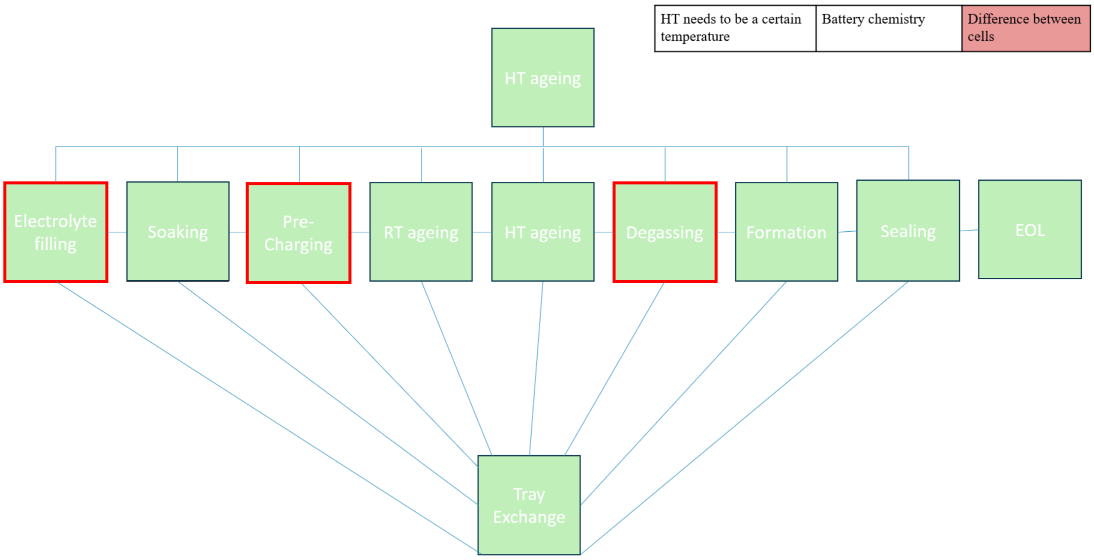

Figure 34: First Iteration

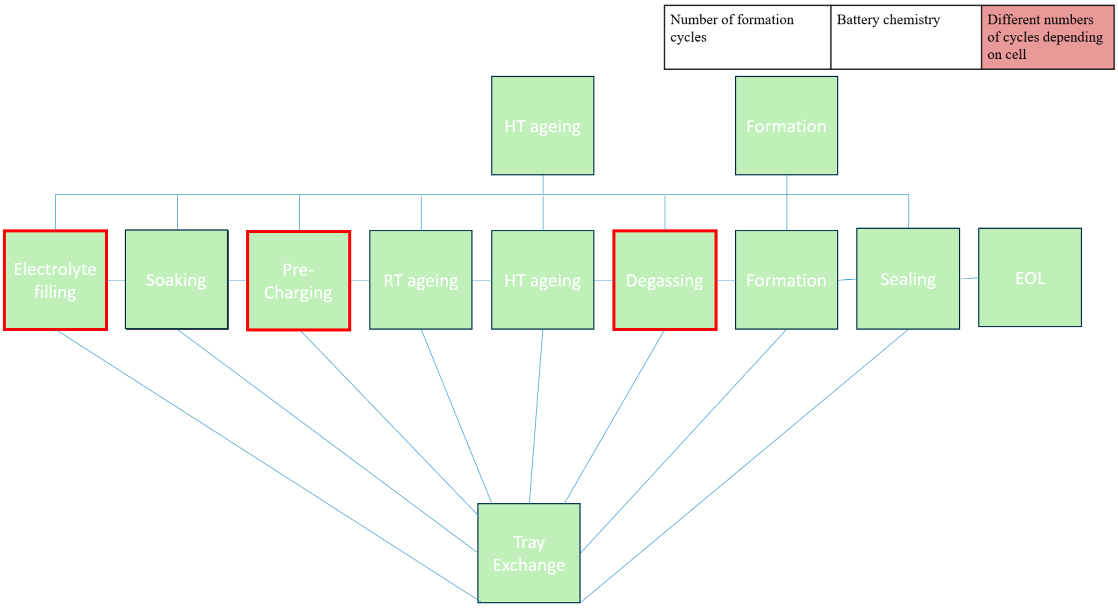

Figure 35: Second Iteration

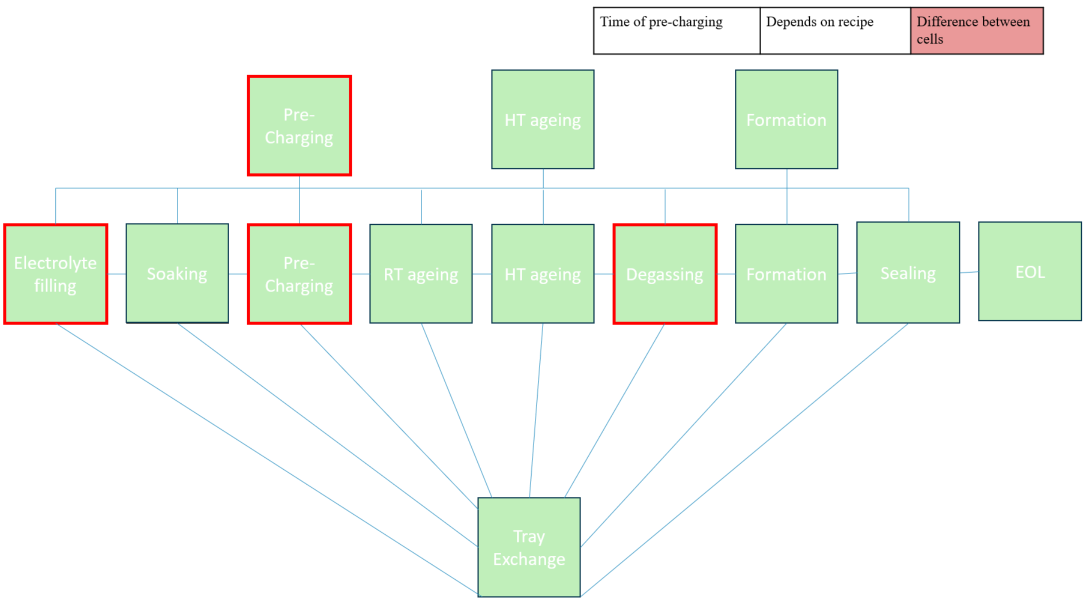

Figure 36: Third Iteration

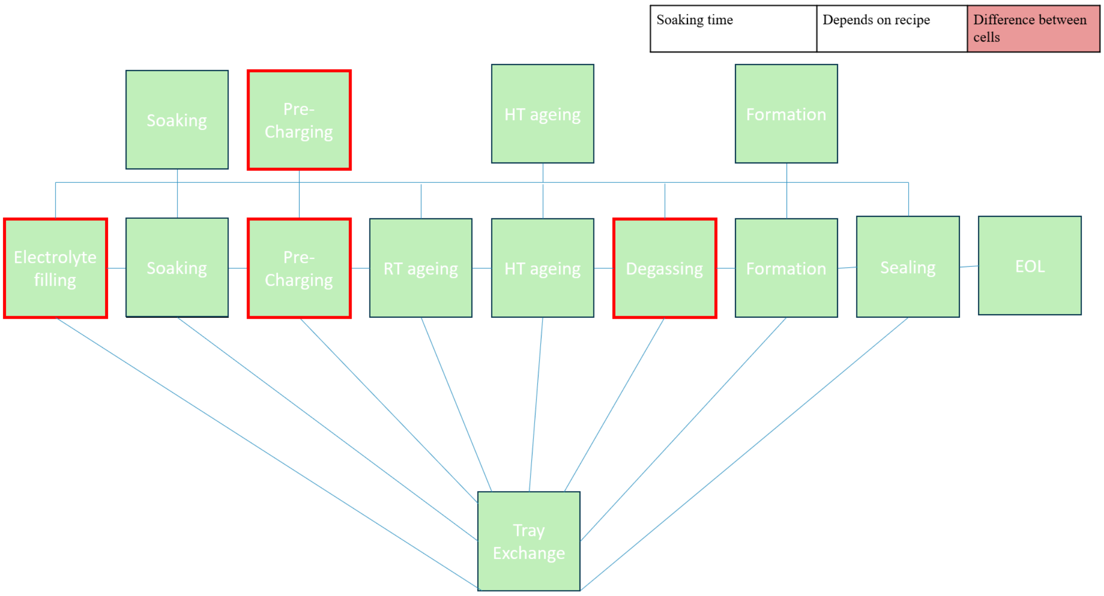

Figure 37: Fourth Iteration

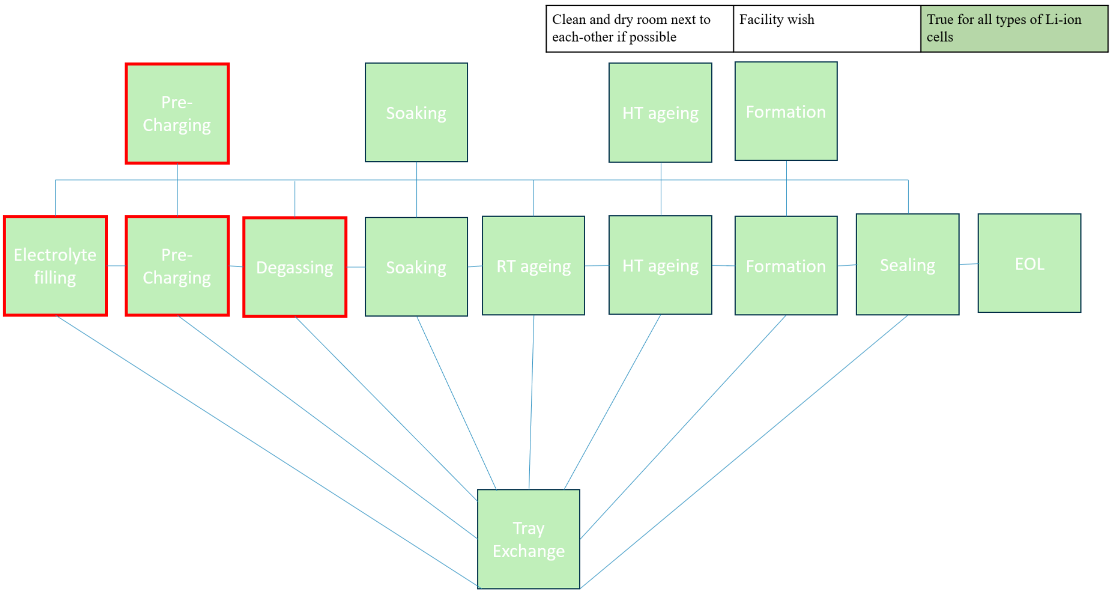

Figure 38: Fifth Iteration

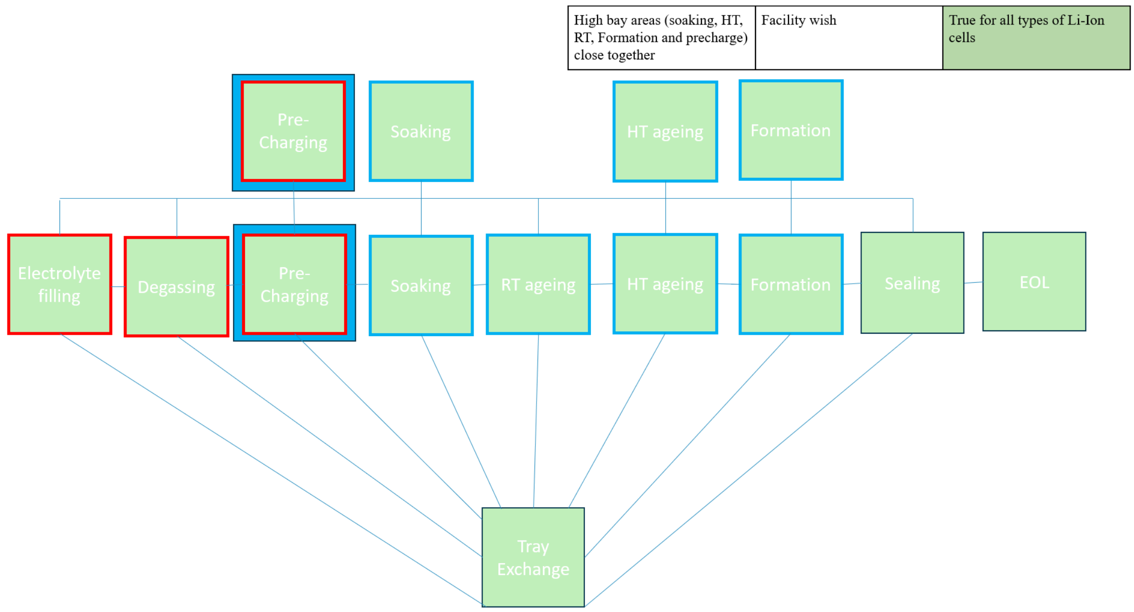

Figure 39: Sixth Iteration

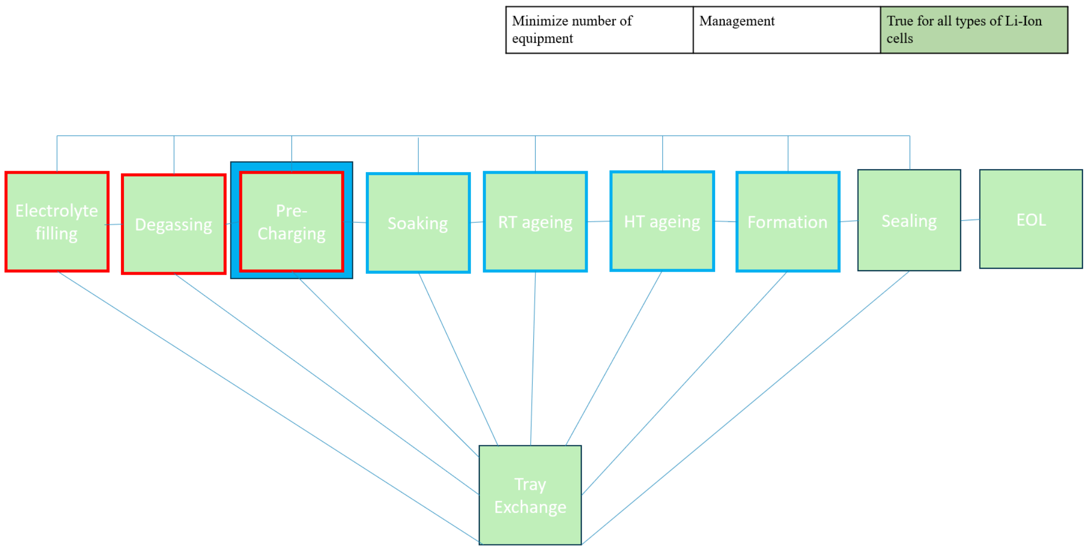

Figure 40: Seventh Iteration