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PRODUCTION REQUIREMENTS FOR 35 GWH LITHIUM-ION BATTERY FACTORY

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LIST OF ABREVIATIONS AND TERMS

BOM	Bill of Material – list of parts and raw materials needed for manufacturing
Car battery	In this study car battery means car's power source consisting of 10 modules and in total 3850 LIB cells.
Cell	Battery cell. Now, 2170 type LIB cell with 21 mm in diameter and 70 mm in height. One 80 KWh car battery is made of 3850 cells.
DSS	Decision-support system is a research method which needs data from many sources. Based on data collection and intuitive reasoning.
GWh	Gigawatt hour – Electrical energy unit, 1 000 000 000 watts. Additionally, 35 GWh factory means a factory with 35 GWh annual production capacity.
Industry 4.0	4th industrial revolution. Describes the current industrial change.
Layout	In this study: physical parts placement. The most typical layout types in manufacturing are production line layout and cellular layout.
LIB	Lithium-Ion battery is rechargeable battery with high energy density. In addition to electric cars, general applications include laptops and mobile phones.
Module	Unit with 385 cells. The car battery needs 10 modules to get 80 KWh capacity.
Ramp-up	In this study: the time required before achieving maximum capacity.
VR	Virtual reality is a computer-generated artificial environment. This battery factory project. Planned battery factory is created in virtual reality.
3D	Three dimensional graphic.

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ABSTRACT

Electric car manufacturers need to develop their operations as demand increases. This has also boosted lithium-ion batteries becoming more common. In current situation, demand may still be met but when taking into account the future prospects of the battery industry, many new factories need to be built. That is why in 2017, the opportunities for building the battery factory were started to evaluate.

The research assignment of thesis is to find out the amount of equipment needed in production and to design an optimal layout solution for the factory. These information are intended for use at the factory's 3D modeling project, of which the University of Vaasa is responsible as part of a larger project. In order to calculate the quantity of production equipment, it is necessary to first study the manufacturing process and the features of the lithium-ion battery (LIB) cells. The topic is extensively discussed but there are also limitations. The factory is fully automated, annual production capacity for the factory is 35 GWh, produced battery cells are cylindrical type and the research focuses on solutions inside the factory.

As can be seen, the theoretical framework consists largely of topics that define the production process of lithium-ion battery cells; the history and prospects of battery production, the manufacturing process, the characteristics of industrial layout types, factory internal logistics as well as the fourth industrial revolution, which is described by the term Industry 4.0.

The study of battery production revealed that manufacturing processes between different factories may differ from each other. By using the selected research method, decision-support system, the efficient manufacturing process was created and dimensioned for the LIB factory.

KEYWORDS: lithium-ion battery, battery factory, Industry 4.0, 3D model

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TIIVISTELMÄ

Sähköautojen kysynnän kasvaessa myös niiden valmistajilta vaaditaan aiempaa enemmän. Tämä on vauhdittanut myös litiumioniakkujen yleistymistä. Nykyisellään akkujen tarjonnalla on vaikeuksia vastata kysyntään ja kun huomioidaan alan tulevaisuuden näkymät, on uusia tehtaita rakennettava runsaasti. Vuonna 2017 ryhdyttiinkin arvioimaan mahdollisuuksia litiumioniakkutehtaan avaamiseksi Vaasaan.

Tutkielman tutkimustehtävänä on selvittää tuotannossa tarvittavan laitteiston määrä ja suunnitella laitteille optimaalinen layout-ratkaisu. Näitä tietoja on tarkoitus käyttää apuna tehtaan 3D-mallinnusprojektissa, joka on Vaasan yliopiston osuus tässä suuremmassa kokonaisuudessa. Jotta tuotantolaitteiden määrä on mahdollista laskea, on ensin perehdyttävä itse valmistusprosessiin ja paristokennojen ominaisuuksiin. Aihepiiriä käsitellään laajasti mutta rajoitteitakin on; tehdas suunnitellaan täysin automatisoiduksi, sen vuotuinen tuotantokapasiteetti on 35 GWh ja valmistettavat paristot ovat sauvaparistoja. Näiden lisäksi tutkielmassa keskitytään vain tehtaan sisällä oleviin asioihin, eli esimerkiksi kysynnällä ja materiaalin saatavuudessa ei ole vaikutusta tutkimuksen lopputulokseen.

Teoreettinen viitekehys koostuu pitkälti aihepiireistä jotka määrittelevät suunniteltavassa tehtaassa valmistettavien LIB (lithium-ion battery) kennojen tuotantoprosessia. Toisessa pääkappaleessa käsiteltäviä asioita ovat paristotuotannon historia ja tulevaisuudennäkymät, itse tuotantoprosessi, teollisuuden layout-tyyppien ominaispiirteet, sisäinen logistiikka tuotantolaitoksessa sekä teollisuuden neljäs vallankumous, jota kuvataan termillä Industry 4.0.

Paristotuotantoa tutkiessa kävi ilmi, että valmistusprosessit eri tehtaiden välillä voivat erota toisistaan työjärjestyksen osalta. Valittua tutkimusmenetelmää, päätöksenteon tukijärjestelmää (decision-support system) apuna käyttäen saatiin kuitenkin luotua ja mitoitettua valmistusprosessi ja tuotantolaitteisto, jolla litiumioniparistokennot on mahdollista tuottaa tehokkaasti.

AVAINSANAT: litiumioniparisto, paristotehdas, Industry 4.0, 3D-malli

1. INTRODUCTION

1.1. Background

These days, the world faces problems related to the consumption of natural resources. Even in automotive industry, customers and scarcity of natural resources bring companies pressure to create more sustainable ways to manufacture cars and those are the main reasons why there is a huge need for lithium-ion batteries (later LIB) for electric cars. In addition to environmental issues, electric cars also reduce dependence on foreign oil (Yuan, Deng, Li & Yang 2017). The first hybrid vehicles (HEV) have been launched at the turn of the millennium and electric vehicles a decade later. By 2016, about two million EV have been manufactured. However, according to the most optimistic forecasts, the number of produced EVs is expected to grow to 200 million by 2030 (International Energy Agency 2017). For these reasons, an idea of building the lithium-ion battery factory in Vaasa, Finland, was born.

The battery factory project is implemented by two municipalities from Western Finland, Vaasa and Korsholm. Near the Vaasa region can be found the raw material used in production and also, there are several energy industry companies in Vaasa region. In addition to municipalities, the project have been planned by, among others, plenty of companies, a working group GigaVaasa and universities.

As part of a larger project, there are plans to do a simulated 3D model from the factory. The model will be made by using simulation software 3DAutomate by Visual Components, by university project researcher and research assistant. When the model is finished, there will be a demonstration video from the factory. In addition, the 3D model has been used as a virtual reality (VR) model. In modeled factory can be seen manufacturing process for lithium-ion batteries in detail.

1.2. Research assignment and the objectives

This research's key objective is to provide the necessary information to create a 3D model and the research assignment is in the form *"the number of production equipment and the requirements for their placement in automated 35 GWh lithium-ion battery factory"*. In order to facilitate answering to research assignment the study will answer to three research questions:

1. What layout type is suitable for the high volume lithium-ion battery factory?
2. What are the issues associated with factory automation?
3. What is the role of material management at the factory and how it can be implemented?

The first two of research questions are answered already in the theoretical part and the third one is divided in theory and Results chapters. The research assignment i.e. dimensioning of equipment are processed in excel, from which the data is transferred to Results chapter. Achievement of objective is assessed in the summary at the end of the study.

The main focus in the research is in clear manufacturing process, which is defined by the following constraints and limitations: 1. the factory is meant to be fully automated, 2. 35 gigawatt hour annual production, 3. manufactured batteries are cylindrical lithium-ion cells, and 4. focus on interior factory. The fifth factor determining the factory is sustainability and green values but these strategic decisions are mostly ignored because of the fourth limitation.

1.3. Structure of the study

The study consists of theoretical literature review and results of the study. Between them, the study methodology is explained and, of course, the study also has a conclusion. The investigation part is implemented via previous literature from manufacturing process and manufacturers of production equipment. Many articles give a different view of making batteries, but the study gives an idea of how the batteries can be manufactured. The results of the research are based on the use of the information found within the limitations allowed. The data is compiled into the Microsoft Excel file and it is used to make calculations for the factory.

The chapters of study are adapted to the content of the work. In addition to introduction, the study includes four chapters. The first of them, chapter 2, is marked to be *Theoretical Background*. It gives paving the way for later examination. Short third chapter, *Methodology*, explains the methods that will be used in the study.

The fourth chapter, *Results*, determines the future factory from the perspectives that have been taken in the account in the literature review. It shows the results for the manufacturing process but also presents calculations for space need and logistical issues.

The last chapter, *"Discussion about the factory*", deals with challenges encountered in research, factory planning and plant operations. There are also mentioned challenges related to the factory, which are not otherwise raised in this work. Also alternative ways are proposed for some work phases. In addition to these, the chapter contains a summary and suggestions for further research.

2. THEORETICAL BACKGROUND

One battery cell is part of bigger system. Typically the cells for electric cars are either prismatic or cylindrical and their number per car depends on the desired features of battery pack (Yuan et al. 2017). One huge difference between these two types of cells are the size and weight of cell. For example, one prismatic cell for Nissan Leaf weights 870 grams (Yuan et al. 2017) while cylindrical cell weights less than 100 grams (Northvolt 2017). Naturally, cells have different technical specifications and in this study, the focus is in cylindrical cells.

The theoretical framework of this study deals with themes related to current situation of lithium-ion battery production, operations of the battery factory and the content of the research. Therefore, it consists of matters within the limitations. In addition to background of current LIB production and demand, the chapter contains a lithium-ion battery manufacturing process, process layout, capacity planning and logistical problems. The last thing discussed in this chapter is factory automation.

2.1. Worldwide LIB production – before, now and then

Electric vehicle production have increased rapidly in the 21st century. In 2005 number of worldwide produced EVs was less than 1500 cars but by 2016, the total number of produced electric cars has grown near 3 million. Only 1,2 million of these cars are registered for road use which is largely explained by incomplete development of EVs and expensive price. Nowadays, electric cars have 1,1 percentage global market share but for example, situation in Norway creates faith for proliferation of electric vehicles. With various concessions and reliefs, the market share has been raised to as much as 29 percentage in Norway. (International Energy Agency, 2017).

The EV production have increased a lot in previous years. From 2009 to 2013 their number doubled annually and in 2016 the percentage increase over the previous year was 62 percentages. Despite the percentage increase decreasing, total amount of electric vehicles grows tremendously. In 2020, the production is assumed to grown 18 % and in 2030 the forecast for production increase is about 16 %. Equally, about 30 million electric vehicles are forecasted to be produced in 2030. (International Energy Agency, 2017). While demand increasing, also worldwide production capabilities must be increased at the same rate.

The most famous electrical vehicle is currently Tesla. However, also other carmakers produce electric or hybrid electric vehicles. Over the next four years, the LIB cell production is estimated more than double and moreover Tesla, the factories will be made by carmakers and governments. Massive factory projects are planned around the world addition to Tesla's gigafactories in Nevada, Buffalo and Australia. (Deign 2017). Irish company, Johnson Controls already has two gigafactories for EV batteries in China and their plan is to set up two more factories there (Ren 2017). Also, in Sweden is planned the factory for LIB cells (Norhvolt 2017). One of the industry leaders is also Germany and, for example, Germany Company BMZ GmbH has produced LIB cells from 2016 (Prophet 2016).

The reason why factory planning is started in Vaasa is that Tesla is envisaged more LIB factories in Europe and Finland is one potential option for factory. However, also other actors are also possible instead of Tesla because resources and knowledge can be found in Vaasa region.

2.2. How are lithium-ion batteries manufactured?

This section holds the lithium-ion battery manufacturing process at a theoretical and general level. Process has about 20 work phases and next sequence is an example order in which batteries can be manufactured. Also, different processing sequence is possible in some respects. As a rule, core processes are electrode manufacturing, cell assembly, formation cycling and packing.

The process consists not only of manufacturing but also of support measures. The work steps directly related to the manufacturing are presented in the figure (Figure 1). The steps shown on the blue background are part of the electrode manufacture and green background indicates the cell assembly. Also formation cycling and module packing are shown in their own colors. The above-mentioned support measures are, for example, solvent recovery, cell case production, electrolyte wetting and module production and wiring. Later in this chapter is presented the role of each stage in production.

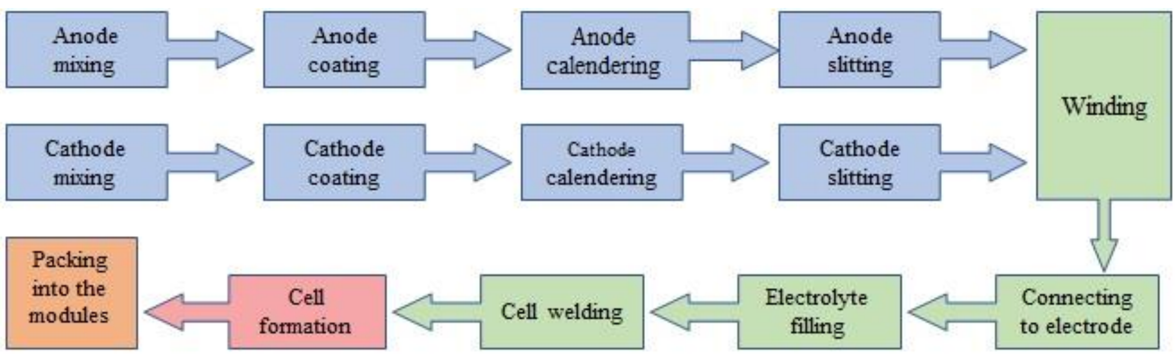


Figure 1. Process map for lithium-ion battery manufacturing.

2.2.1. Electrode manufacturing

Electric current flows inside the cell between positive and negative electrodes. That is why finished electrode foil stripe is one of the main components of lithium-ion battery cell. Electrode manufacturing process comprises electrode slurry mixing, coating, calendaring and slitting stages. In addition, solvent recovery system must be implemented alongside mixing and coating stages.

2.2.1.1. Electrode slurry mixing

Electrode manufacturing is divided in two parallel lines. This is purely because of anode and cathode materials must not be in contact with each other. Mixing of electrode materials is the first step in the electrode manufacturing. This stage requires few tanks in which raw materials are stored, mixing tanks and one more storage tank for finished electrode slurry.

Positive electrode slurry consists of graphite, conductive material, binding material and solvent (D. Liu, Chen, TJ. Liu, Fan, Tsou & Tiu 2014). More information about raw materials is portrayed in chapter 4.1.2. Each raw material needs own storages, from which the raw material can be delivered to the mixing tank. Mixing tank blends slurry for three hours and then slurry is transferred to final storage tank before coating.

Cathode slurry mixing is comparable with anode mixing. Main difference between these two operations is active material which is LNMC (lithium nickel manganese cobalt oxide) in cathode slurry (Liu et al. 2014). In other respects, slurry consists of conductive and binding materials and solvent. Such as anode slurry, also cathode raw materials require raw material storage tanks, mixing tank and mixture storage tank.

2.2.1.2. Electrode coating

Both anode and cathode electrodes are coated in the same manner. Positive anode material is coated with thin copper foil and aluminum foil is used with negative cathode material. Coating foil rolls are mounted into the machines. While unwinding foils, the machine will coat it on both sides so that the foil remains inside the coating. The end result of the coating is coated stripes in foil and between them is bare foil. A small part of the bare foil will be utilized later as tabs.

Normally, the drying is individual stage, for example after calendaring or slitting but there are also coating machines with a long drying section. When the coated foil passes through the furnace, extra liquid is removed from the coating and thereafter it is possible to reel foil again. (Electropedia 2018).

2.2.1.3. Solvent Recovery system

Anode and cathode slurries contain an environmentally hazardous NMP (N-methtyl-2-pyrrolidone) solvent. This is why it is important to remove it after the coating stage, during the drying. According the Babcock & Wilcox Company (Babcock & Wilcox 2018a), one of the major Solvent Recovery System producers, with the closed solvent recovery system, it is also possible to recycle solvent in such way that it does not have to purchase so much.

In lithium-ion battery cell factory, solvent recovery is a multi-part system which captures the solvent from coated foil, cleans it and returns it back to the mixing process. Even the heat used for drying is recyclable. Main parts in solvent recovering are filter, heat exchange system, solvent storage and distillation tank. The system also includes combustion of non-recyclable waste and emission. (Thomas 2017.)

2.2.1.4. Calendering

The purposes of the calendaring process are thinning of coated foil and compacting the pore structure of the coating. Meyer, Bockholt, Haselrieder and Kwade (2017) demonstrated that the coating thickness is reduced by up to 40% by calendaring. Coated foil roll is fed to the calendaring machine and after compression it can be wound again. Anode and cathode processes are quite similar. The difference with these two processes is the compaction. Cathode electrode calendaring requires more than double the amount of newton meters (Nm) (Meyer et al. 2017).

2.2.1.5. Slitting

Wide calendered foil is cut with slitting machines to the shapes required. In practice, foils are cut into 7cm wide slices. Edges of foils are cut off except the small tabs which allow the electrode to lead electricity later.

2.2.2. Cell assembly

After electrode manufacturing, battery cell case has to be filled with electrode and electrolyte and these components must be interconnected as required. Thereafter, cell can be closed and sealed.

2.2.2.1. Winding

The first phase in cell assembly is winding. It means that slitted electrode rolls are reeled with separator as a tight wrap so that anode and cathode electrodes do not be in touch with each other (Reinhart, Zeilinger, Kurfer, Westermeier, Thiemann, Glonegger, Wunderer, Tammer, Schweier and Heinz 2011).

2.2.2.2. Cell case production and connecting to electrode

Then, winded reel is ready to be placed in empty cell case which can also be made in factory. Empty cell cases are cut from long stainless steel pipe. Automatic circular saw cuts several pipes at once to the right length. It is also possible to have ready-made empty cases and if so, cell case sawing stage can be removed from the factory.

Cell cases will be combined with cell covers. These covers are cut from steel plate. After sawing, covers will be cold pressed to achieve the desired shape. As above, this stage can be left to subcontractors. Before electrolyte filling, electrode roll will be placed in cell case with robot.

2.2.2.3. Electrolyte production, electrolyte filling and wetting

Electrolyte has a major role in conveying lithium-ion inside the cell (Targay 2018). The mixture that consists of organic carbonates, electrolyte salt and solvent is prepared in a closed system. Pipes transfer finished electrolyte to the assembly line where the cells are filled with electrolyte. Wood, Li and Daniel (2015) explain that electrolyte may deteriorate if in contact with air or moisture. For that reason, vacuum room is necessary for the stages from filling to final cell welding.

One of the most time consuming phases in lithium battery production is electrolyte wetting, also known as aging. Normally, wetting process may require 24 hours but even that does not always guarantee a good result. Long wetting time means large amounts of cells in wetting storage at the same time and therefore this stage requires a large space (Wood et al. 2015). In addition to wetting, the cells are dried because extra electrolyte solvent must be recovered before cell formation.

2.2.2.4. Cell welding and sealing

Before cell formation, cell must be covered, welded and sealed. These operations are implemented in vacuumed space. Robot covers cell with cap and after laser welding cell will be hermetically sealed.

2.2.3. Formation cycling and charge retention

Purpose of formation cycling is to create a capacity into cell. In addition, Pinson and Bazant (2013) claims, that high quality formation also extends cell lifetime. In short, type 2170 cells are charged and discharged at least three times. Therefore, formation cycling is time consuming and there will be multiple cell batches in stage at once. Hence, this stage desires a large space in high volume production. A certain charge amount is left inside the cell after formation. This allows the completed car battery modules to be ready for use after leaving the factory.

Yuan et al. (2017) explicate the whole operation of the lithium-ion cell production, and at the same time, charging and discharging reaction in their article as follows: the battery cell charging process means that coated cathode material, for example the LNMC (introduced later), generates lithium-ions that pass through the separator into the anode by means of an electrolyte. In turn, during the discharging operation i.e. when the battery uses electricity, those lithium-ions flow back to the cathode. Battery cell life cycle depends on endurance of this kind of charging and discharging operations.

2.2.4. Cell module production and packing

Finished cells are placed in empty modules. Modules can be made of metal or plastic. Polypropylene is suitable material for use due to its properties (Vink. 2018). Common way to brought plastic into the desired form is injection molding. According to Nykänen and Höök (2015), the plastic is injected into the closed mold by molding machine and after cooling, the cells can be moved to the modules.

Finished cells are assembled into the modules. Cells in the module must be connected together to achieve the desired voltage and capacity. A further welding stage is needed to achieving it. Welded modules are covered with molded plastic cover and then modules are ready to palletizing and shipping.

2.3. Capacity

The factory capacity means its maximum production volume within a given time (Haverila, Uusi-Rauva, Kouri & Miettinen 2009: 399). Usually capacity is announced as an annual output. Capacity is influenced by many things such as resources, production equipment and space. One important factor, which in this work is not, however, be taken into account is demand forecasting. The worse success of one component will immediately affect the entirety and reduce the maximum capacity and that is why actual net capacity may be only a fraction of theoretical maximum capacity (Haverila et al. 2009: 400-401).

Maximum capacity corresponds to the stage with the lowest capacity called a bottleneck. The bottleneck improvement theory is widely known as Theory of Constraints (TOC). This continuous improvement tool aims to strength process by improving the weakest work stage. (Goldratt 1992: 301-302; Jan & Ho 2006: 859.) At the beginning of the new factory, it is important to focus on stages with the most critical problems because it will increase the actual capacity.

When talking about an automated factory with continuous production, it is more difficult to improve capacity if there are any problems; production shortage cannot be captured by extra shift if the factory is running at nights anyway. Under these circumstances the most critical stages must have lower utilization rate or at least they cannot be bottlenecks. Increasing capacity takes always lots of resources, especially when speaking about an automated production line (Haverila et al. 2009: 475). Thereby it is advisable to plan capacity carefully for each stages.

Estimates have been made that about 2 % of production can be found to be unusable in formation cycling stage (Saario, Kontiokari, Pitkämäki & Heikinheimo 2017: 21). Especially at the beginning of production, the real number for quality defects may be even more and that is why the electrode manufacturing and assembling stages are more important to focus. Work phase requirements to meet the desired capacity are presented in chapters 4.1 and 4.2.

2.4. Layout

Term *layout* means the placement of physical parts in a factory. These factory parts are for example machines, intermediate stocks, pathways and material flow. (Haverila et al. 2009: 475). Therefore, a good layout is one where the plant facilities and equipment are used as efficiently as possible (Roy 2005: 37).

The bigger the plant is, the more things to consider. That is the reason why layout selection is always a compromise (Haverila et al. 2009: 480-481). Planned battery factory will be fully automated. Additionally, it has a large production volume and that is why material flow is one of the main priorities. Another highly important thing to carry about is locations of maintenance department. Even short breaks in production greatly affect the volume of the production. As Tompkins, White, Bozer and Tanchoco remind in their book, *Facilities Planning*, (2003: 13) layout must be carefully planned. Especially in automated large volume factory, changing the layout requires a lot of time and money.

The plant aims to produce batteries for electric cars as efficiently as possible. Instead, the goals of the selected layout are minimizing material handling costs, investments, throughput time and use of space. This means that utilization rate is desired to be high. Hence, capacity planning and layout planning are essentially related to each other.

2.4.1. Choosing layout

In sixth edition of his book Haverila et al. (2009: 481) lists different factors for layout planning:

- Bill of material (BOM) is list of parts and raw materials of which the product is composed
- Determining and sequencing work phases
- Production volume and capacity
- Total duration of production in years.
- Support functions – maintenance, employee facilities, monitoring room etc.

The same book presents different layout types with their characteristics. The most common layout types are production line, cellular layout and functional layout. The production line causes a massive investments because usually the line is highly automated. Due to automation, the material flow is clear and the utility rate is possible to keep high but in the event of an equipment failure there is risk that whole production will stop. The production line is also inflexible and that is why large production volume and low product range is recommended. (Haverila et al. 2009. 475-478).

Functional layout means that workstations are organized into groups based on their similarity. For example, all sawing takes place in the same room. Number of machines depends on production volume. The functional layout is characterized by the fact that the material moves much in the factory. Also, intermediate stocks are common. (Haverila et al. 2009. 477-478).

Cellular layout is used in low volume production. There is an independent group of workers, tools and machines who manufacture a particular products. The equivalent entity can be placed in the adjacent room. In cellular layout, a wide product range is normal and there is not much Work in Progress production. (Haverila et al. 2009. 477-478).

When choosing and planning layout, the above-mentioned factors must be read again. Because there are more than 20 work stages in LIB cell production and they are always in the same order, the production line sounds the most sensible choice. Also, the high production volume is suitable for the production volume. Production is meant to last for long time and the factory will be fully automated which are also characteristics for production line. On these grounds, the production line is chosen as a layout type.

2.5. Logistics

The factory logistics review focuses mainly on material handling and flow. External logistics is only dealt with in terms of the delivery size and frequency. However, there is no information on the availability of raw materials, so it is assumed that materials are always ordered on a two-day delivery. In a broader sense logistics also includes information flow management, supply chain management and raw material purchasing as part of logistics (Haverila et al. 2009: 461-462), but now aim is to clarify the operations of the factory.

Material handling which is subordinate concept of internal logistics, is one of the most important things to be well-planned in the factory. With improved material handling, both factory space and production time can be significantly decreased. In other words, material handling aims to improve the material flow. (Tompkins et al. 2003: 164.)

Tompkins et al. (2003: 164-166) lists several points to focus on material handling. The most important of these are right amount, right sequence, right orientation, right place and right method. Below you will see how these are related to an automated battery factory.

Right amount means the chosen philosophy to the material storage size. In accordance with the currently popular JIT principle, pull control is thought to be better choice than large stock push control. Pull control involves essentially small inventories, but in high volume and stable production large storages are possible too. Right sequence is associated with right amount because both of them determine the batch sizes in purchasing, production and delivering.

Right orientation and right place help to plan material positioning and storing. Orientation is momentous particularly in automated factory in which robots and automated conveyors are responsible for manufacturing and material flow. Production will be paused immediately, unless the material feed is not smooth. Raw material and equipment placing must be planned well because previously mentioned robots and automated forklifts are programmed to operate according to the formula that does not tolerate changes.

Last thing to consider about material handling is right method. If there are right method to product goods and handle materials, it means that there have to be more than one way to do it. To achieve the best way, it is necessary to plan and find widely different methods.

2.6. Industry 4.0

As mentioned, the factory will be fully automated. Automating is a new trend in production and in Germany it has even got the name "4th industrial revolution". Lasi, Fettke, Feld and Hoffmann illustrate its features in their article *Industry 4.0* (2014). Term Industry 4.0 describes changes, mostly in information technology, and its impacts on future industry. According the article, this revolution has major impact to whole organizational structure but in this study the focus is in technological solution inside the factory.

Automation makes it possible to utilize financial resources more efficiently and at the same time to save natural resources. This can be done through digitalization. The digitalization leads to that all machines can collect and register data on reliability, defects and maintenance issues. Another significant thing related the Industry 4.0 is equipment development and miniaturization; nowadays and especially in the future, the efficient machine requires less space than before. (Lasi et al. 2014).

At best, automation system is that production start due to customer's order and the whole production is implemented without a human (Ma, Wang & Zhao 2017). Planning, developing, implementing and maintenance of automated factory is challenging and complex (Lasi et al. 2014). Particularly, noticing maintenance need and gathering data from equipment can be done with this integrated automation system. Advanced version of that is called Jidoka. Even though it is part of Toyota's Lean thinking, it can be used in variety of modern production. (Ma et al. 2017).

One essential term in modern automation system is Internet of Things (IoT). It means that machines and equipment are connected to internet and they can communicate and synchronize data with each other without the human. Success of fully automated production requires careful identification for each material and machine in the factory. Modern ways to achieve it is, for example, bar codes, Quick Response (QR) codes or Radio Frequency Identification (RFID) tags but also other sensors are possible. (Ma, Wang & Zhao 2017).

Ma et al. (2017) introduces architecture of modern Jidoka system. The system is more than just Andon system that stops line when the fault arises. Whole system bases on synchronizing the system and equipment with each other but gathering and analyzing data ensures the system's functionality and continuity. Figure 2 below illustrates the interrelationship between the various parts of automation system.

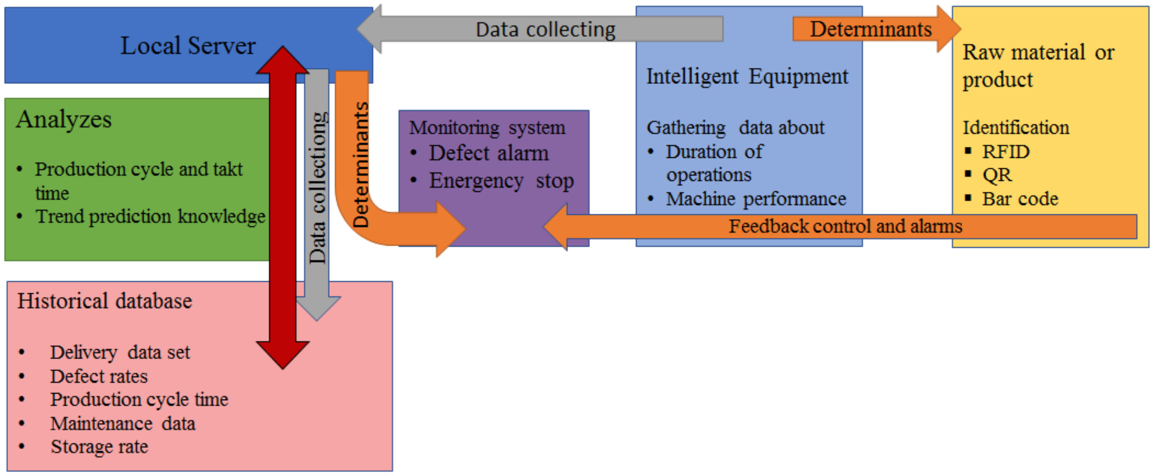


Figure 2. Smart Jidoka System (Ma et al. 2017).

3. METHODOLOGY

As told in introduction chapter, the factory planning process includes the 3D model made with Visual Components’ 3DAutomate software by working group of University of Vaasa. Altogether, there are five people in the group: supervising professor Prof. Petri Helo, project coordinator Dr. Rayko Toshev, project researcher Ebo Kwegyir-Afful and two research assistants Sulaymon Tajudeen and Mikael Hintsala.

Besides the modeling skills, creating the 3D model necessitates, among the other things, knowledge about equipment needed inside the factory, equipment capacity and raw material consumption. These issues are examined and the results are reported in this paper. Different methods are used to obtain necessary information for 3D model and project, and these methods are introduced later in this chapter.

3.1. Research strategy

The research exploits inductive reasoning, theoretical research and decision-support system. These methodologies are chosen because there are several styles to product lithium-ion battery cells. A generic way to product LIB cells is created based on the data founded literature and research.

Developing of Decision-support system (DSS) is for decision makers who deal with semi-structured or unstructured problems. It is a methodology, which needs data to solve the problem, and this data can be collected from many different sources. In addition to data, DSS also requires other components that are model, knowledge and users. Hence, DSS is a way to support decision-making in cases where more research on the subject does not exist. Normally, when using DSS, the process is iterative which means that researching is done in small parts and the process is repeated. Thus, the results are growing towards final shape a little at a time. (Turban, Sharda & Delen 2014: 16-17, 31, 75).

Turban et al. (2014: 17) resemble that above-mentioned components must be customized for each study. In this study, the data for equipment are founded from the articles and equipment manufacturers' websites. Data received from there consists of machine working speed and capacity, way to process and dimension. Used model in DSS is Microsoft Excel and knowledge consists of limitations presented earlier in chapter 1.2.

DSS is intrinsically linked to the idea of inductive reasoning which means that after reading, a decision can be made by intuition, earlier experience and knowledge. However, the results obtained are reproducible and verifiable. Definitely, there will always be newer and more efficient ways to product battery cells but the current assumptions are made on the basis of the widely discovered and estimated material. Provided that the construction of the project does not start immediately, it would be sensible to explore the latest solutions for production. Namely, even though the results are valid, the subject is constantly being studied more.

Two the most important circumstances are that the factory is automated and the production volume is high. It is necessary to take them strongly into account when determining the properties of the used machines.

3.2. Data collection and analysis

Data can be collected with several methods. As described earlier, literature and articles contain information and it is collected in Microsoft Excel file for processing. This Excel file acts as a tool for writing the entire "Results" chapter which contains requirements for raw materials, work stages, space and logistics. Hence, the tables justify the choices made for the factory.

Mostly, the data is shown clearly in chapter 4 but more extensive tables can be found in the Attachments section at the end of thesis. Data-based results are presented in figures and tables but they are also explained in words. Addition to this, work stage equipment are shown in pictures from factory 3D model made by Tajudeen and Kwegyir-Afful.

4. RESULTS

The purpose of this research is to provide guidelines and accurate calculations for 3D model. Outline of finished factory model can be seen in Figure 3. As shown in the figure, raw material movement is implemented mostly by conveyors. The production starts from mixing section in right rear corner and after fully automated round, finished cell modules are palletized in the right front corner of the factory. The linear production line is perceived from the figure; the electrode production is done in long back wall and rest of operations in the front wall.

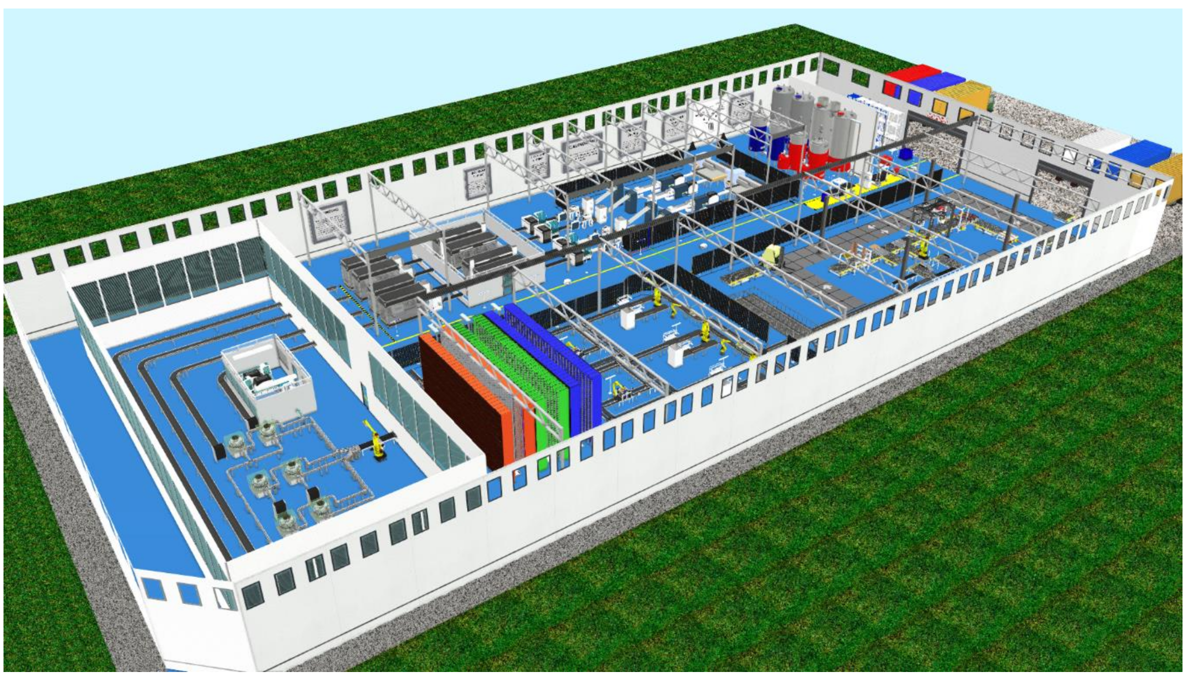


Figure 3. The factory model (Tajudeen 2018).

Although the layout presented in figure 4 describes well the LIB production, it distorts the real need for space. The model includes the main stages needed in production but their dimension and quantity of the machines is not realistic. The real space need for production area is about 15 000 m^2 and the biggest differences between model and reality come out in cell case production, welding and electrolyte mixing stages.

When full capacity operating, production requires a lot of electricity. Estimate for production equipment electricity consumption has made and according this estimate the production requires about 250 MWh in 24 hours which means 2,6 kilowatts needed per one produced kilowatt. However, this estimate includes only machines, robots and conveyors used in production. It is possible that energy consumption is partially covered by windmills mounted in connection with the factory.

Data from cylindrical cell manufacturing electricity consumption is not found but in pouch cell manufacturing the total electricity consumption has proven to be significantly larger with almost 1000 kilowatts needed per produced kilowatt. However, these two factories cannot be compared to each other because the factory presented in the article can produce only 400 cells in a day and meanwhile, Vaasa gigafactory project aims to produce 3,8 million cells every day. (Yuan et al. 2017)

Overall, this chapter gives the reasoned results for material selections, production equipment, space need and production automation. The research strategy is examined more accurate in chapter 3. Methodology and factory related thing beyond the limitations are discoursed in chapter 5. Discussion about the factory.

4.1. Cell and factory requirements

The basis for lithium-ion battery cell production is the capability of the finished cell. The following describes capabilities for type 2170 li-ion cell and after that, the necessary raw materials will be specified.

Examination start with target capacity. When designing the plant, it is important to be aware of its desired future production volume. No the factory’s target capacity is set to 35 GWh. The subject of investigation is the possibility of producing 80 KWh car batteries, but also different types of batteries can be manufactured in this factory.

4.1.1. Technical information

New type 2170 cell is comparatively big cylindrical battery cell. The completed cell dimensions are 21 mm in diameter and 70 mm in height (Figure 4.) (Nouveau Monde Graphite 2017). 2170 cell delivers current 5,750 mA and it is almost double more than older 18650 type cell (Evannex 2017). With nominal voltage of 3.7 V, the average cell capacity can be calculated to be around 21 Wh. Fully charged cell has 4,2 V and nearly 25 Wh. This information can be used to calculate the desired number of cells per year which is 1,4 billion (35 GWh / 25 Wh = 1 400 000 000).

Figure 4. Lithium-ion battery cell (Tajudeen 2018).

Different number of cells means different capacity of completed car battery. The purpose now is to make 80 KWh batteries. That is why one battery consists of 3850 single cells. The way to achieve it is compile it from ten modules, each with 385 cells (Figure 5). The electric car battery must be about 400 volts. Accordingly, the cells are assembled in parallel and in series.

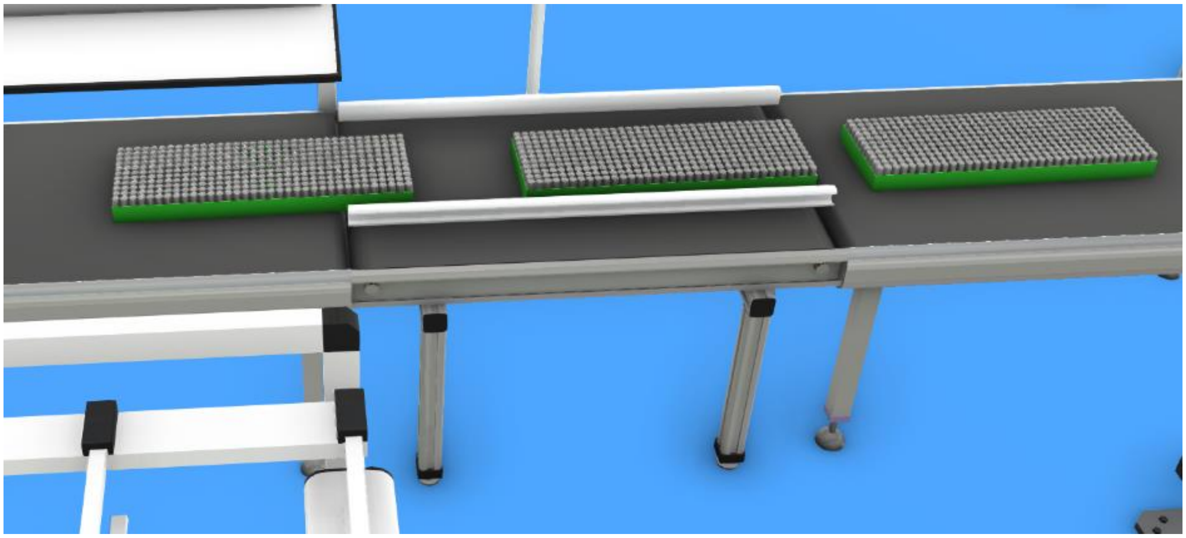


Figure 5. 385 cells in module batches in module assembly section (Tajudeen 2018).

It is important to be aware that production is difficult to keep continuous even in an automated factory. The following figure (Figure 6.) shows production volumes with different working hours. However, there are many unpredictable things, which have affect to volume such as equipment breakdown, material availability problems, maintenance breaks and demand.

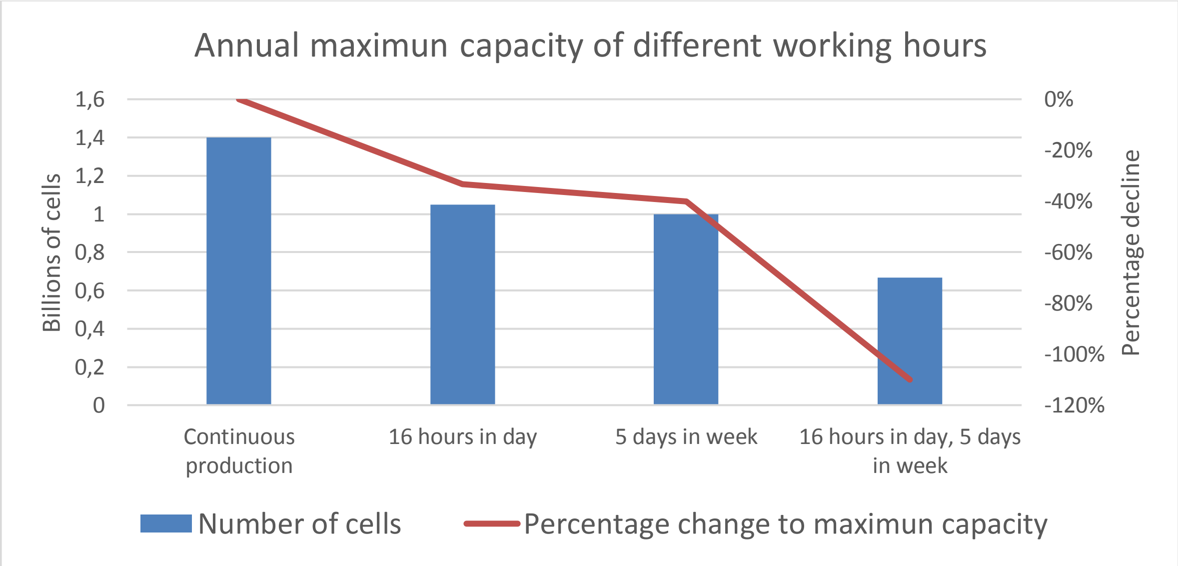


Figure 6. Annual maximum capacity of different working hours.

4.1.2. Raw materials

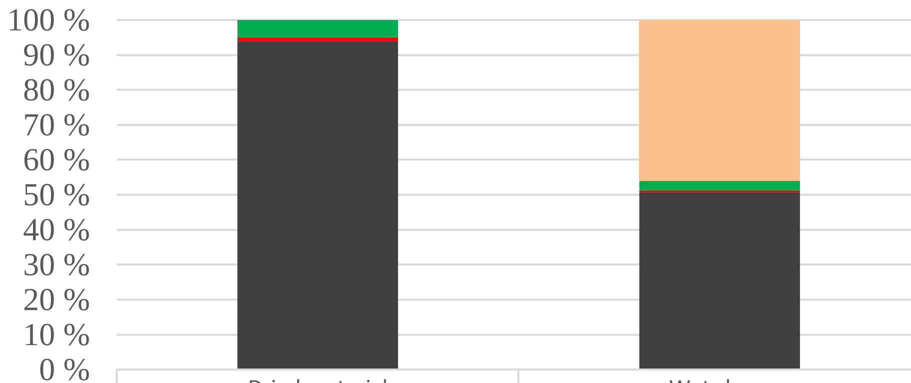
When talking about raw materials, they can be separated into electrode raw materials, electrolyte raw materials, cell case materials and connection materials. The following table (Table 1.) shows the quantities of materials for one cell and the annual consumption with 35GWh production (Meyer et al. 2017: 173; Liu et al. 2014: 517; Vink 2018; Northvolt 2017).

Table 1. BOM for single cell and factory.

	Material for one cell (g)	**The annual material need (tons), for 1,4 billion cells**
Anode material	17	23660
Copper foil	7	9772
Dispelled solvent from anode	14	19740
Cathode material	38	53480
Aluminum foil	6	7770
Dispelled solvent from cathode	22	30800
Electrolyte material	7	10164
Dispelled solvent from electrolyte	6	8540
Separator	2	2128
Cell case and cover material	11	14700
Module pack material	1	1470
Cell connection material	0,05	70
Total need	130	182294
Cell weight	87	

4.1.2.1. Electrode slurry

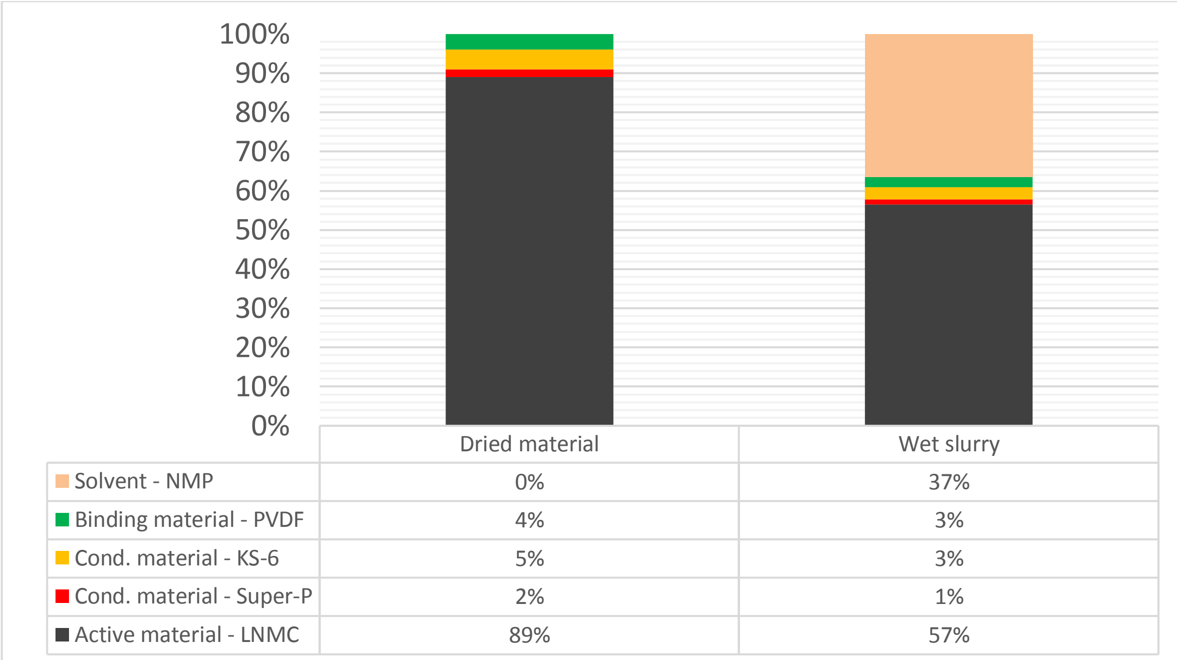
In anode electrode slurry, Graphite is the active material and rest give it features it needs to lead electricity. The figure below shows the concentrations and materials of Anode slurry (Figure 7). (Liu et al. 2014.)



	Dried material	Wet slurry
Solvent - NMP	0%	46%
Binding material - PVDF	5%	3%
Cond. material - Super-P	1%	1%
Active material - Graphite	94%	51%

Figure 7. Anode slurry concentration (Liu et al. 2014).

There are few possibilities as cathode active material. Väyrynen and Salminen say in their article (2012), that today the most common options are LNMC (LiCo1/3Ni1/3Mn1/3O2) and LNCA (LiNi0.8Co0.15Al0.05O2). Article explains that LNMC's energy density is abt. 10 % higher than LNCA's. These grounds, it is assumed LNMC to be used as a cathode material in the factory. In other respects, slurry consists of conductive and binding materials and solvent (Figure 8) (Liu et al. 2014). However, it is possible to use other materials as an active material without changing process significantly.



	Dried material	Wet slurry
Solvent - NMP	0%	37%
Binding material - PVDF	4%	3%
Cond. material - KS-6	5%	3%
Cond. material - Super-P	2%	1%
Active material - LNMC	89%	57%

Figure 8. Cathode slurry concentration (Liu et al. 2014)

4.1.2.2. Cell case and covers

By measuring the volume of the empty cell case, the length of electrode and the separator strips can be calculated because total volume of the four strips must be the same as the case volume. Copper foil thickness is 9 µm (MTI Corporation 2018c) and after calendaring, anode slurry thickness is slightly below 0,1 mm (Meyer et al. 2017: 173). In turn, aluminum foil is 15 µm (MTI Corporation 2018d) with 0,12 mm calendered slurry thickness (Meyer et al. 2017: 173).

$Cell\ volume$:
$Ah = \pi r^2 \mathrm{h}$
$Ah\ =\ \pi * 10{,}25mm^2 * 70mm$
$\mathrm{Ah}\ =\ 23104{,}5\mathrm{mm}^3$

$Anode\ strip\ size$:
$70mm\ *\ (0{,}009mm\ +\ 0{,}097mm) *\ X$

Cathode strip size:
$70mm\ *\ (0{,}015mm\ +\ 0{,}119mm) *\ X$

$Separator\ strip\ size$:
$70mm\ *\ 0{,}016mm\ *\ X$

Equation:
$23104{,}5\mathrm{mm}^3 = Anode\ strip\ size + Cathode\ strip\ siz + 2 * Separator\ strip\ size$

$Strip\ length$: $X = 1214mm$

Formulas determine that the length of each strip should be about 1,2 meters. This information can be used later to calculate the need for production equipment.

4.1.2.3. Electrolyte slurry

Electrolyte gives the cell ability to conduct electricity. Lithium hexafluorophospate ($LIPF_6$) is used as the electrolyte salt and organic carbonates act as a solvent. These carbonates can be for example dimethyl carbonate (DMC), ethyl methyl carbonate (EMC) and ethylene carbonate (EC). Slurry weight percent are showed in following table (Table 2.) (Grützke, Kraft, Hoffmann, Klamor, Diekmann, Kwade, Winter & Nowak 2015: 83, 85).

Table 2. Weight percentages of electrolyte slurry.

DMC	EMC	EC	LIPF6	Other substances
30 %	22 %	30 %	16 %	2 %

As a conducting salt, $LIPF_6$ is a powder. Carbonates are liquid which will be evaporated at a later stage. Total amount of electrolyte slurry for one cell is 7 grams (Northvolt 2017) and the proportion of $LIPF_6$ is near 1 gram.

4.1.2.4. Cell case and cover

According to MTI Corporation (2018a) empty cell case is 70 mm long stainless steel case and it is cut from several meters long pipe. Cell also has both bottom and top covers which are made from stainless steel and inside the covers there is a nylon ring as an insulation and a seal. Electrode tabs will be welded in these covers so that electricity can flow from the cell and into the cell. One empty case weight is about 9,0 grams and with covers, total weight is about 10,5 grams. When considering outsourcing opportunities, empty cell case production is one of the most sensible stages to outsource.

4.1.2.5. Other materials

Finished cells are placed in molded modules so that each modules has 385 cells. Estimation is that one module requires approximately 4,5 dl i.e. 400 grams of polypropylene. Module wiring in series and parallel is done with thin copper stripe. 9,5 meters of copper stripe is needed for one module. Its weight is about 18,5 grams which means less than 2,5 cm and 0,05 grams per cell. The cells are soldered with aluminum in the strips as needed

4.2. Work stages

Each of stages is dimensioned so that when the factory works at full capacity, the 35 GWh annual production will be achieved. It means 364 000 completed batteries to electric cars. Following figure (Figure 9.) shows each stage maximum capacity with 24 and 16 hours production in a day. As shown in the figure, the most stringent utilizations are in electrode and electrolyte mixing, welding and drying stages. Wider utility can be found in coating, slitting and module molding stages. Some of the stages work with only one station but for example welding stage requires almost 90 welds to achieve needed.

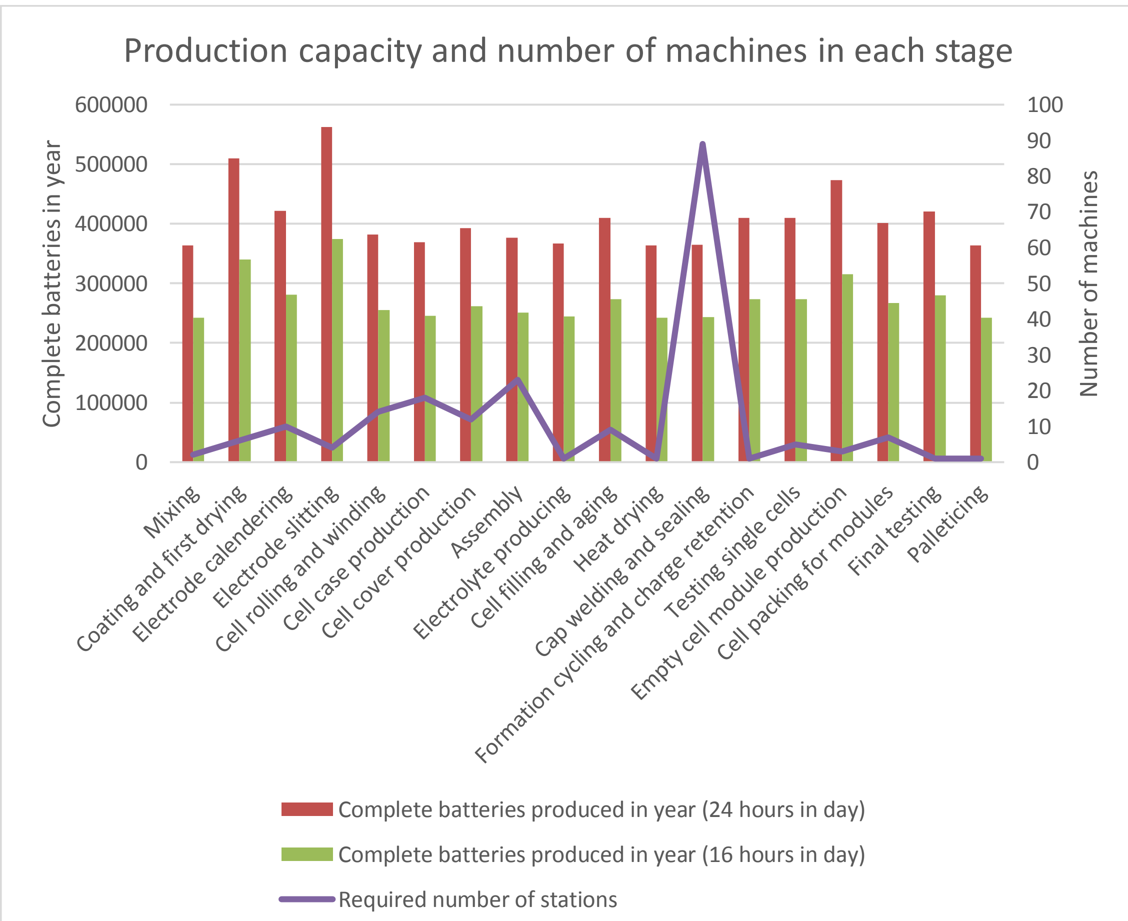


Figure 9. Stage capacity and number of machines

This subsection introduces the work stages of the case factory. The aim is to describe the use and change of raw materials between the stages and to explain the way the machines work in practice. Number and size of machines will also be explained.

4.2.1. Electrode manufacturing

Electrodes are made as a roll and various work stages has different capacity and working speed. Because of different number of machines between stages it is necessary to re-reel rolls after each step. Rolls can be moved either by means of conveyor belts, robots or automated forklifts. An easy way to complete these transitions is conveyor belts and robots; robot will lift the roll on the conveyor belt and after transition, another robot will place it to the next machine.

4.2.1.1. Raw material transmission and mixing

Disregarding solvent, slurry raw materials are powders. Every one of them needs own tank from which the material is transferred to the mixing tank along the pipe. Mixing phase takes almost three hours (Liu et al. 2014: 522, 524), and it means that mixing tanks have to produce slurry for three hours at a time. 31 grams anode slurry and 60 grams cathode slurry needed for one cell (Meyer et al. 2017: 173) and these can be used to calculate mixing tank sizes; 15 000 kg for anode slurry and 29 000 kg for cathode slurry.

In anode side, one mixing batch needs almost 7500 kg of graphite. 1 m^3 of graphite weights around 1350 kg (MTI Corporation 2018b) and hence, graphite tank must be at least 5,6 m^3. The bigger the tank is, the less often it will have to fill. In cathode side, LNMC tank must hold more than 16 000 kg and 7,4m^3. N-Methyl-2-pyrrolidone (NMP) can be almost entirely recycled so it does not need big tank. All raw material tank sizes shown below in table X.

Table 3. Raw material tank sizes.

	Minimum ability to hold (kg)	**Minimum ability to hold (m^3)**
Graphite for anode	7481	5,5
Super-P for anode	79,6	0,04
PVDF for anode	398	0,2
NMP for anode	531	0,5
LNMC for cathode	16318	7,4
Super-P for cathode	577	0,3
KS-6 for cathode	1444	0,8
PVDF for cathode	1155	0,6
NMP for cathode	421	0,4

Figure 10 clarifies mixing section. Three tanks can be seen in a row and between them, transferring pipes move the slurry to the next tank. Additionally, even though it does not appear in the figure, solvent recovery system transfers recovered solvent to the first tank where raw materials are already placed. Tank in the middle stores mixed slurry before dosing tank feed the slurry into the coater.

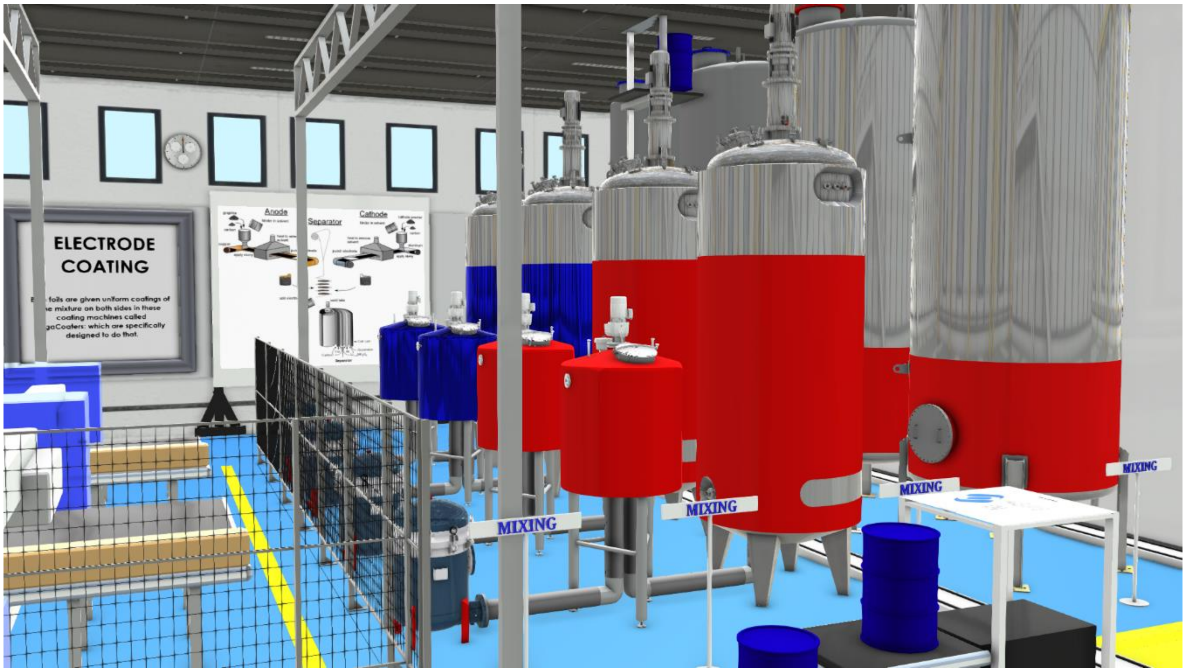


Figure 10. Mixing tanks (Tajudeen 2018).

4.2.1.2. Electrode coating

After mixing, slurry will be stored at the storage and dosing tanks. These tanks have to be as big as mixing tanks. The slurry is applied on both sides of the foil by a coating machine so that to square meter area of copper foil is placed 238 grams of anode slurry and of aluminum foil is placed 550 grams of cathode slurry (Meyer et al. 2017: 173). Foil width is 2125 mm and there are 25 pieces of 70 mm wide coating areas with a 15 mm blank foil in between. Overall, 82% of the foil is coated with a slurry. According to Meyer et al. (2017: 173), copper foil is coated on both sides with a 135 µm slurry layer and aluminum foil is coated on both sides with a 125 µm layer.

Nowadays, best available technique for coating is Babcock & Wilcox Company's GigaCoaterXL. It can coat 2200 mm wide foil and its working speed is 60 meters in minute. Thus, needed number of coaters for meet wanted capacity is three for anode production and three for cathode production and each of them are abt. 76 meters of length with 3,2 meters width and 3 meters height. Figure 11 elucidates the operation of the coater. (Babcock & Wilcox 2018b).

Figure 11. Coater, GigaCoater (Babcock & Wilcox 2018b).

4.2.1.3. Solvent Recovery System

Solvent recovery system aims to reduce solvent consumption in electrode manufacturing. It comprises from recycling system and sustained emission combustion. The next chart shows the parts of the system (Figure 12, Thomas 2017). Emission concentrator and carbon bed is possible to combine for these two lines but in other respect both anode and cathode lines requires mainly their own system because recovered NMP solvent contains residues of anode and cathode active material.

Filter, heat exchange and demister needs about 20 m^2 space together (4 meters width and 5 meters length) and tanks volumes for unprocessed solvent, distillation and processed solvent must be near 9 m^3 (Thomas 2017). Diameters for tanks should be 1,5 meters if these tanks are 5 meters high.

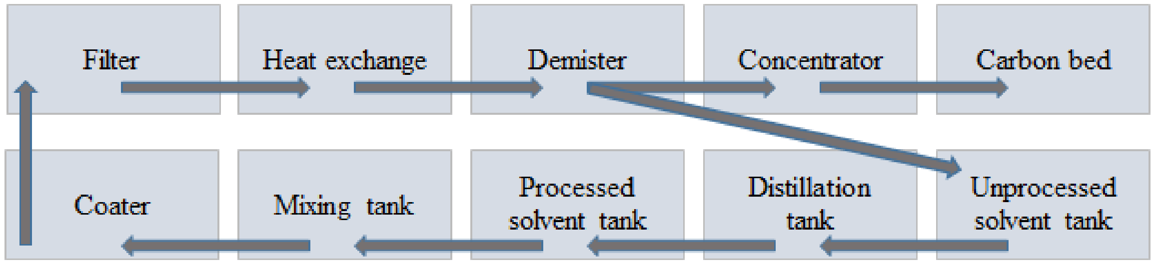


Figure 12. Solvent Recovery System (Thomas 2017).

This closed-loop system removes slurry by using heat. After this, heat is taken apart from slurry and it can be reused in drying section. The slurry is refined and purified in the order shown in above figure (Figure 12.) and eventually it can be returned to the mixing tank and later to the coater. (Babcock & Wilcox 2017a)

4.2.1.4. Electrode calendering

Coated film rolls can be transferred to the calendering machines with conveyor belts aided by robots. Figure 13 shows how coated foil is fed into the machine. Pressure rollers thinner the foil and after calendaring the foil is reeled again.

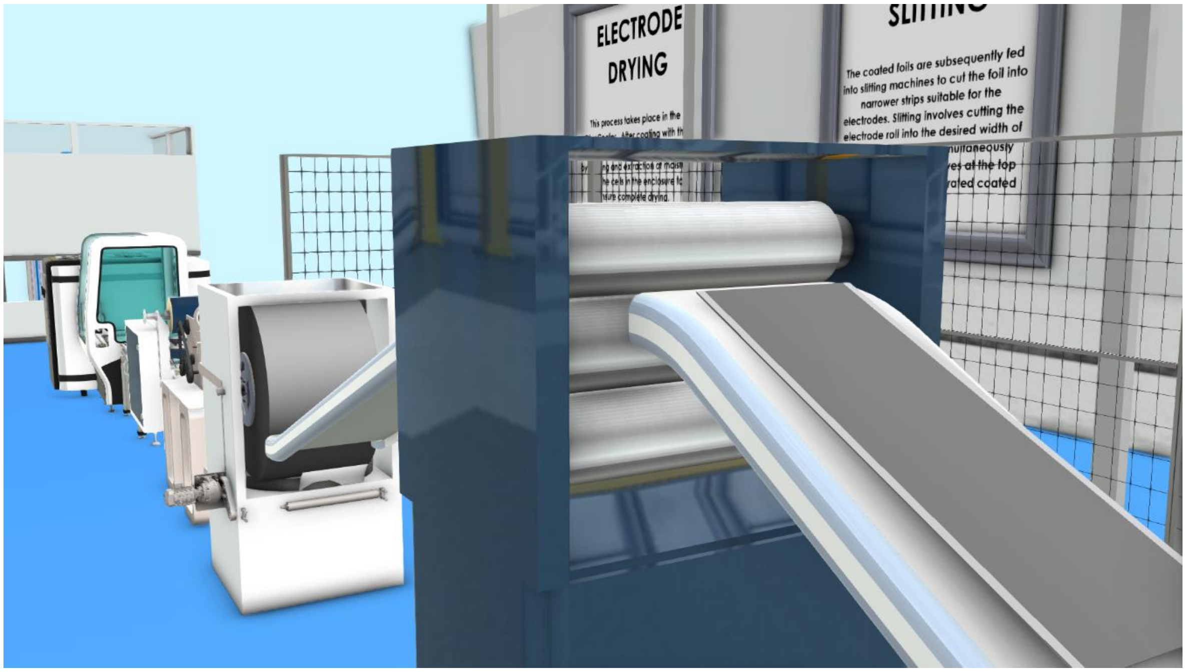


Figure 13. Calendering machine (Tajudeen 2018).

Efficient calendaring machines calender 30 meters foil in minute (Alibaba 2018a). Desired number of produced meters is near 130 meters in minute. Hence, totally 10 calendering machines needed and divided, 5 in both lines. The dimensions of each machine are approximately 4,5 meters width and 5 meters length. Due to calendaring, total thickness of coated anode foil decreases from 0,28 mm to 0,17 mm and cathode foil thins from 0,26 mm to 0,16 mm.

4.2.1.5. Electrode slitting

Calendered foil is transferred to the slitting stage with conveyor belt and robot. Now, wide coated foil is cut into the slices. The most powerful slitting machines process up to 100 meters of foil per minute (PNT Inc. 2018). Due to this, only 2 slitting machined is required in both anode and cathode sides. Slitting machines for 2,2 meters wide foil can not be found on the market, but such a machine is possible to make. This machine dimensions are near 4 meters wide and 4,5 meters length.

Figure 12 describes way the slitting machine works. System push coated foil from the right side of the figure through the stage. Blades cut the foil as desired, in this case to the 7 cm wide strips. Also slitted foil is shown in the figure 14. After slitting the electrode is ready for winding and assembly.

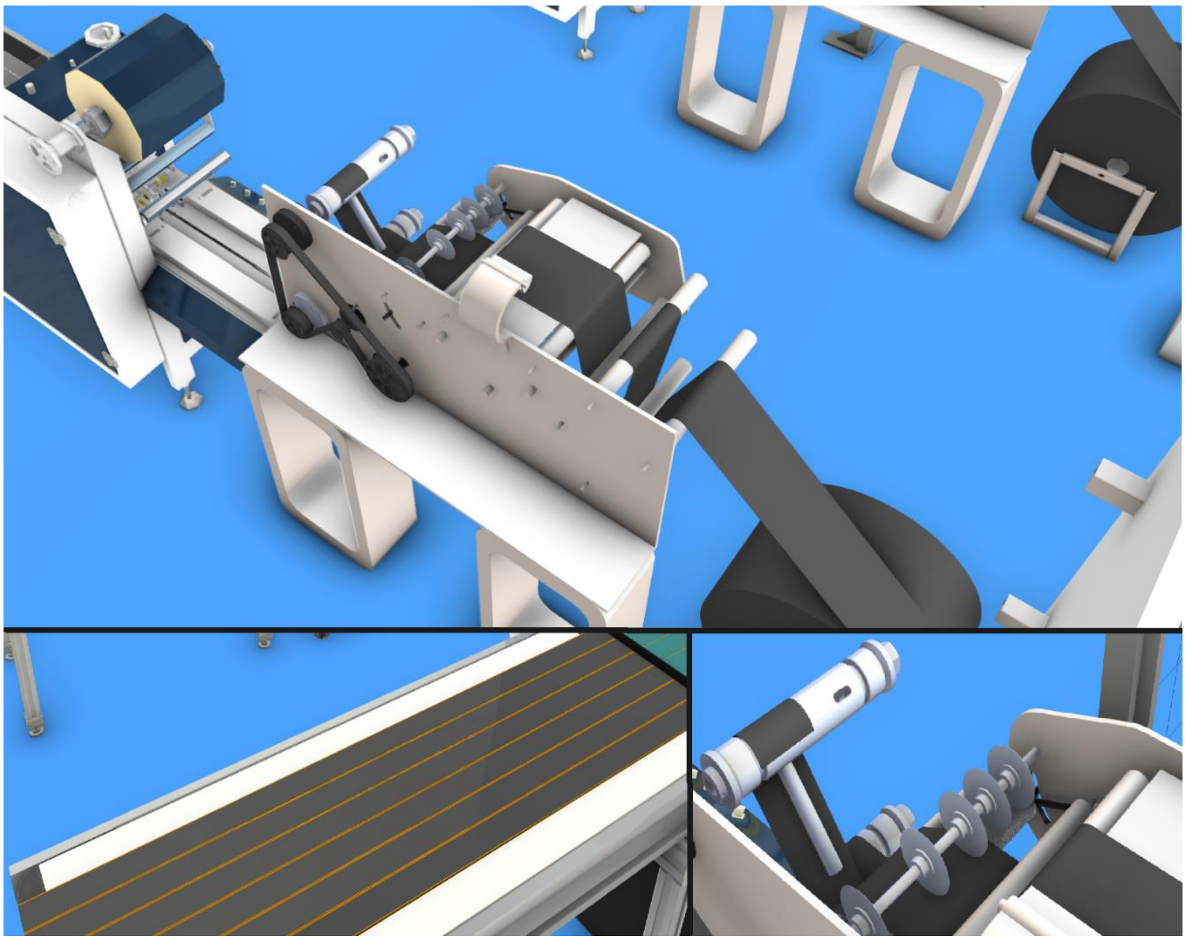


Figure 14. Slitting machine (Tajudeen 2018).

4.2.2. Cell assembly

Cell assembly includes the stages from electrode winging to cell sealing. During these stages cell cases are manufactured, filled with electrode and electrolyte, dried and finally sealed.

4.2.2.1. Electrode winding

The purpose of the winding machine is reeling four rolls into a tight roll. These rolls are anode, cathode and two separator rolls and in our case, each of them is about 7 cm wide. There will also be at least 4 assisting robots in winding stage whose task is to ensure that these rolls are constantly available to the machines.

Separator is placed between positive and negative electrode so that they do not touch each other. Each roll is fed to the machine at the same rate and meanwhile time they are winded in tight wraps. When the roll is of the right size (about 2 cm diameter), stripes are cut off and the machine will automatically continue rotating next reel. (Reinhart et al. 2011.) At the bottom of the reeled roll there is a tab of the positive electrode and at the other end a negative electrode tab.

Figure 15 presents the design of the winding machine. Described reels rotate as shown and electrode rolls will be finished inside the white box. As can be seen in the figure, several electrode rolls can be reeled at once. However, it is considerable that when using dual (two side) coating method, separator is required on the both sides of the reel. In other words, another separator roll is needed in this stage.

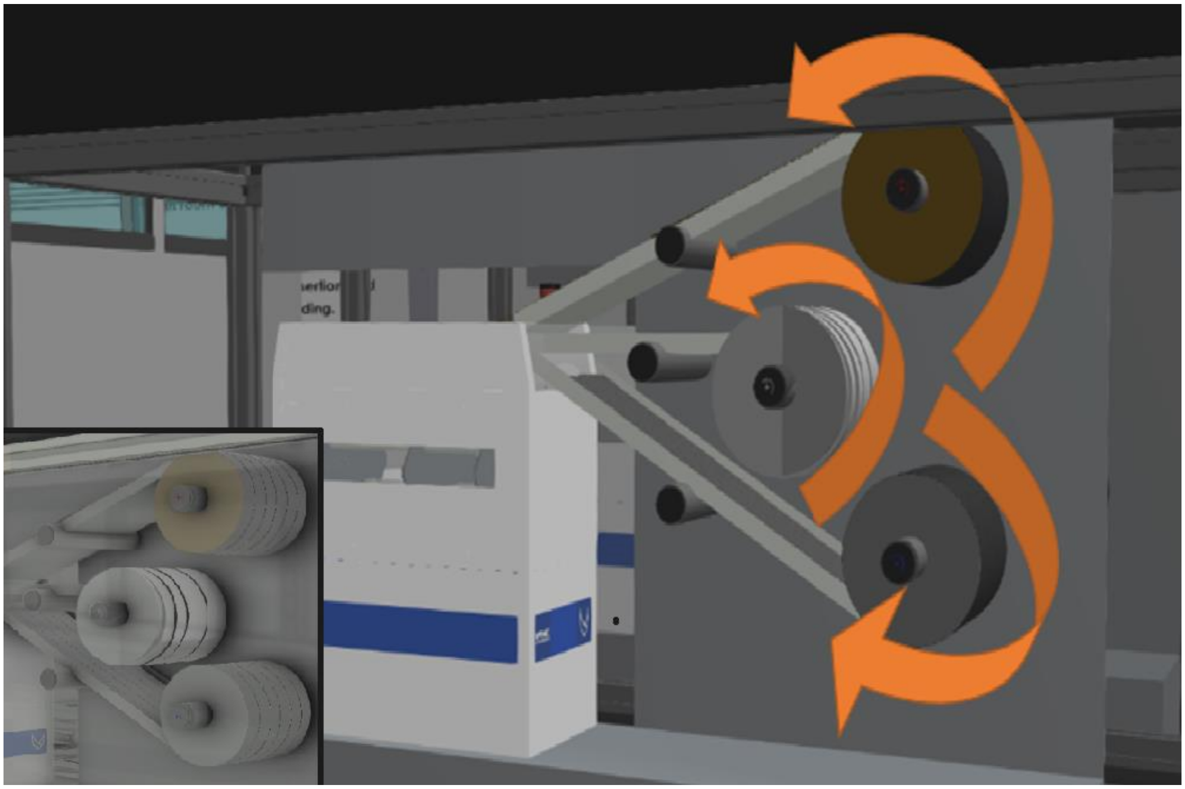


Figure 15. Winding machine (Tajudeen 2018).

There are machines on the market that can produce 10 cells per minute of strips of our length (Xiamen Tob New Energy Technology Co. 2018). However, it is desirable that the cells can be manufactured effectively and that is why it would be good to have machines that could rotate multiple cells in parallel at once. If the machine produced 20 cells at once 10 times in minute, the total number of needed machines would be 14. Size for one this kind of winding machine is probably almost 4 meters wide and less than 2 meters long.

4.2.2.2. Cell case production

Circular saw will cut 70 mm pieces from long stainless steel pipe. Thickness of pipe edge is 0,5 mm and that is how each case weights just over 9 grams. The sawing process is automated and the material feed is continuous. It is possible to cut several pipes at once with one saw. If the saw cuts 10 cases 15 times in minute, 18 circular saws are needed to meet the 1,4 billion cell annual volume. Because of length of steel pipes, saw dimensions are about 8,7 meters in length and 2 meters in width.

Cell covers are made from same material than cases. Major difference is that plates are used instead of pipes. Cover diameter is 21 mm and its weight is less than gram. Cover saw has many blades and it can cut 40 covers at once. The saw cuts new batch in every 5 seconds and because every cell needs two covers, desired numbers of caver saws which is 12. In case of overheating, a water cooling system is connected to the saws.

Cut cover plate is cold pressed to achieve wanted shape. Due to cold pressing, cover can be clamped with cell case. The spinning rollers shape circular metal sheet to be a cover (Ernst Grob AG 2017). The cover forming process needs only one forming step and that is why the processing time is assumed to be less than two seconds. However, totally 90 spinning roller pairs are needed to product bottom and top covers.

Both cases and covers are conveyed by chute conveyors, from which the robots combine bottom covers with cases before placing electrode roll. When placing a cover to the cell, a nylon ring is inserted inside (MTI Corporation 2018a). Its function is to prevent the flow of electricity from the cover to the cell case. In addition, it helps to seal the cell.

4.2.2.3. Assembly – electrode placing to the cell case

Next stage is assembly where robot will put winded electrode roll into the cell case so that electrode tabs can be connected later by welding. In this stage, bottom cover is already set in place. The cell cases move in conveyor belt in suitable batches and the robot fills them. If robot places 10 electrode rolls at the same time to the cases in every 5 seconds, 23 assembly robots is needed.

4.2.2.4. Electrolyte production, electrolyte filling and wetting

In electrolyte production, carbonates will be mixed together. Then, conductive salt is added to the solvent and the slurry can be transferred along the pipe to the electrolyte filling stage. Electrolyte mixing is implemented as closed-loop system and filling is placed in vacuumed room, because electrolyte decomposes when in contact with air (Electropedia 2018).

Slightly less than 10 cm^3 of electrolyte mixture is needed for one cell. Dosing is executed by robot while cell cases are moving on the conveyor belt. The belt is programmed to collect 25 cells in a row and one robot has as many dispensing nozzles. Robot can fill these size batches 12 times in minute and one robot capacity is 300 cells in minute. Thus, 9 filling robots are required to meet 1,4 billion cell production in year.

Wetting is constituent part of electrolyte filling. It will be implemented by large automated storage shelfs, robots and conveyor belts. Bigger batch size reduces the number of shelves and with continuous production it will not cause breaks in production. For example, if the batch size is 2500 cells, the new batch will pass the stage in every 56 seconds. With 24 hours wetting time (Pfleging & Pröll 2014) it means 3068 wetting shelves. Each batch needs about 15 cm of height, so the shelf can have 53 layers. In the circumstances, shelf length must be 75,4 meters. If there is two shelves, both of them are 37,7 meters long. Elsewhere Wu, Liao, Wang and Wan (2004) told, that vacuuming reduces the wetting time to a few hours. With 6 hour wetting time only 384 wetting shelves needed, meaning 10,4 meters long shelf.

Wetting section is mounted a same way than later presented heat drying and formation cycling stages. Figure 16 shows how these sections operate. Cells are transferred via conveyor line. Then, an automated system picks cell batches by cross belt sorter which moves cell to the wetting, drying or formation. The figure shows stages as follows: orange racks mean wetting, green racks heat drying and blue racks are for formation cycling and charge retention. Additionally in real life, welding section would be between drying and formation phases.

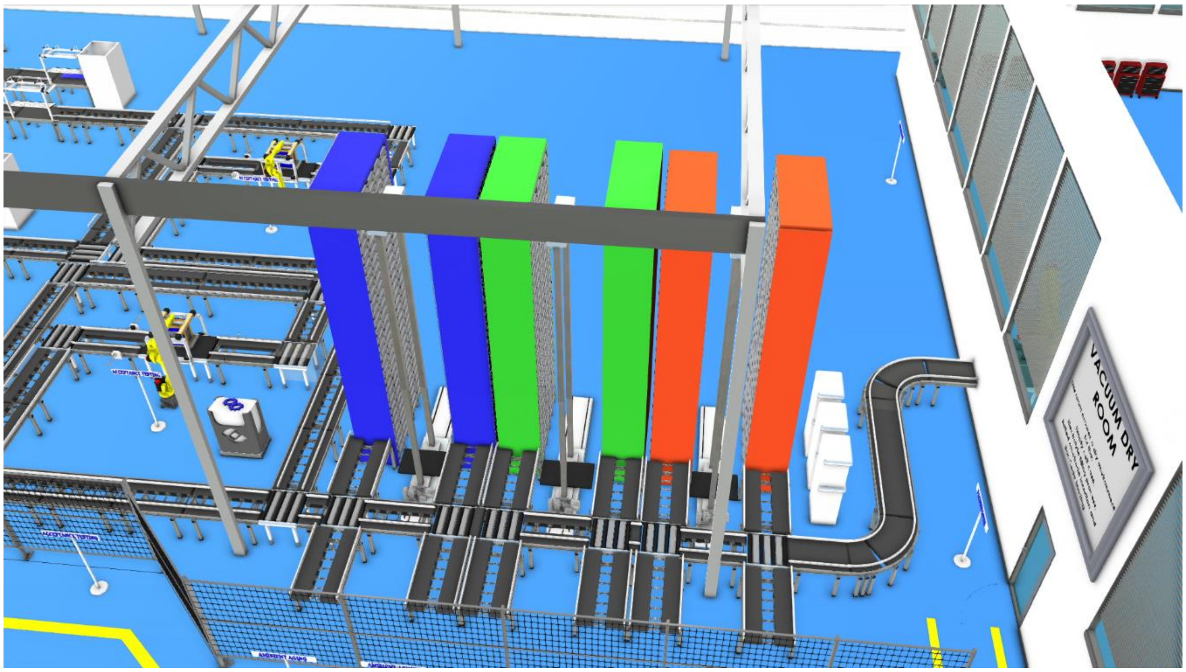


Figure 16. Wetting, heat drying and formation racks (Tajudeen 2018).

4.2.2.5. Drying

When the cells are wetted, excess solvent must be recovered from them by heat drying. It is next phase for wetting and in here, cell batches from wetting keep going to the drying ovens, which are implemented mainly same way than in wetting stage. Drying takes 3 hours (Schalkwijk & Scrosati 2002: 179) and by previous dimensions, 192 oven lockers are needed. One oven dimension are assumed to be 1,5 meters of length and width and 0,5 meters of height. It means 16 layers in drying shelf and 12 ovens in a row (18 m).

4.2.2.6. Welding and sealing

Dried cell cases must still be vacuumed until they are sealed. Bottom cover is already placed in case and now robot places corresponding the top cover. The robot places cover on the top of cell case, welds it from the bottom and the top before moving to the next cell.

Next thing to be done is electrode connection with covers. Conveyor belt brings cells to the robot and weld seam will be done by robot with automated laser. Welded tabs allow electricity to move into and out of the cell. Positive electrode tab is spot welded with top cover and negative tab is connected with bottom cover. One cell tab weldings take less than two seconds in automated process (New Amada Miyachi Europe’s laser welding capabilities 2017). Under the circumstances, 45 laser welding machines are needed for bottom tabs and 45 for top tabs. Each welding robots dimension are less than 2 meters of length and 1 meter of width (ABB 2018).

The last step that must be carried out in the vacuumed space is sealing. It is also sensible to do as above by welding because another option, the heating process, needs more time (Electropedia 2018; New Amada Miyachi Europe’s laser welding capabilities 2017). The cell case is welded from the edges of the covers so that it prevents the contact of the components with air. Sealing stage requires as many welds as tab welding so the total number of welds is 180.

4.2.3. Formation cycling

Cylindrical lithium battery cells, which are produced in this factory, are 1C type. It means that charge current is 1 times the rated capacity. Cells must have at least three charge and discharge cycles (An, Li, Du, Daniel & Wood 2017; 849). Based on An et al. (2017; 848) study, it can be said that three charge and discharge cycles takes about 6,6 hours. With 2500 batch size, 422 formation cycling points are needed. It means that one batch will pass the stage in every 56 seconds.

Formation cycling stage is implemented in the same way than electrolyte wetting and drying stages. Conveyor belts transfer batches and by means of robots, they are moved to the shelf where the formation takes place. One formation batch is 1,5 meters wide, 1,3 meters long and it needs 0,4 meters of height. 20 layers can be overlapped and hence, there will be 22 lockers in a row. Totally two 16,5 meters wide shelves are needed. Figure 17 exhibits the rack solution from factory 3D model. Each batch has own locker and when the batch is formatted, it will be moved to the next stage by high technology conveyor belt which has robot. Also wetting and heat drying racks are implemented same way. After formation, robot will automatically move batch to the conveyor belt from where finished cells continue to cell testing and module packing.

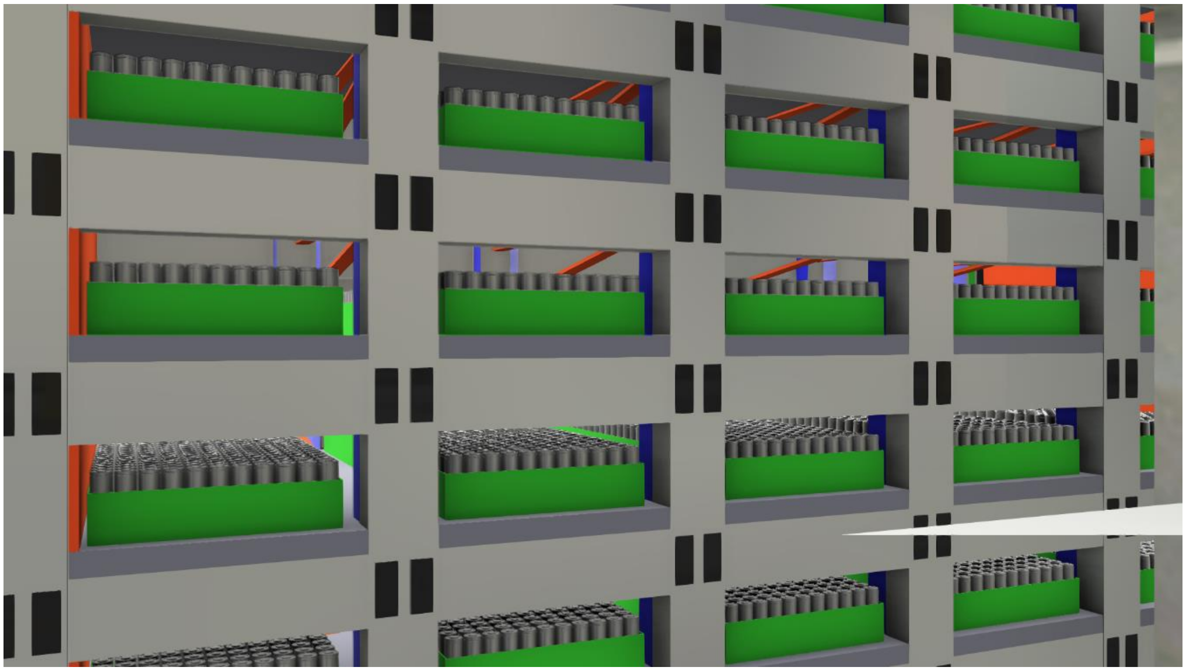


Figure 17. Cells in formation cycling rack (Tajudeen 2018).

In single cell acceptance testing each of cells have tested. Cell can fail, for example, in electricity conduction, charge retention or voltage. In total, 5 testing robots needed to meet desired capacity. One robot tests 50 cells at once which means that 2500 cell batch testing takes little more than 4 minutes. Testing robot in action can be seen in figure 18. In case of faulty cells, they are removed and cells are rearranged before packing into the modules.

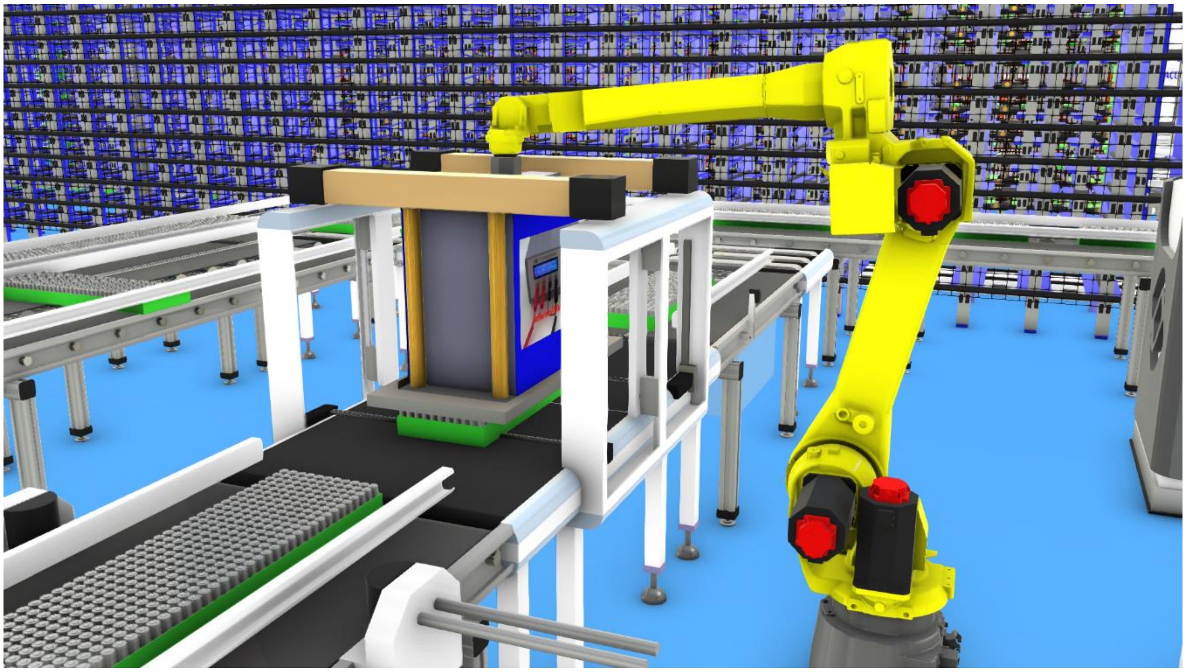


Figure 18. Single cell testing (Tajudeen 2018).

4.2.4. Cell module production and packing

As mentioned above, modules are made by injection molding. Molded module consists of two plastic parts. The total production time for one molded part is about 10 seconds and approximately half of the molding time is for cooling (Nykänen & Höök 2015; 3). Almost 7 module bottoms and covers are needed in minute. To achieve it, the factory requires 3 injection molding machines. A normal dimension for one molding machine is about 7 meters long and 2 meters wide (Alibaba 2018b).

When module parts have molded, 385 cells are placed into the bottom of the module. Totally 7 robots fill modules by lifting cells from batched of 2500 cells to modules of 385 cells. Defected cells are removed and recycled before module filling to ensure the car battery working. Robot operation is described in figure 19. Robots move cells to the modules before cell wiring.

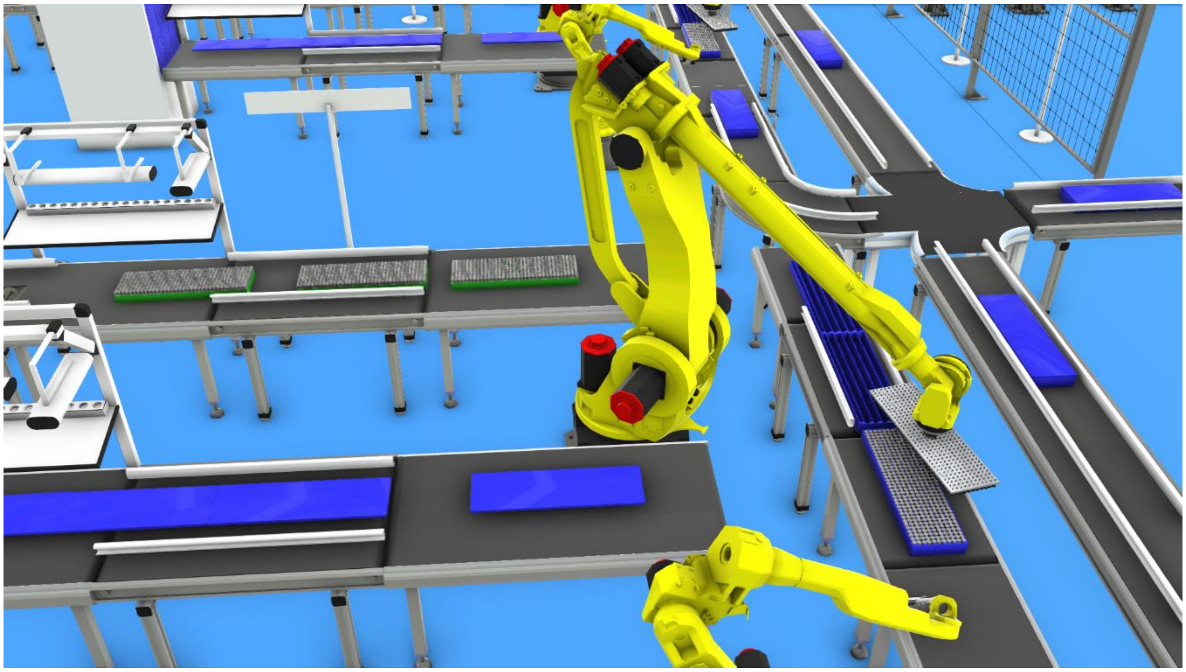


Figure 19. Module assembly (Tajudeen 2018).

Copper connection stripes are already placed on the bottom and top of cells. A module is transferred to the final welding stage, in which cells are connected together. Voltage of the completed car battery tends to be about 400 V (Tesla 2013; 4). Thus, each of the ten modules has a voltage of 40 V. It is achieved by connecting 9 or 10 of 4,2 V cells in series. Then the series are connected in parallel.

The best available technique to connect cells is still a laser welding which can weld 60 spots in minute (Metalworking World magazine 2017). Cells are welded both to the bottom and to the top and one module welding takes almost 13 minutes. Connecting 7 modules in minute can be done with 90 welds. When the cells are wired, the module is covered with top part of module.

When the cells are connected and modules are covered they will be tested for the last time. Conveyor belt transfers modules to the testing machine in which will be tested module's voltage and capacity. Now the module is ready for palletizing and shipping if it passes the inspection. There is no need to have more than one testing machine because maximum production volume is near 7 modules in minute.

If they pass the test, the next step is transferring to the palletizing stage. Conveyor belt conducts them to the palletizing robot, which stacks them to the EUR-pallet. Pallet's carrying capacity is 1500 kg (European Pallet Association 2018). Hence, on one pallet can be stacked 6 layers of 6 modules, one module having dimension approximately 25 cm * 80 cm. The height of the loaded pallet is 65 cm.

The maximum capacity of the factory is one module in every 9 second. It can be achieved with one palletizing robot. Conveyor belt transfers finished modules to the stage. Robot collects two pallets at once and when the pallet reaches the desired height it will move to the plastic wrapping. This can also be seen in figure 20.

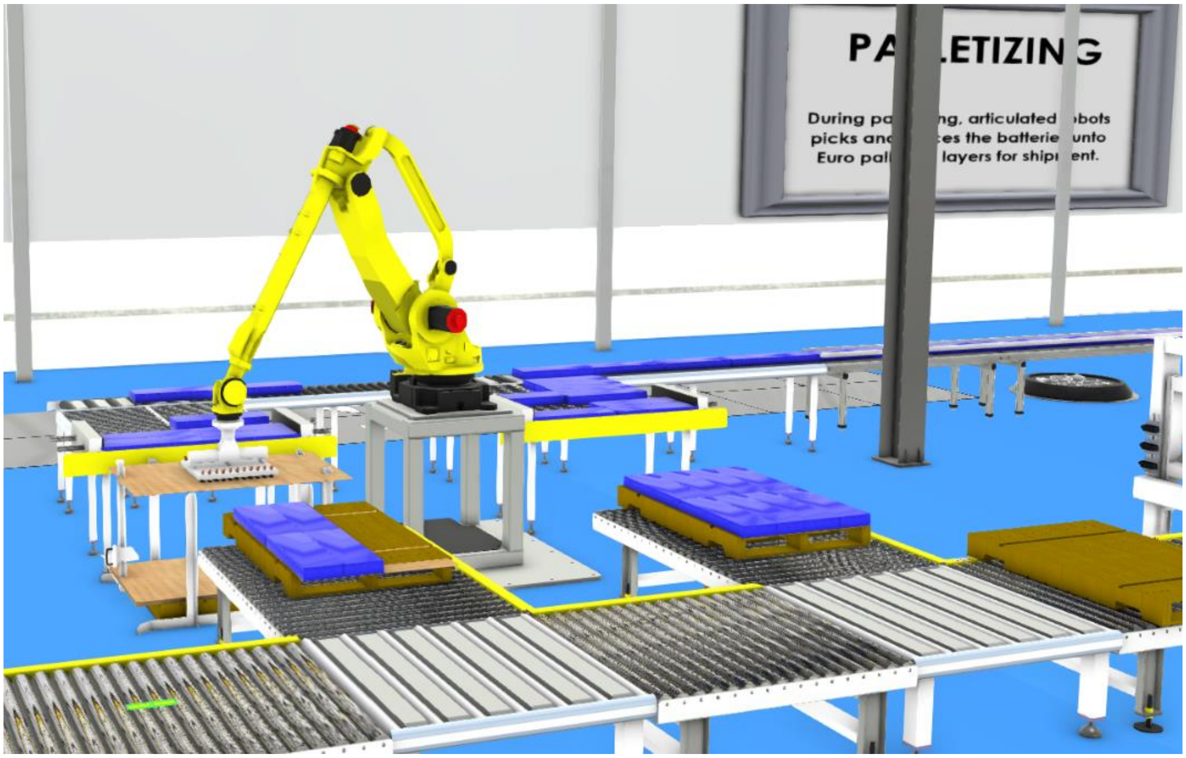


Figure 20. Palletizing robot (Tajudeen 2018).

Loaded pallet is transferred to the plastic wrap packing machine. Figure 21 shows how module pallet is stopped at wrapping machine. The pallet will be wrapped to withstand truck transportation better. After wrapping, pallet is moved to the shipping area by automated forklift. Another option is conveyor belt system directly to the trucks.

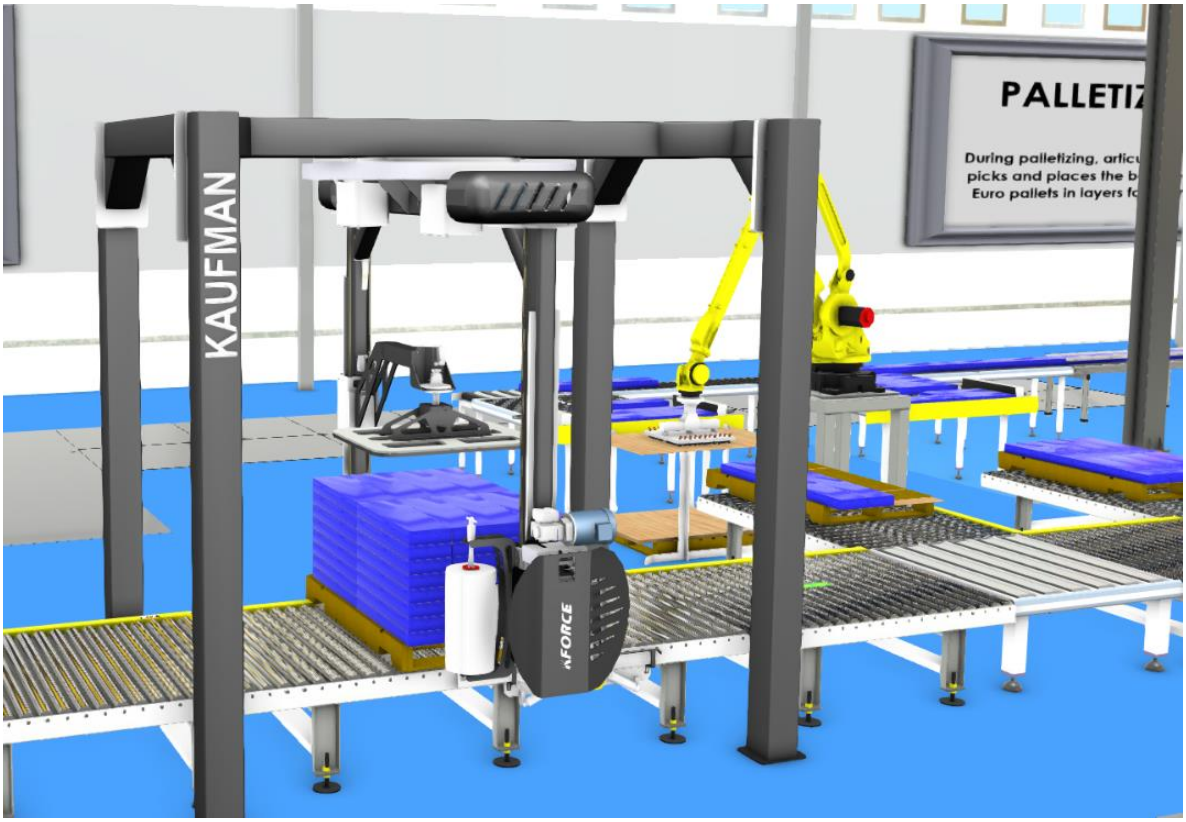


Figure 21. Plastic wrapping machine (Tajudeen 2018).

4.3. Space and Layout

Physically, the factory consists of many sections, such as storages, equipment, conveyors, paths, monitoring space and receiving and shipping halls. All of them need their own space, but the overall space need depends on how well they can be merged.

4.3.1. Space for raw materials

The objective is that the material and goods are not unnecessarily stored. Means that except for the necessary storage steps, such as wetting and drying, there are no intermediate stocks in production line. The raw material storage can be located into one or more parts. For example, cell case and cover materials, electrolyte substances and wiring stripes can all be stored in their own spaces but though, the size of the storage shelves does not change. The following figure shows the space needed to store the raw materials in cubic meters. The ceiling height is 8 meters and it is the main determinant of the amount of layers. In figure 22 can be seen space needed for each of raw materials. The left side of the graph has a scale for layer amounts for each raw material shelves. On the right side, the total space need of each material is shown. For more information, see the attachment 1 at the end of study.

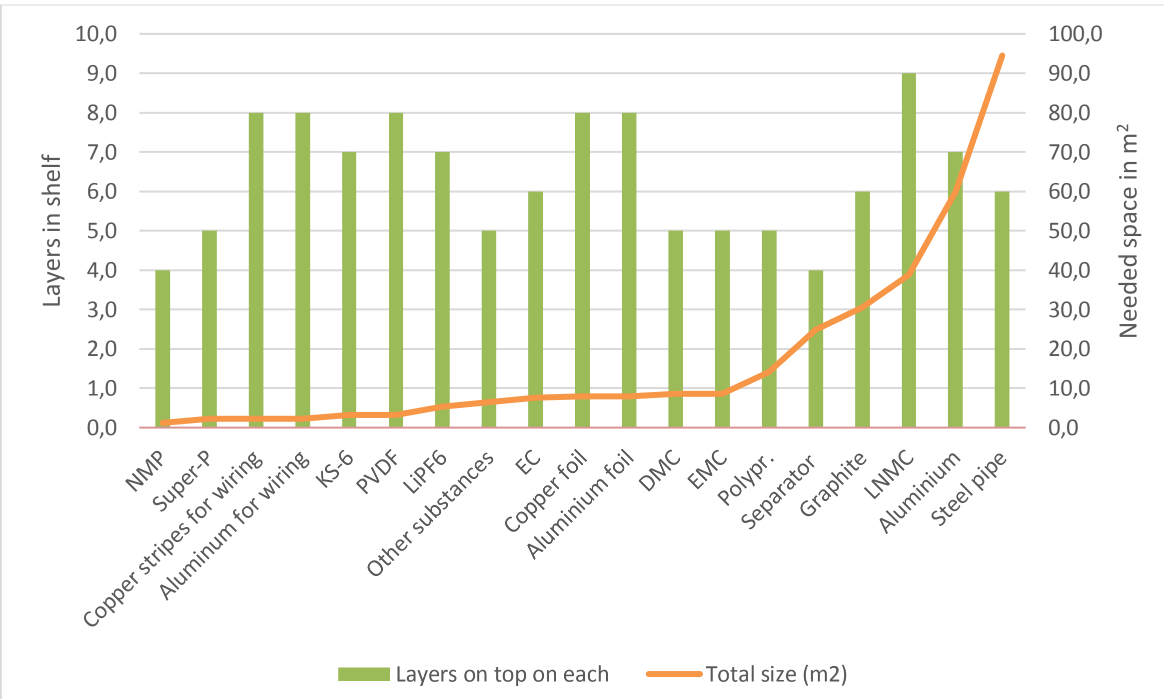


Figure 22. Raw material storage space.

4.3.2. Space determinants for each stage

To get desired capacity requires several machines, assisting robots and conveyors in most stages. Naturally, more equipment needs more space. In the following graph (figure 23), number of machines and conveyor belt lengths are presented for stages from electrode manufacturing to electrode placing into the cell and filling with electrolyte.

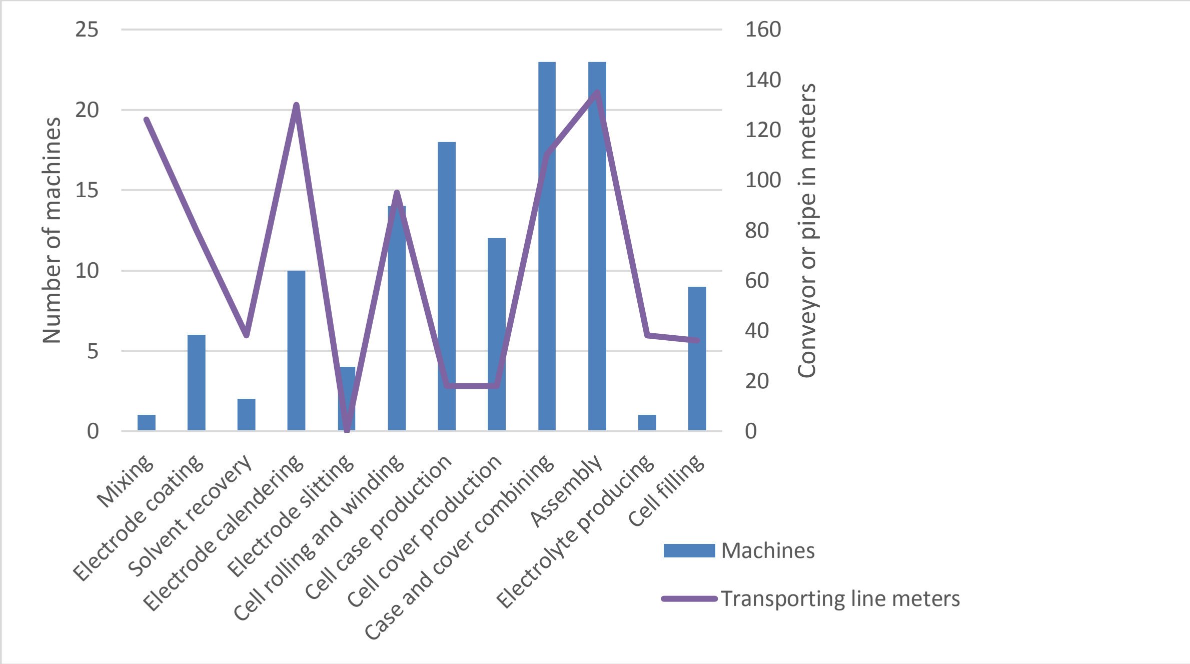


Figure 23. Amount of machines and length of conveyors I.

The rest of the work stages are presented in the following chart (figure 24) to improve comprehensiveness because the scale would be too extensive for many stages. Notice that number of lockers for wetting, heat drying and formation cycling have been notified as machines (see figure 17).

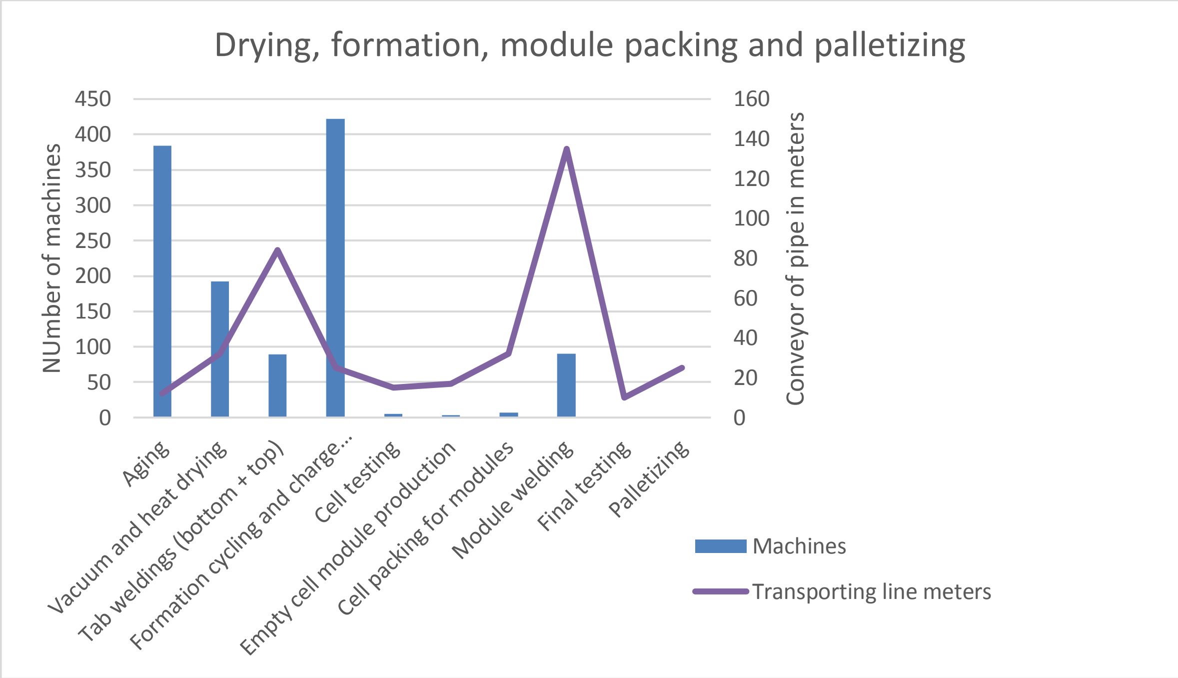


Figure 24 Amount of machines and length of conveyors II.

Many of the transporting lines are just normal conveyor belts, but some of them are chutes and cross belt sorters, which means that there are automated crossed belts in conveyor which moves goods to other stages. Below figure from drying racks (figure 25) clarifies the way the cross belt sorter operates. Occasionally, the material is also transferred along the pipes. This is accomplished when the material is in a liquid or paste-like form, i.e. in electrode slurry and electrolyte mixing stages.

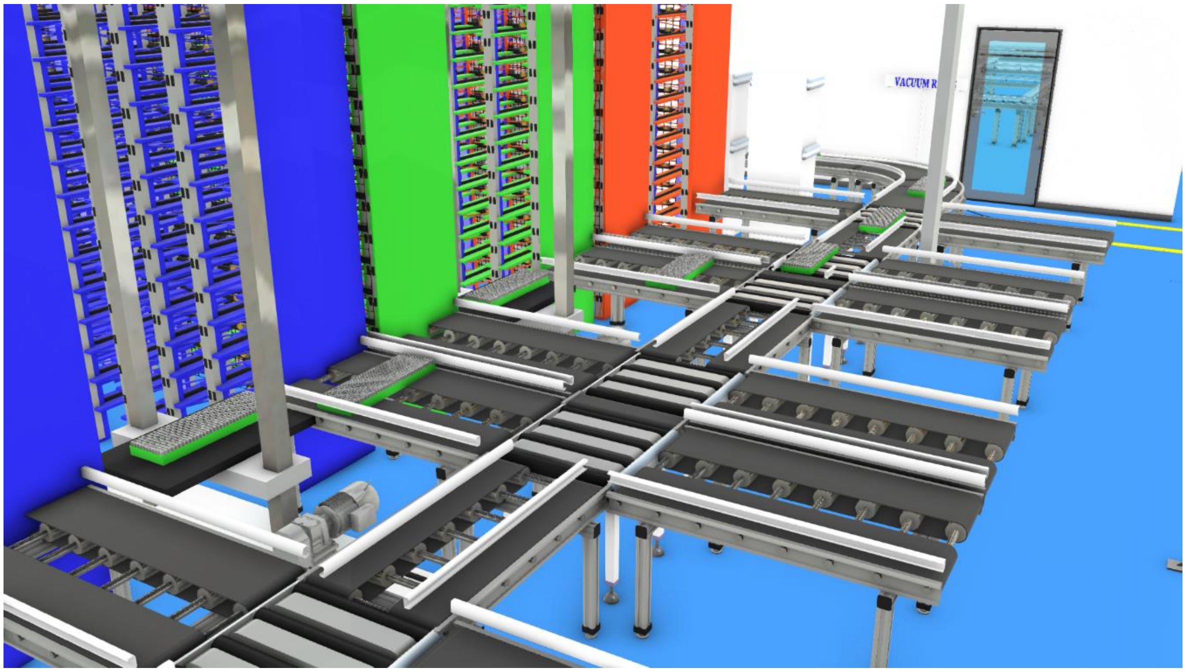


Figure 25. Cross belt sorter (Tajudeen 2018).

The material and goods transferring are implemented in many cases with help of assisting robots. These robots pick products to the conveyor belt along which the transfer to the next point takes place. In addition, robots may form larger batch of individual cells. Total amount of this kind of assisting robots is assumed to be 22 (Figure 26), but it strongly depends on the capabilities of manufacturing machines.

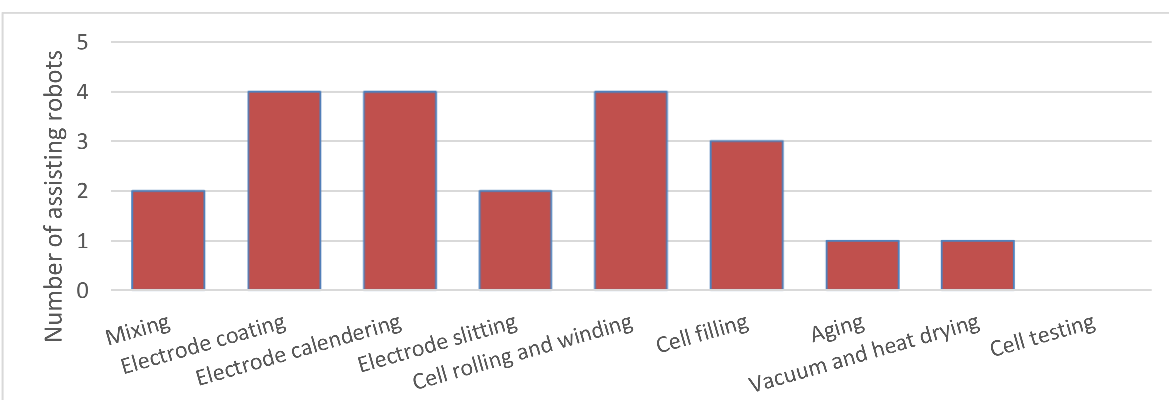


Figure 26. Assisting robots.

Wider collection from machines, robots and conveyors needed in production can be found in attachments section in the last page of the study.

4.3.3. The factory layout

The total space need for stages from goods receipt to winding, in other words electrode manufacturing is less than 9000 m^2. Tightly assembled equipment need 130 meters of space, which is about 66 meter wide. Respectively, assembling, formation and shipping area needs about 6000 m^2 space; 89 meters of length and 68 meter of width. Thus, the factory is near 14500 square meters in total. Later in figure 27 is shown the potential production line layout.

Systematic production line is easy to fit into a small space. However, especially assembling stages have multiple robots and workstation closely which may require additional space for maintenance work. Though, it has been taken into account that the maintenance of one device does not stop the whole line. Other thing to consider about is material transferring between stages which is, in this case, mostly carried with conveyors. In table 4 can be seen that total space for production stations are 7700 m^2 but it does not include conveyor belts and maintenance space around the equipment.

Table 4. Space for stages.

Stage	Width, meters	Length, meters	Total, m2
Raw material storage	25	25	625
Mixing	19	3	114
Coating	17	76	2584
Solvent recovery	4	14	98
Calendering and Slitting	25	16	800
Winding	35	13	455
Cell case sawing	21	18	378
Space for pipes	16	18	288
Cell cover sawing	11	17	187
Space for plates	12	17	204
Combining	9	34	306
Electrode placing	17	17	289
Electrolyte mixing	7	5	35
Cell filling	9	6	54
Assisting robots	9	2	17
Wetting	12	3	30
Heat drying	11	4	39
Welding	12	35	420
Formation cycling	6	17	99
Testing	3	12	36
Injection molding	6	16	96
Packing into the modules	5	12	54
Module welding	20	18	360
Module testing	2	2	4
Palletizing area	14	8	112
Total			7684

The material flow is very simple in the factory. Also, the production volume is large. Because of these, production line is only reasonable option for layout type. In following picture (Figure 27) is presented the production space. Space boxes for stages includes machines and robots needed in production but the conveyors are placed either inside or outside the boxes.

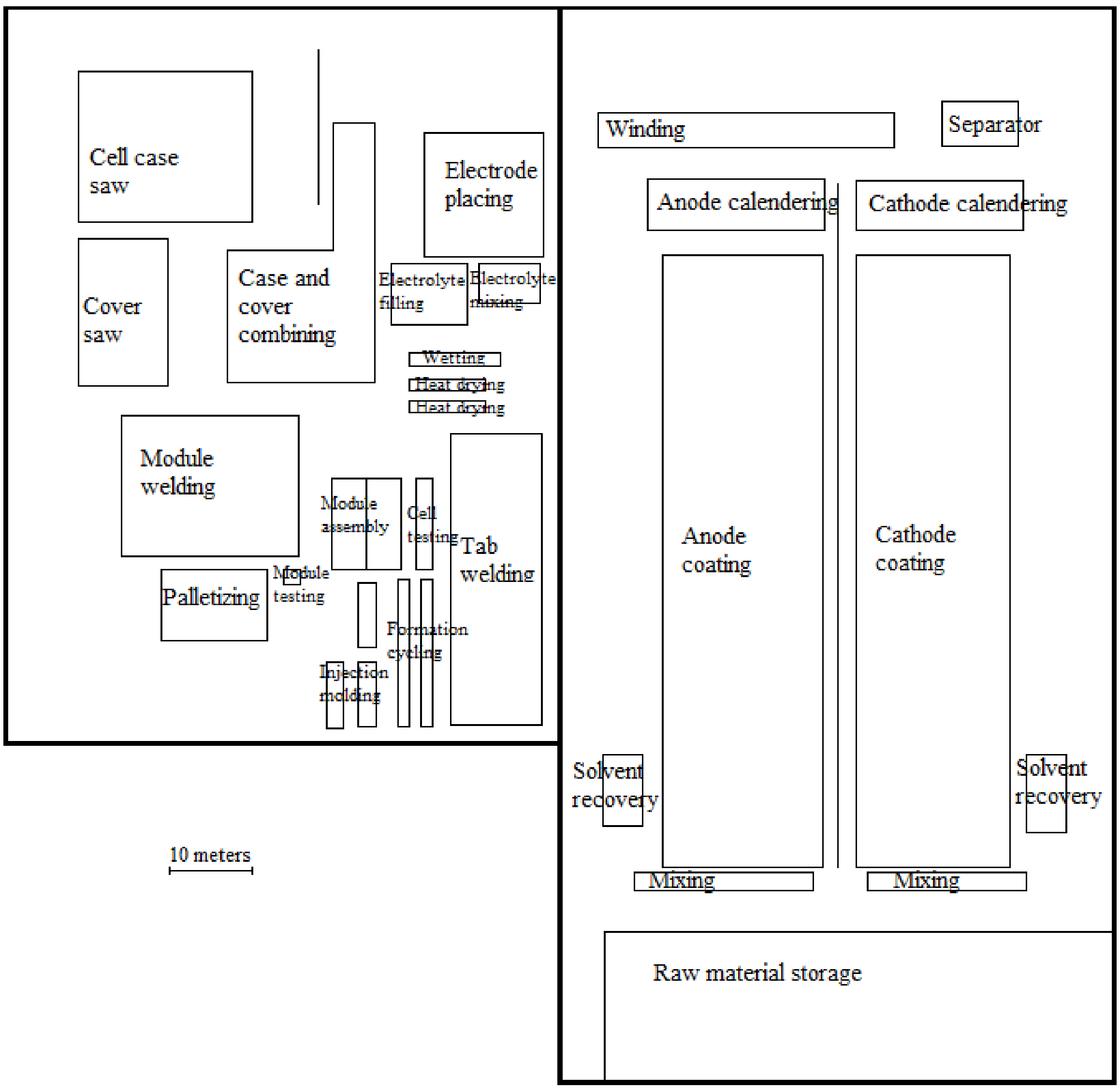


Figure 27. Factory ground plan.

4.3.4. Other necessary space

There is also other space in the factory than the space needed for production. Requirements for them is not of primary importance in this study but still need to be aware of their existence. These are for example monitoring room, maintenance spaces and server room.

One possible option for monitoring room placing is between electrode manufacturing and cell assembly areas because it would minimize movement due to maintenance. The factory ceiling height is 8 meters and hence, the monitoring room can be built to the second floor. If this is the case, no need to increase the factory size due to the monitoring room.

Basic maintenance tools are worth to put near machines and access to them should be unobstructed. In most cases, these tools do not need a lot of space and they are possible to place with machines.

The server room space size is unknown but if it is not outsourced, it can be placed in spacious raw material storage.

4.4. Logistical issues

At this point is assumed that both inbound and outbound logistics are implemented by trailer combinations. In Finland, maximum total weight for 7 axle combination is 60 tons (Finnish law 2013/407: § 20) i.e. the maximum weight of the cargo is about 35 tons. The same relegation (§ 24) determines the load volume to be about 130 m^3. However the stainless steel pipe, the lightest material needed, weighs only 370 kg/m^3 (MTI Corporation 2018a) and therefore the weight limit is the only determining factor.

Most of materials are imported by using EUR-pallets. The height of the pallet depends on material density because the pallet weight limit is 1500 kg. The powders are also packed into barrels that are transported on the pallets. Because there is not yet information on the availability of materials, it is assumed that the material is available for the desired time. In addition, each raw materials are transported by their own truck. The delivery of the material is expected to last two days after ordering. In figure 28 below is presented raw material consumption (scale on the left) and average number of truckloads (scale on the right) needed per day.

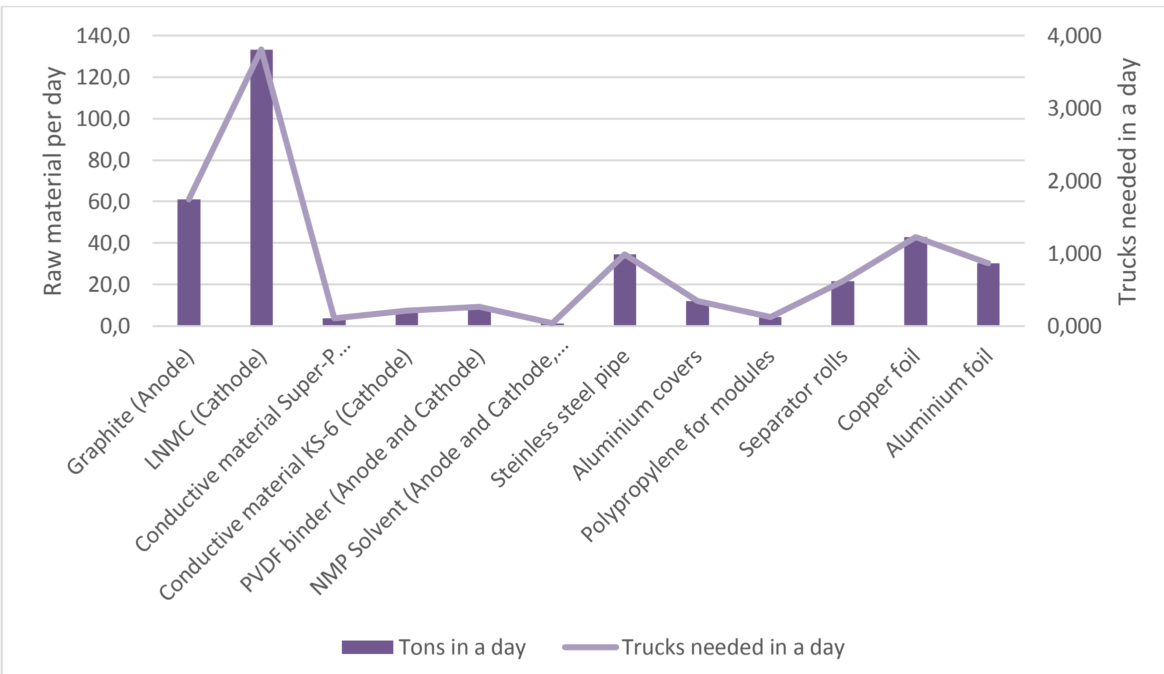


Figure 28. Raw material consumption and truck loads needed in a day.

4.5. Automation and maintenance

This study does not focus directly on automation system. However, it is clear that automation is an integral part of the factory and planning it must be done properly. Below is presented thoughts about automation and its subordinate concepts.

Automated factory still needs workers to attend and response for the operation monitoring and maintenance operations. They have to be trained for equipment defects and other problems. The monitoring room is good to be centrally located so that in case of errors, it is possible to react quickly. Jidoka system reports in detail any errors so that they are easy to locate and fix by humans. It is critically important to have well-functioning identifying system for errors because break in production in one stage causes decreasing total volume of production. In spite of knowledgeable workers, it is important to know that proactive maintenance is good to have at high level. For example, sensors can monitor temperature of machines or energy consumption (Shrouf, Ordieres & Miragliotta 2014. 699).

Another thing to consider about is importance of operations. There are processing stages with only one machine, like solvent recovery, and some of stages work with dozens of machines. Here it is important to know which stage needs fixing most critically. Well planned Jidoka system can calculate the most sensible way to do repairs and, most crucially, need for maintenance can be predicted (Ma et al. 2017).

Maintenance time frame for robots and machines always varies depending on the situation and the robot manufacturer. Some of the robots needs maintenance every 3850 hours or 12 months. It means two maintenance a year in continuous production. However, for example, KUKA Robotics recommends 10 000 hours maintenance time frame for their robots. (RobotWorx 2018). Elsewhere ABB urges to maintenance their robots once in a year. For some parts, like fan unit or gasket, it is enough to check them every three years but many require an annual inspection. (ABB 2013).

4.6. Cycle Time

Each stage is carried out in such a way that when operating at maximum capacity, the desired annual capacity, 35 GWh, is achieved. It means that average cell production is 2664 cells in minute and almost 160 000 cells in hour in each working stage. The whole cycle consists of the actual production and material movement in the line. At this part is presented cycle time for production from the mixing to the palletizing. The cycle time includes only the stages which increase the total cycle time. Hence, the missing operating stages, also called support stages, are solvent recovery, cell case production, cell cover production, electrolyte mixing and module injection molding.

Later, the cycle time is shown by batch size. As seen in the table 5, the batch size varies a lot because there are huge differences between processing times for distinct stages; batch size in mixing must be almost 500 000 cells because mixing takes 160 minutes. Following stages until the winding have 2675 cells batch size which is one foil roll capability. After assembly, batch size will change to 2500. While packing to modules, the batch size will decrease to 385 but in palletizing and wrapping section the batch size is equal to the size of the pallet (13 860 cells).

Table 5. Batch sizes for each of working stages.

Stage	**Batch size**
Mixing	479452
Coating and first drying	2675
Electrode calendering	2675
Electrode slitting	2675
Cell rolling and winding	2675
Assembly	1
Increasing the batch size	2500
Cell filling	2500
Wetting	2500
Heat drying	2500
Cap welding and sealing	2500
Formation cycling and charge retention	2500
Testing single cells	2500
Cell packing for modules	385
Module welding	385
Final testing	385
Palletizing and wrapping	13860

The cycle time is shown by batch size in waterfall graph, figure 29. Now, the figure presents the time from beginning of batch production to beginning of next batch. In figure can be seen time used during the stages in minutes and the total time for cell production. The last bar in the figure is for conveyor belts. As in chapter 4.3.2 stated, the total length of factory transporting lines (conveyors and pipes) is about 1140 meters. However, the maximum length that one cell can move on conveyor related cycle time is about 510 meters. The difference is explained by previously mentioned support stages and parallel conveyor belts. Several sources claim the standard pace tend to be 65 feets per minute (Cisco-Eagle 2018; Chantland

2018; Hytrol 2017) which means 19,8 meters in minute. Thus calculated, time spent in belt for one cell is about 26 minutes and the total cycle time is 1199 minutes i.e. 20 hours.

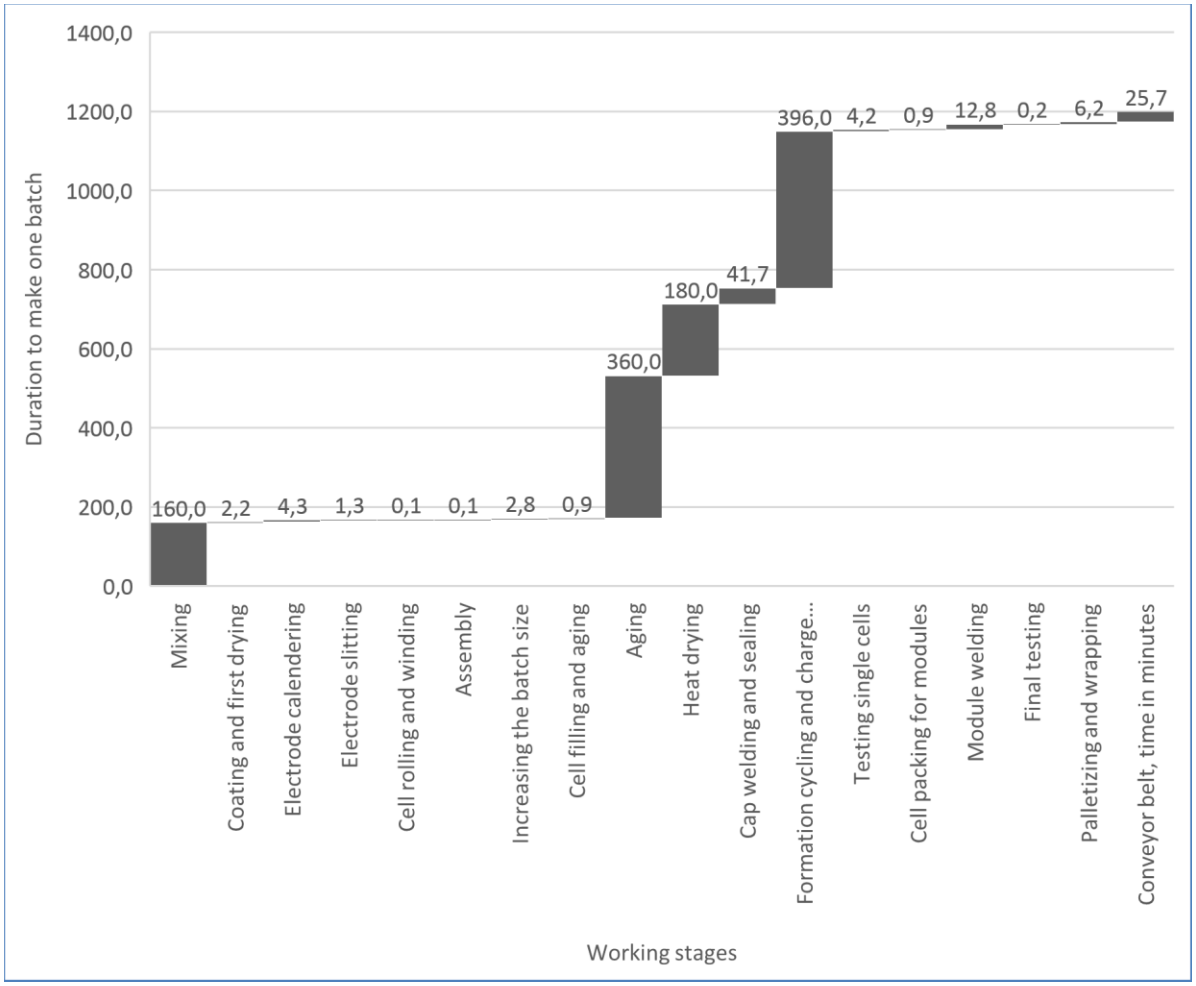


Figure 29. Production Cycle Time.

5. DISCUSSION ABOUT THE FACTORY

5.1. Challenges

5.1.1. Challenges in project

Such as projects tend, there were several challenges also in this project. One of the main challenge is lack of industry information. The information found is often contradictory. This problem arouse while working with this thesis but it will also cause problems later when the factory planning continues. For example, Yuan et al. (2017) who has studied the energy consumption of the battery manufacturing tells that used energy in battery manufacturing is reported between 0,4 kWh/kg and 22 KWh/kg.

There are several reasons for these differences. In the first place, cells can have difference features. A good example for that is above mentioned Nissan Leaf and Tesla Model 3. One cell for Nissan Leaf weights almost 900 grams but for Tesla weight is one tenth of that. Another reason is meaning of battery cell manufacturing. Some factories produce cells from mixing to complete car battery but in some factories, part of operations can be outsourced and only cells are manufactured without battery management system (BMS). Third difference is production volume, as the production of a large volume factory can be made more efficiently.

The factory project faces faced also other problems. One of the thesis's objectives was to help with 3D model by calculations. However, because of limited capacity of used computers, the finished model did not succeed exactly as planned. This is the main reason why the 3D model is narrower than firstly planned. For example, the model has not as many machines in many stages as needed. Also, the separation of anode and cathode production lines could be presented more clearly. Dearth of support operations can be seen in model too. However, the procedure for production is still presented well.

5.1.2. Challenges in production

In addition to the above-mentioned energy consumption, other challenges in production will relate with operating temperatures, electricity output and battery cell quality and lifetime (Yuan et al. 2017). Battery cell quality must be high to secure demand and in case of defects, material re-use and recycling must be planned well.

One of the biggest things that causes uncertainty is future technological development because it defines action of competitors. It is very important to use the best available technology because otherwise the factory will not be able to match the price level and demand prevailing in the LIB industry. However, although the factory uses the latest technology, the requirements for manufactured battery cells can change in the future and if it is as described above, the manufacturing process may need to be changed.

In the new factory, production begins usually in small scale. Even in automated factory, there will be a lot of learning before the factory is running at full capacity. It is challenging to develop action in a rapidly evolving field such as LIB cell production. Fast learning is necessary to reach success. The related terms, learning curve and ramp-up, are explained shortly in chapter 5.3.

5.2. Factory safety and sustainable battery cells

Factory safety mainly bases on Finnish legislation. Regulations on waste treatments (Finnish law 2012/179), the plan of salvation (Finnish law 2011/407), the environmental protection act (Finnish law 2014/527) and work safety (Finnish law 2002/738) are all dealt in a legislative collection. Compliance with them is required in the placement of equipment, pathways and operations. Equally, safety issues can be divided on safety of premises, quality for raw materials and finished cells and operations safety. Taking care of them ensures that possibility of disaster will decrease and partners and it increases customers rely. The safety may also be promoted by making choices in raw material selection and working stage design.

5.2.1. Cell quality – safety and recycling

Many heavy metals and plastics are used in the LIB manufacturing process. Their proper handling not only save environment but also improve safety. In addition, some materials such as cobalt and lithium are valuable and rare. Therefore, it is advisable to recycle them carefully. When selecting materials it is possible to choose those who are easier to handle. (Xu, Thomas, Francis, Lum, Wang & Liang 2008).

One of the choices made is cathode slurry materials. Comparison between LNMC and LNCA tells that addition to earlier-mentioned energy density, LNMC cell has longer life time (1000-2000 cycles) and it is more resistant to heat (210°C). The corresponding numbers for LNCA are 500 cycles and 150°C. (Buchmann 2017c; Blomgren 2017).

According to Saario et al (2017), most of the quality and safety deficiencies are identified as mentioned above after formatting. At this point, the cells are mostly finished which means that their recycling requires a lot (Saario et al. 2017). LIB cell recycling consists of both physical and chemical processes and there are several ways to implement it. Below figure (Figure 30) presents the sensible way to separate materials from each other. First of all, cell case have to be opened. After that the electrode can be recycled by mechanical and chemical operations. All in all, the recycling process can consist of 30 steps. These are for example, different solvent extraction processes, dissolution processes, leaching processes and thermal treatments. (Xu et al. 2008).

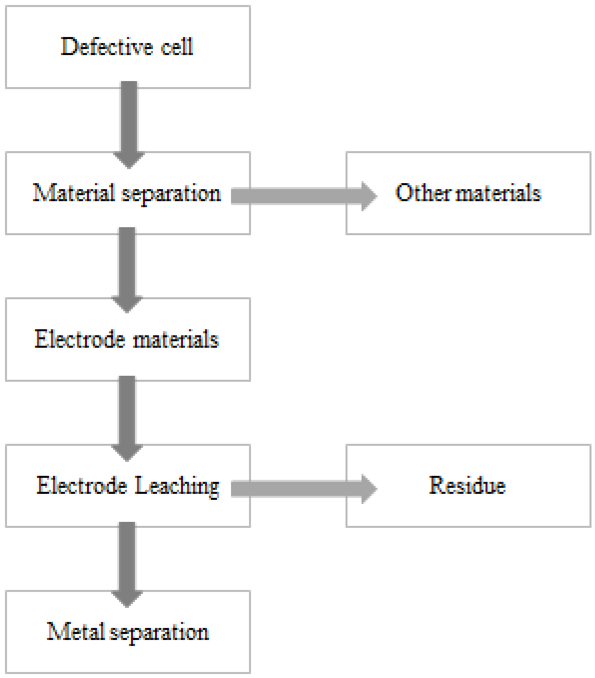


Figure 30. LIB cell recycling (adaption from hydrometallurgical recycling process by Xu et al. 2008).

Even the choice of the cell type can have an impact on safety. Cylindrical cell design allows the possibility to make safer than other cell types (Buchmann, 2017a). Single cell safety can be made by circuit interrupt devices, safety vents and separator. When talking about whole car batteries in which the cells are wired together, other safety systems are needed too. The more battery total volts increase, the bigger Battery Management System (BMS) is required. (Buchmann, 2017c).

5.2.2. Operations Safety

Besides the safety of the end product, it is important to ensure the safety of the work stages. Many operations causes a lot of heat. It must be monitored and handled with care, since many of the ingredients to be considered are sensitive to it. In poorly executed stage, the temperature of the cell or machine increases which may cause fire and in case of sealed battery cell, even explosion is possible. That is why there have to be cooling systems in both cells and used machines. (Doughty & Roth, 2012).

5.3. Ramp-up and learning curve

Term ramp-up is used when speaking about time frame from starting production to achieving full capacity utilization. Many high technology industries, including the electric vehicle battery industry, has short life cycle for their products. Thus, it is necessary to have well-planned and implemented learning curve because otherwise the plant will not be utilized during its lifetime. (Terwiesch & Bohn 2001).

The learning curve can be evaluated by many factors as production costs, production time, production volume or defects. Ramp-up period duration depends highly on industry and automation level. For example, in oil industry, the average time to achieve 50 percent utilization takes 18 months (Stroud International 2017). The current information on LIB cell industry is low. The original target for Tesla Gigafactory in Nevada was to produce batteries for five thousand cars in at the end of 2017 and Planned ramp-up is batteries for 500 000 cars by the end of 2020. (Tesla 2018).

However, Tesla’s goal has not been reached in 2017. The problems they faced are specifically in battery production and production has been suspended on several occasions. According to Tesla's statement, the problems are caused by a wealth of automation that has not been worked out as desired. This example reinforces the importance of automation planning and orientation. (Hull 2018).

Studies show that normally in automated factory learning curve is still steeper than while human work. The biggest problem with automated factory is equipment synchronization and orientation (Tompkins et al. 2003: 165). If these work well, the factory is able to work with high utilization. When problems arise, it is important to keep part of production line going on because otherwise there may be multi-day break in production, just like in Tesla situation (Hull 2018).

5.4. Proposed options for suggested solutions

It is important to remember that the presented procedure and way to product LIB cells is just one option. In real life, there are multiple ways to organize production and different choices can be made in material selection, working sequence and equipment selection. All decisions made are tried to justify by factory limitations but there are still few things that could be organized a different way.

One of these things is batch size while production. Now the batch size is calculated to be 2500 in assembly and formation stages. Its benefits are lower takt-time for batches and smaller wetting and formation racks. On the other hand, it requires more setup due to batch making. If there was information about machine and robot purchasing and operating costs, it would be possible to calculate the most reasonable way to execute production. Earlier moving to the module size would remove one working stage but it would require more from some of stages.

Some of stages will have newer technology in few years. If factory building takes several years, it is good to prepare for re-planning for part of stages. These kinds of stages are at least coating, electrolyte mixing, formation cycling and winding stages. For example, in the future, coating can be made with ceramic separator i.e. the detached separator may not be necessary in following years but it can be added in coated foil in coating stage (Shi, Zhang, Chen, Yang & Zhao 2014). Also formation cycling is researched a lot and it may achieve a breakthrough in formation time in the near future. According to An et al. the formation time is possible to decrease by 170 % but more research and tests are needed to prove that the battery cell quality does not suffer as a result of a new technology (2017; 847, 850).

This study have made by assuming that factory will produce cylindrical LIB cells which are packaged in modules. Other options for that are production of finished car batteries or production of pouch or prismatic cells. In these cases, the electrode manufacturing process would remain mainly unchanged but the cell assembly and packing operations would need a various changes. If factory will produce completed car batteries, there must be more working stages and materials to create well-functioning Battery management system (BMS) whose features depend on the car to which the battery is made. This would bind the factory to a particular partner.

As mentioned above, it is also possible to manufacture pouch cells, prismatic cells or even coin cells. Their electrode manufacturing is largely the same than with cylindrical cells but, for example, in cell sealing and packaging, there are big differences due to cell size and cell construction.

One more thing to consider is outsourcing. There are several operations in the factory which could easily be outsourced. In this case, core competence can be concentrated narrowly and equipment synchronization is simpler to implement. Vaasa region is known for its energy, industrial companies and proximity of necessary raw materials. Thus, both electrode manufacturing and cell assembly may be sensible to keep but more precise calculation are needed for electrolyte mixing, cell case and cover making and module molding. Because of complexity of the recycling process, recycling of damaged cells is one more operation to consider to be outsourced.

5.5. Costs for factory and production

The factory building and purchasing costs are not studied in this research. Such a large entity would require a lot of research and tendering to get a reliable estimate of total price of project. Instead, the production costs can be evaluated by material purchasing and electricity consumption.

Traditionally, cylindrical cells have had lower production costs than other cell types. This is because cylindrical cells are normally produced with high volume and at least part of operations are automated. In addition, higher energy density causes that less raw materials are required in cylindrical cell production. When considering only the manufacture of cells, average production cost for cylindrical cells have decreased more than 25 percent from 2005 to 2014. In 2014 the price was about 220 $/KWh (at that time, 159 €/KWh). Thus one cell costs about 0,04 € but it must be remembered that the price does not include material costs, equipment purchasing or maintenance of the factory space. (Pillot 2015; Buchmann 2017a; Buchmann 2017b).

5.6. Summary

The subject of the thesis “Production requirements for 35 GWh lithium-ion battery factory” describes well the main goal of the work; giving the reader insight about features needed to achieve desired 35 GWh capacity. Although the work is primarily done for helping people who know the industry it also can be read by person who is not familiar with LIB production. The work also is a little superficial due to its broad character. The big factory consists of many processes in each of which could be made a single research. A more profound examination of the working phases would have resulted more work and pages, and in addition, it would have had no effect on answering the research assignment.

The first research question “What layout type is suitable for the high volume lithium-ion battery factory?” is discussed in section 2.3. After examining the features of different layout types and requirements for planned factory, production line was chosen as a layout type. A potential floor plan and layout have presented in figure 27, in chapter 4.3.3.

“What issues associated with factory automation?” is rather broad question. It is mainly dealt in chapters 2.5 and 4.5 but also in 2.4, 4.3.4 and 5.1. Factory automation is not a new trend but nowadays, acceleration of automation is huge and it will accelerate further. If the synchronization between operations fails in critical stages, the whole production will stop. That is why its importance cannot be overemphasized. Other significant automation related issue is detection of errors or, in fact, detection of them before occur.

The last research question formed as “What is the role of material management at the factory and how it can be implemented?” focuses on material movement inside the factory. Chapters 2.4 and 4.4 tell that internal logistics is implemented by automation and conveyor belts. Furthermore, liquids are passed along the pipes and also more robots are used to move of material and cells.

Research objective was to provide needed information of production equipment for the 3D model. The objective was achieved in terms of the number of equipment and their dimensions. However, when comparing the model and the reality, working stages need more equipment in real factory and material transferring needs more complex conveyors. Although the 3D model does not give the most realistic picture of the factory, it still presents LIB cell production very clearly; the electrode foils are produced from raw materials and after that, the cells are combined with electrolyte. Before shipping, the cells are dried, welded and formatted.

The research assignment “the number of production equipment and the requirements for their placement in automated 35 GWh lithium-ion battery factory” is discussed in chapter 4 and its effects are reflected in a fairly well in completed 3D model. Section 4.3.2 includes the information about number of machines and conveyors and following 4.3.3 tells the total size that each stage requires. To see more information from equipment, see Attachment 2. All in all, the production space size is almost 8000 m^2 containing more than 20 working stages and over one kilometer conveyor belts.

5.7. Reliability and validity

The study is intended to be valid and reliable. It is commonly known that it means the consistency and repeatability of the research i.e. the results should be similar regardless of the researcher.

Because of many different ways to manufacture lithium-ion battery cells and the lack of available equipment information, things are necessary to examine from many sources. Major part of the machines found are primarily intended for smaller volume production. Large battery factories exist, but used equipment is usually manufactured as a custom work for those factories and public information about them is not available. However, all of the decisions presented can be implemented.

Despite the careful searching of reliable information, there are still uncertainty in few working stages. One of them is drying. Usually drying is implemented at least two times during process. The first drying is done during the electrode manufacturing. It has to be done after coating but before winding. Electrode drying has been studied for decades and nowadays, many researchers and equipment manufacturers showcase that the drying takes tens of seconds (Susarla, Ahmed & Dees 2018; Babcock & Wilcox 2018b). The other one tells about up to 1,5 days of drying time for the electrode (Saario et al. 2017). The difference between space need for these two option is huge as far as number of produced cells in 36 hour is 5,7 million.

Another drying is placed after electrolyte filling. Many articles suggested 24 or 48 hours drying time (Northvolt 2017; Pfleging & Pröll 2014) but Wu et al. (2004) advice to dry only few hours in vacuumed space. If the longer-lasting options turn out to be better, then the value of unfinished inventory increases as well the production cycle time. Also, physical space needed for drying sections will grow a lot and that will cause more investments. For example, room air drying stage, in other words wetting section, would require 150 meters of wetting racks instead of current 10 meter rack.

Second stage which requires more researching is electrolyte mixing. Electrolyte slurry contains 2-4 different carbonates the amount of which depends on the content of the electrode slurries. This is why mixing time can change due to further examination.

When designing the placement and quantity of robots used in production it has been assumed that the robot can operate accurately while full power working. Also, many robots have several simultaneous tasks such as moving two components at the same time. These kind of stages are for example cell case combining with cell case cover and welding stage. The number of robots may need to be increased if it is not possible to control multiple tasks with accurate and quick robot orienting.

5.8. Further Research

LIB cell related further research can be divided on cell properties and process efficiency. The biggest research subjects in cell properties are developing safer cell, cell life time improving and energy density increasing. The trend seems to be that more powerful cells are created by new materials or bigger cells. For example, the cell voltage is investigated and in near future, 4.6V voltage is possible to realize instead of present 4.2V (Blomgren 2017).

Process efficiency can be increased by improving equipment energy efficiency and working capacity. It helps to increase the capacity with less equipment. One of the most important development targets also is recycling of unsuccessful and used cells.

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ATTACHMENTS

Attachment 1. Raw material storage dimension.

	Shelf width (	Length (m)	Layers	Total height (m)	Total size (m3)	Total size (m2)
NMP	1,0	1,2	4,0	6,0	7,2	1,2
Super-P	1,8	1,2	5,0	4,8	10,4	2,2
Wiring Copper	1,8	1,2	8,0	3,3	7,2	2,2
Wiring Aluminum	1,8	1,2	8,0	5,9	12,7	2,2
KS-6	2,7	1,2	7,0	6,8	22,1	3,2
PVDF	2,7	1,2	8,0	7,8	25,3	3,2
LiPF6	4,5	1,2	7,0	7,5	40,5	5,4
Other substances	5,4	1,2	5,0	7,3	47,4	6,5
EC	6,3	1,2	6,0	7,3	54,8	7,6
Copper foil	3,6	2,2	8,0	7,8	61,8	7,9
Aluminium foil	3,6	2,2	8,0	7,8	61,8	7,9
DMC	7,2	1,2	5,0	7,3	63,2	8,6
EMC	7,2	1,2	5,0	7,5	64,5	8,6
Polypr.	11,7	1,2	5,0	7,9	111,2	14,0
Separator	20,7	1,2	4,0	6,5	161,6	24,8
Graphite	25,5	1,2	6,0	7,2	220,1	30,6
LNMC	32,4	1,2	9,0	7,6	296,5	38,9
Aluminium	12,0	5,0	7,0	2,3	135,5	60,0
Steel pipe	13,5	7,0	6,0	5,8	549,4	94,5
Total					228	**329,6**

Attachment 2. Collection of factory equipment

Machines	Machines	Shelf places	Assisting robots	Transporting line (m)
Raw material tanks			*2*	124
Coating and first dry	6		4	0
Solvent recovery	2		0	80
Electrode calenderi	10		4	130
Electrode slitting	4		2	
Cell rolling and wind	14		4	95
Cell case production	18			18
Cell cover productio	12			18
Case and cover com	23			110
Assembly	23			142
Electrolyte produci	1			*38*
Cell filling	9		3	36
Aging		384	1	12
Vacuum and heat drying		192	1	32
Tab weldings (botto	89			84
Formation cycling		422	1	25
Cell testing				5
Empty cell module p	3			17
Cell packing for mod	1			0
Module welding	90			135
Final testing	1			10
Palletizing	1			25
Total	307	998	22	1136