UNIVERSITY OF VAASA

SCHOOL OF TECHNOLOGY AND INNOVATIONS

INDUSTRIAL MANAGEMENT

Sulaymon Tajudeen

3D SIMULATION AND VIRTUAL REALITY AS METHODS FOR CONCEPTUALIZATION, DESIGNING, AND VISUALIZATION OF AN AUTOMATED LITHIUM-ION BATTERY FACTORY

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABREVIATIONS

3D	Three-Dimensional
AB	Agent Based
AGV	Automated Guided Vehicle
AR	Augmented Reality
ASRS	Automated Storage and Retrieval System.
BOM	Bill of Material
CAD	Computer Aided Design
DOF	Degree Of Freedom
DE	Discrete Event
DS	Dynamic System
EPBA	European Portable Battery Association
EV	Electric Vehicle
IEO	International Energy Outlook
HMD	Head-Mounted Display
LIB	Lithium-ion Battery
NMP	N-methyl-2-pyrrolidone
OECD	Organization for Economic Cooperation and Development
PVDF	Polyvinylidene Fluoride
R&D	Research and Development
SD	System Dynamics
SEI	Solid Electrolyte Interface
VC 4.0	Visual Components 4.0
VR	Virtual Reality
WIP	Work In Progress

UNIVERSITY OF VAASA	
School of Technology and Innovation	
Author:	Sulaymon Tajudeen
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Degree:	Master of Science in Economics and Business Administration
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Supervisor:	Rayko Toshev
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ABSTRACT

3D modeling and simulation have proven to be important methods when it comes to manufacturing process planning and conceptualization. With recent development in computer processing capabilities and Virtual Reality (later VR), 3D modelling and simulation methods for prototyping in manufacturing industry has become even more powerful when used together with VR for design optimization, realistic visualization, and information dissemination for everyone.

This research is part of a bigger research project at the University of Vaasa that utilized both experimental and case study research strategies to conceptualize an automated lithium-ion battery (later LIB) manufacturing factory simulation model that can be viewed with a VR headset. The VR glasses were used for optimization during modeling and it also helped with information dissemination of the simulation model for non-technical managers. A video of the complete simulation model was produced and a dedicated website that explains different stages of the automated LIB manufacturing factory using pictures and videos from the layout was developed as well. The entire 3D simulation was done with Visual Components software and a complementary VR software called visual experience developed by Visual Components Oy.

The results of this research show that 3D simulation together with VR can help any simulation engineer to effectively and quickly optimize simulation models in order to prevent future mistakes in real life projects, thereby reducing lead time and saving money.

KEYWORDS: 3D modeling and simulation, Automated factory, Lithium-ion battery, Optimization, Visual Components, Virtual Reality

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1. INTRODUCTION

According to International Energy Outlook report issued by the Energy Information Administration, worldwide energy consumption is expected to increase by 28 percent from 2015 to 2040 with more than half of the increase associated with non-OECD Asia (including China and India) with high rising middle class and thriving economy (IEO17 2017).

The automotive industry relies heavily on oil as evident in the case of a staggering statistics of 70% of oil consumed in the U.S. alone is used in the transportation sector where vehicles account for 70% of this amount. More so, the rising needs for a better living standard by middle class in countries like China and India will make the demand for oil to skyrocket at an estimated amount as high as 1.5 billion cars on the road by 2050 (Lee & Lovellette 2011). These kind of projections and high future energy demands are some of the reasons why automotive manufacturing industries have invested a significant amount of money in the field of alternative energy source for vehicles and hence the Electric Vehicles (EVs) are recently gaining momentum as a good solution. In order to achieve desirable results, a lot of research and development is geared towards manufacturing of lithium-ion battery (later LIB) for EVs which have been proven to be environmentally friendly (Kronthaler, Schloegl, Kurfer, Wiedenmann, Zaeh & Reinhart 2012). Such research requires detailed planning and iteration of different manufacturing processes and stages in order to achieve maximum result. 3D modeling and 3D simulation makes that possible with less amount of capital investment in R&D, virtual reality on the other hand helps to simultaneously optimize the 3D simulation models in a 3D simulation environment. Research have shown that different processes and stages of manufacturing activities can be explored effectively and critically analyzed for efficient planning and optimization purposes using computer simulation environment (Mc Lean & Kibira 2002; Schmitz & Wenzel 2013).

1.1. The LIB manufacturing factory project

The LIB manufacturing factory project is a joint project among two municipalities from Finland (Western region), a company around the region and two universities in Vaasa (University of Vaasa and Vaasa University of Applied Sciences). Due to confidentiality and Intellectual property rights, not all part of the parameters will be revealed in full details, but appropriate level of generalizations shall be used. This research is one of the goals of the project which is to design a conceptual visual representation of an automated lithium-ion battery factory in a three-dimensional environment using visual components 4.0 software (later VC 4.0) developed by a Finnish company called Visual Components Oy. The 3D simulation model produced using the software is expected to be further explored for optimization in a virtual reality environment using a complementary software called visual experience provided by the same company. Aside from the production volume target, the visualization design is expected to entail the required layout planning, and process modeling considering internal logistics as well as raw material supply and shipping of final products. Important production parameters such as batch processing size and time requirement, cycle time, throughput time, required machineries/equipment and energy requirements are the deliverables of the entire project. This research is part of the bigger project that focus on the visualization aspect of a lithium-ion manufacturing factory in a 3D simulation environment using VC 4.0

1.2. Justification for the research and contributions

The uniqueness of this project is that it involves the 3D modeling and simulation of the entire manufacturing process of a LIB starting from raw material offloading into the storage area through material transport within the factory to different stages such as aging, module assembly, packaging and final shipping of battery modules. The final layout has different manufacturing processes which is about 20 different stages and it uses different components such as robots, Automated Guided Vehicle (AGV), calendaring machine, stacking machines, conveyors, automated racks, tank storage, mixers and so on. Different processes and specific components were modelled and optimized individually (smaller area dimensions) due to the limited computing power before finally integrated in the overall layout. Majority of the components used are available in the e-catalogue of the software (VC4.0) while specific machines and components were creatively modelled and programmed to achieve desirable results. The entire design is based on real data derived from real machines used in the LIB manufacturing factory. Other supporting software used for modeling are SolidWorks, Fusion360, Tinker CAD and so on. Throughout the whole modeling process, the simulation model was visualized using virtual reality glass for assessment and optimization purposes in order to meet the required target. At the end, the completed layout can be viewed using Virtual Reality (later VR) glass and a professionally edited video of the entire factory simulation was also made. A dedicated website was also created to show all the processes and stages in great detail (pictures and videos for stages).

1.3. Research objectives and questions

The main objective of this research is to construct a realistic 3D modeling and simulation model of a conceptual automated LIB manufacturing factory considering processes integration, synchronization and connections, production constraints, layout optimization and visual representation of an entire LIB manufacturing factory. The 3D simulation model was optimized and assessed by the simulation engineer using VR headset. Managers and other stakeholders in the project can also experience the virtual factory environment using the VR glass. From the scope of the research objectives, the following research questions were formulated.

i. *How can 3D modeling and 3D simulation be used for conceptualization of an automated lithium-ion battery manufacturing factory layout?*

ii. *How can virtual reality be used in design optimization and result dissemination of a 3D simulation model of an automated lithium-ion battery manufacturing factory?*

iii. *Which factory design layout is the optimal one for an automated lithium-ion battery manufacturing factory using a three-dimensional simulation and virtual reality?*

1.4. Research Limitations

This research is limited to 3D modeling, 3D simulation and Virtual Reality application in conceptualization, designing, optimization and layout planning of an automated LIB manufacturing factory in a virtual environment.

1.5. Thesis Outline

The structure of the research is such that **Chapter 2** contains the literature review section. In this section, key definitions, related concepts, relevant theories and studies were investigated. **Chapter 3** discusses the research methodologies used in this study. The rationale behind the selected research methods will be discussed as well in this section. **Chapter 4** contains the main results of the research. The results are analysed in detail as well in this section. **Chapter 5** is the final section of this thesis. It draws a useful conclusion about the entire studies and suggest areas of future studies.

2. LITEARTURE REVIEW

This chapter is about the theoretical background of this research. Important keywords related to the research topic are being presented followed by literature review about 3D simulation, 3D modeling, virtual reality and factory layout. The final section of this chapter presents the LIB manufacturing processes in light of previous academic research done on the subject.

2.1. Basic definitions

This section explains the basic terms commonly used in modeling, simulation and virtual reality.

2.1.1. System

Law & Kelton (1991) describe a system as the process/ facility of interest. More so, Schmidt & Taylor (1970) define a system as "a collection of entities, e.g., people or machines, that act and interact together towards accomplishment of some logical end". A system can be explained in a number of ways in terms of its properties (***attributes***), or in terms of ***activities*** within the system which explains the action and time frame of events within the system, or in terms of ***state*** of a system which explains current state of the system variables and finally in terms of ***event*** which defines the instantaneous occurrence that influences the state of a system or part of it. (Law et al. 1991; Dey 2017.) A system can be either discrete or continuous. A discrete system has its state variables changing instantaneously at different point in time. A continuous system has its state variables changing continuously with time (Law et al. 1991).

2.1.2. 3D world

The basics of 3D experience using a 3D modeling and simulation software involves creating, manipulation and interacting with 3D objects in a virtual environment. This virtual environment is called a 3D world. In 3D world, the user's view is controlled by a camera in the software. 3D world can be navigated using a mouse with combination of left/right buttons and center wheel, a track or touch pad or using a 3D mouse. (Visual Components 2018a.)

2.1.3. Components

The objects being navigated in the 3D world are called components. they can be statically or dynamically created in a 3D world during simulation. A component can be exported as an image or different geometry file types (Visual Components 2018a).

2.1.4. Layout

Different types of components in a 3D world combines to create scenes which can be saved in a 3D modeling and simulation software as a layout. The components form a building block of any layout. A layout can be exported into a 3D PDF format, a video/image format or an animation that is viewable in a VR glass. (Visual Components 2018a.)

2.1.5. Virtual reality

Merriam Webster (2018) defines 'Virtual Reality' as

> an artificial environment which is experienced through sensory stimuli (such as sights and sounds) provided by a computer and in which one's actions partially determine what happens in the environment; also: the technology used to create or access a virtual reality.

From the last part of the definition given above, a VR glass is used to explore the layout generated in a virtual reality environment.

2.2. Modeling, Simulation & Digital factory

This section explains the concepts of 3D modeling and 3D simulation as digital methods for planning and realization of an effective factory layouts and operations. According to Westkämper, Spath, Constantinescu & Lentes (2013), a digital factory uses a network of digital methods to achieve factory planning and realization of improved factories. More so, Bracht, Geckler &Wenzel (2011) lay more emphasis on predictive and visual imitative nature of digital factory for the purpose of process optimization of future products. The visual representation nature of 3D models and 3D-simulation layouts of factories makes these methods applicable in digital factory. However, there is no agreed upon standards for methods for digital factory as mentioned by Bracht et al. (2011). They suggested a number of classes of methods in the context of digital factory as mathematical methods for analyzation and optimization, simulation methods, visualization methods and artificial intelligence methods. All the methods above are static except the simulation methods which can be effectively used to imitate complex systems involving a realistic time-dependent events nature of real life factories.

2.2.1. 3D modeling

3D modeling involves generating and creating a 3D model of any object, system or process in a 3D world using a 3D modeling software. The 3D model is simply a visual representation of the object/system or process in a three-dimensional space. Speaking generally about models, models could be physical or mathematical in nature (Swart & Donno 1981; Law et al. 1991; Dey 2017). The physical model can be something realistic as a small physical model or prototype of a city made with wood and cardboard materials or it can be generated with a 3D modeling software generally referred to as CAD (Computer Aided Design) software and then printed out with a 3D printer. There is a lot of 3D modeling software in the market today, some of them are SketchUp, SolidWorks, Fusion 360 and so on. The physical models are very good for visual representation of the final product and it gives room for identifying possible errors and hence improvement and prevention of future mistakes and reworks that cost time and money.

Mathematical models on the other hand are abstract in nature. They are usually represented with mathematical equations using system variables and parameters based on specific system requirement and constraints (Law et al. 1991).

In general, there are number of reasons and benefits why designers and process engineers will want to build either physical or mathematical model of systems before embarking on such projects in real life. One of the main reasons is that models gives room for experimentation and flexibility of changes with little amount of money and time (Fritzson 2011; Khemani 2008). A number of different scenarios of the system could be tested, and the results observed. Models have limitations in terms of time-dependent behaviour and events for example in a real-life factory as mentioned above. This is why simulation is developed to solve this kind of problem associated with time-dependent complex systems.

2.2.2. Simulation

As mentioned above, simulation is used alongside modeling in research for complex systems and it is an established planning method in manufacturing industry. Simulation tends to emulate a system and its attributes over time in order to improve an existing or futuristic process. This emulative ability of simulation help Process Engineers to better understand the system being studied and transfer the knowledge gained in the virtual simulation environment to the real system. (Banks, Carson, Nelson & Nicol 2010.) It is important to understand that simulation is very useful in designing and analyzing manufacturing systems and thereby preventing future breakdown from production lines (Law et al. 1991).

In manufacturing research, a number of simulation approaches and methods such as Monte Carlo simulation which involves models with random variables being repeatedly executed, tools such as 3D simulation software tools such as the one use in this research which is Visual Components 4.0, other software such as SolidWorks, AutoCAD and so on, and other mathematical model-based simulations software such as Octave, Modelica, SimPy and so on.

The simulation approach is further divided into four main categories by Borshchev & Filippov (2004) based on different levels of abstraction of the related models. The four categories which are ***discrete event (DE)***, ***Dynamic systems (DS)***, ***Agent based (AB)*** and ***System dynamics (SD)*** are explained briefly below.

Discrete event (DE)

In this case, the state of the models is discrete in nature and only passive entities which trigger variable changes are used by the simulation. DE is considered useful at tactical level and has middle degree of abstraction.

Dynamic systems (DS)

Simulation uses the mathematical models of dynamic systems made up of state variables and algebraic equations. This is best suited for continuous physical systems. Examples are Finite Element Method (FEM) or Computational Fluid Dynamics (CFD) approaches. This is considered useful at operational micro level and has low degree of abstraction.

Agent based (AB)

In this case, simulation can use active agents behavior in a defined environment for modeling purpose. Individual agent's behavior is based on some defined logic but can interact dynamically with other agents, no central control within the system and the system behavior is decentralized in nature.

System dynamics (SD)

System dynamics is considered to be a high level of abstraction because models description of a corresponding system is based on a set of differential equations representing interacting feedback loops and flows affecting stock variables.

Figure 1 shows the simulation approach according to their level of abstraction as well as discrete or continuous behavior.

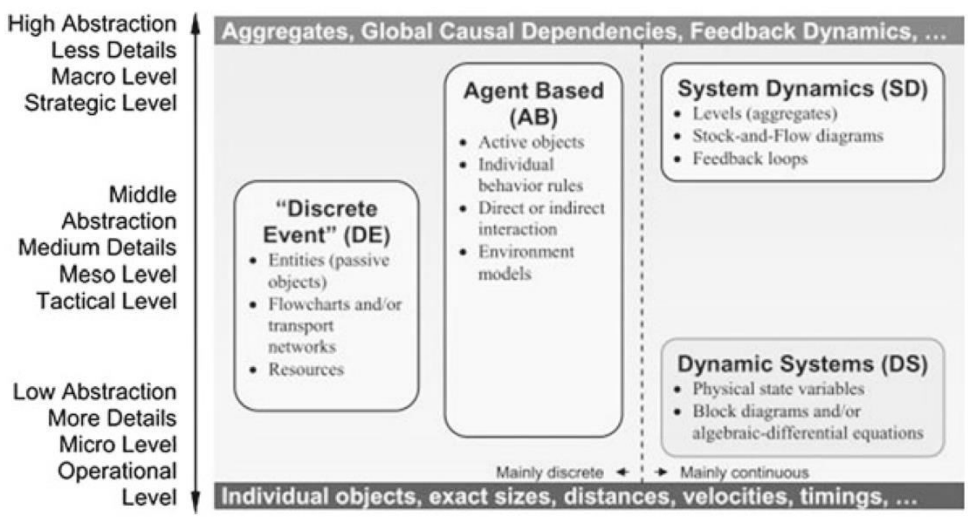

Figure 1. Simulation approaches on abstraction level scale (Borshchev & Filippov 2004).

The simulation approaches mentioned above (section 2.2.2.) have different use applications. For example, DE and AB simulation approaches is employed for manufacturing processes such as inventory management and scheduling, assembly line balancing, capacity planning and resource allocation. SD is employed in supply chain management, organization design and project management for strategic decision making. (Jahangirian, Eldabi, Naseer, Stergioulas & Young 2010.)

Simulation in manufacturing and production systems

Simulation is a powerful method to evaluate and assess the possible layout configuration and layout optimization of a manufacturing factory (Naik & Kallurkar 2005). It is possible to plan a whole production starting from material flow to the final product using system dynamic behavior based on discrete event simulation approach (Schuh 2006; Rose & März 2011; Bergmann 2014; Negahban & Smith 2014). In recent years, there have been a rapid development of discrete event simulation software. One of them is VC 4.0 software which provides a three-dimensional (3D) view of the layout in a virtual environment. This kind of possibilities make the simulation engineer to later have a feel of the actual setting of the factory in order to prevent potential problems such as safety issues, aisle, walkway, machine locations and other layout problems associated with manufacturing factories (Naik et al. 2005). According to research, simulation provides important input in decision making for designing, analyzing and improvement of manufacturing systems. Computer simulation has a number of useful results such as productivity and product quality improvement, reduction in lead time and future cost due to error that could have been prevented with simulation. (Mc Lean et al. 2002; Ahola 2018.) Another interesting argument to show that Simulation is indeed a useful method in manufacturing is in the case of IAS Inc. IAS Inc. used Visual Components simulation software to simulate their engineering and marketing workflow and make the simulation model available for their customers for sales promotion, planning and conceptualization. Weise (2017), a Lead Marketer at IAS said that *"Not only does it help us avoid costly repositioning or rework on a cell, but it assures us that the robot we have specified truly is the best one for the job"*.

Due to the nature of simulation models being designed first by simulation engineers and then the result analyzed or viewed with VR glass, it is obvious that there is a time lag between simulation results and the real world. This implies that a real-time factory simulation is inevitable. Hence the concept of industry 4.0 is currently becoming area of interest among researchers. Fowler & Rose (2004) aimed to solve this problem and they proposed that a real-time factory simulation which runs at the same time as the real factory operation with instant results is an important tool for short term decision making. Industry 4.0 is an initiative to develop intelligent factories using latest technologies that can interface both physical and virtual environment using cyber-physical systems (CPS). The CPS is made up of not only physical and virtual elements but also digital technologies such as virtual reality, augmented reality (AR) and internet of things (Kagermann, Wahlster & Helbig 2013).

2.2.3. Virtual Reality

In case of 3D simulation, 3D visualization is an important aspect since it helps the simulation engineer to see all the high level of detail (LOD) present in the simulation layout. With the high LOD of simulated manufacturing systems such as assembly line, 2D visualization is not adequate any longer (Masik, Schulze, Raab & Lemessi 2016). 3D visualization also helps the simulation engineer in validation and optimization of the simulation layout as well as presentation of results to all the stakeholders in the project (Schmitz et al. 2013; Ahola 2018). Some of the 3D visualization tools is a virtual reality glass. The VR glass is used to view a simulation model in a virtual reality environment. At this point, it is important to understand the term virtual reality.

The word virtual reality itself is naturally self-explanatory. From the word “virtual”, one could simply say that virtual reality means “near-reality” (Virtual Reality Society 2018a). But in technical terms, Virtual Reality Society (2018a) defines virtual reality as stated below:

> Virtual reality is the term used to describe **a three-dimensional, computer generated environment** which can be explored and interacted with by a person. That person

> becomes part of this virtual world or is immersed within this environment and whilst there, is able to manipulate objects or perform a series of actions.

Virtual reality aims to achieve both visualization and perception of the interactive virtual environments. Virtual reality generally requires a higher level of immersion which implies the boundaries between the real and the virtual world are blurred in the user's perception (a form of imagination). (Masik et al. 2016.)

Historical background of Virtual Reality

Virtual reality has evolved over decades and the first sense of virtual world and illusion was first noted from nineteenth century. Since then, different kinds of changes from breakthrough in technology and the influence of literature and movie industry that used science fiction scenes to predict and depict virtual reality scenario have contributed to what has become the virtual reality of today.

According to Virtual Reality Society (2018b), early attempts of virtual reality were first recorded from nineteenth century. A panoramic painting of 360-degree mural gives the viewer an illusionary sense of presence at the scene of the paintings. In 1838, Charles Wheatstones developed the first stereoscopic photo viewer that helped viewers to experience a sense of immersion and depth on two-dimensional objects. This kind of experience is normally observed on three dimensional objects. More advance stereoscope was developed by William Gruber in 1939 which was used for virtual tourism. Google Cardboard and low budget VR head-mounted display (HMD) for mobile phones today use the same design principles. After the first stereoscope was developed, the advent of electronics and computer technology experienced in the twentieth century has made virtual reality even more sophisticated.

In 1929, Edward Link, created the first commercial flight simulator using electromechanical system to mimic a virtual flight environment for the purpose of training pilots. In 1930s, a visionary science fiction writer Stanley G. Weinbaum in his book called (Pygmalion's spectacles) depicted a scene where a pair of googles can make the wearers experience a fictional world through holographic touch, smell and taste. This kind of scenario represents a ground breaking forward thinking of modern virtual reality system. (Virtual Reality Society 2018b.)

In 1950s, Sensorama was developed by Morton Heilig for application of sense of immersion in a theater film. In 1960, the first example of HMD was developed by Morton Heilig as well. The HMD provided stereoscopic 3D and wide vision with stereo sound, but it does not have any motion tracking. Comeau and Bryan from Philco corporation developed the first motion tracking HMD also commonly referred to today as Headsight. The Headsight was originally meant for military application where the wearer can use head movements to experience immersive remote viewing and natural look around of dangerous situation. The Headsight was not meant for virtual reality application at the time of development so the term VR did not even exist by then. (Virtual Reality Society 2018b.)

In 1965, Ivan Sutherland developed the Ultimate display that he claimed it could be used to simulate reality to the point where the boundary between the actual and the virtual environment cannot be differentiated. In his paper which forms the blueprint for modern virtual reality, he argued that his concept of virtual reality cover three key areas which includes computer hardware being able to create virtual world and maintain it in real time; possibility of users to interact with objects in virtual world in a realistic way and finally possibility to use HMD to view a realistic virtual world through augmented 3D sound and tactile feedback. In 1968, Ivan Sutherland and Bob Sproull who was his student created the first VR HMD called Sword of Damocles. The graphics generated from the HMD were very primitive and wireframe in nature. (Virtual Reality Society 2018b.)

1969 was the year of Artificial Reality which was developed by Myron Kruegere, a virtual reality computer artist. He created series of experiences called artificial reality that helped computer-generated environments to respond to people in it. The artificial reality forms the basis of videoplace technology that allows people miles apart to communicate in a responsive computer-generated environment. (Virtual Reality Society 2018b.)

Despite the series of development in the field of virtual reality as discussed above, the term virtual reality was only coined by Jaron Lanier in 1987. His company named visual programming lab (VPL) was the first to sell virtual reality gear including virtual reality googles (Eyephone) and Dataglove which leads to a major development in the field of virtual reality haptics. (Virtual Reality Society 2018b.)

Since early 1990s, virtual reality started becoming a technology available to the public in form of Virtuality Group Arcade Machines for immersive stereoscopic 3D visual game developed in 1991, also in form of Lawnmower Man movie that introduced the concept of VR to wider audience, SEGA new VR glasses released in 1993, Nintendo Virtual Boy used a 3D gaming console in 1995 and finally in the late 1990s, The Matrix movie was introduced in 1999 as well just like Lawnmower Man of 1992. It is argued that the movie had a major cultural impact of how the wider audience become more aware of simulated or virtual reality. (Virtual Reality Society 2018b.)

Virtual Reality in the 21st century

It is evident that the early years of the 21st century was years of rapid development in the field of VR. With cheap and powerful mobile phones of high-density displays and 3D graphics capabilities, VR experience is seen to be more common and more lightweight and practical virtual reality devices are readily available. Video game is another key driver of virtual reality among the public. Different technologies such as sensor suites, depth sensing cameras, motion controllers and natural human interfaces are daily human computing tasks nowadays. More so, big technology giants are also main drivers and they are encouraging wide audience adoption of virtual reality among people using their products. Google cardboard is an example of DIY VR headset that can be incorporated into mobile devices, Samsung Gear is another VR device with even more advance feature like gesture control. Other companies in the VR industry includes HTC and Valve Corporation, Microsoft, Sony Computer and recently Facebook that purchased Oculus Rift in 2014 for the sum of $2 billion dollar. That shows clearly a great future for the field of VR. The software component of VR technology is developing as well. More software developers are creating different contents ranging from games to city and Astronomical views for VR devices (Virtual Reality Society 2018b.)

Application of Virtual Reality

Virtual reality system is used in many fields such as flight simulation, building design and selling, urban planning and manufacturing simulation. As mentioned above, a head-mounted display (HMD) with hand-held controllers for navigation and base stations produce a virtual environment of simulation models. A typical example of different VR systems available include Oculus rift, Oculus Go, HTC Vive, Samsung Gear VR and Sony Play Station VR (PCmag 2018). Figure 2 shows a typical virtual reality system from HTC vive.

Figure 2. VR system - HTC vive showing headset, controllers and base stations (HTC Vive Europe 2018).

Virtual Reality in manufacturing

Manufacturing systems have developed over decades as new ways of production systems, manufacturing operations and planning have been discovered and adopted in order to achive more reliable, fast and error free manufacturing sytems. The greatest and most impacting discovery have been observed in the field of information technology. This had led to differernt forms of digital manufacturing technologies becoming a comon place worldwide. computer-integrated manufacturing and computer simulations using CAD modelling tools, VR and finite element analysis have proven to be helpful in achieving faster and efficient manufacturing decisions. (Nee & Ong 2013.)

In the past, VR have been used in manufacturing industries for product design planning, VR based manufacturing robots, factory layout planning and so on. In terms of product design, Nee et al. (2013) argue that VR helps product designer and process engineers to interact with their designs intuitively in terms of visualization and ovreall picture of interaction of downstream and upstream machines. Additionally, for simulation engineer/designer, virtual reality gives an intuitive interaction with the 3D simulation models since the real dimensions can be experienced and such experience provides a clearer engineering data. The areas of possible adjustment are noted in the VR session and it is simultaneously improved on the CAD models during design phase thereby cutting down design time. (Neugebauer, Weidlich, Zickner & Polzin 2007.) Chen, Ong, Nee & Zhou (2010) used VR to achieve efficient path palnning for both virtual assembly systems and virtual robot arm with a 6 degree of freedom (DOF). VR was also presented as an optimizing method to 3D simulation since all the individual components can be visualized all at once with realistic machine size and spacial requirement (Nee et al. 2013), this kind of possibility of achieving a well designed and optimzed factory can help companies save up to 50% in operating cost of a manufacturing factory (Xie & Sahinidis 2008).

2.3. Factory layout

The possibility of visualization of a simulation models in the virtual reality environment makes it possible to realize a clear perception of the final factory layout even before any investment and actual construction. A simulation engineer can quickly change and design better factory layouts by moving production cells around, change process flow and or even change entire factory layout in a fast and efficient way. The chosen factory layout is very important since the entire processes, physical machine location and process flow of a manufacturing factory depend on it. Also, it must be flexible enough for easy change and further modification in the nearest future for line expansion. Other important considerations in planning a factory layout include but not limited to minimal material handling cost, reduce investment, efficient throughput time and efficient use of physical space. (Shariatzadeh, Sivard & Chen 2012; Singh 2012; Okpala & Chukwumuanaya 2016.) At this point, simulation engineer must understand the nitty gritty of factory layouts and the different types of common factory layouts before attempting to design a 3D simulation factory model.

Factory layout is simply a mechanism to physically allocate space for machineries and equipment, process flow, raw materials and so on within a factory in order to reduce operating cost (Naik et al. 2005). The next section discusses the different types of common factory layout available.

2.3.1. Different types of factory layout configurations

Over time, different types of factory layout have emerged for different needs and applications. It is not uncommon to see different types of layout at different sections of a manufacturing plant. There is commonly three basic types of factory layouts based on the type of work flow, this include process plant, product layout and fixed position layout.

Cellular layout or hybrid layout is another recent layout type which combines the basic types mentioned above. (Singh 2012; Okpala & Chukwumuanaya 2016.)

Process layout also referred to as functional layout is employed for a batch production (based on flexible work station activities and not based on products being processed) where the upstream process depends on the operations of the downstream machines. A machine shop is a good example since similar functions and activities by people and machineries at different work stations like milling, drilling, pressing and so on can be placed at different sections within the shop. Each section must be in sequence and must be close to one another to reduce Muda in the manufacturing process. Some of the advantages of process layout is that it requires low capital investment, greater flexibility and low overhead cost. Some of the disadvantages are high Work in Progress (WIP), not suitable for a standardized product and it requires highly skilled labour. It is a suitable layout for low volume and varying products. (Singh 2012.)

Product layout involves arrangement of machineries in one line based on the production sequence. The product being processed moves automatically from upstream machine to downstream machine in a sequence without backtracking or deviation. This means that the output of one machine is the input to the next machine in the sequence. In product layout, the WIP storage and material handling time is low. This layout t is suitable for mass production of standardized products with simple and repetitive manufacturing process. It is strongly recommended that assembly line, testing and packing must be embedded in the product line. Some of the advantages of product layout is low cost of material handling, smooth and uninterrupted operations, it requires less skilled labour and most importantly low cost of manufacturing. On the down side, it requires high initial capital investment in special purpose machine, less flexibility, high overhead and downtime cost in case of any breakdown on the line. Automation is commonly used in product layout. A good example is vehicle assembly line as well as a LIB manufacturing factory (Singh 2012; Okpala & Chukwumuanaya 2016.)

Fixed position layout differentiates the major product being produced at a fixed location where other manufacturing components such as labour and equipment are being moved to and around the location. It is suitable for construction of major projects like bridges, warehouse, aircraft construction, ships building, locomotive construction, manufacturing plant and so on. Some of the advantages includes cost and time saving since there is no movement of work from one work station to another, ease of flexibility in terms of adjustment to shortage of material or absence or workers. However, fixed position layout requires large space for material and equipment storage and it requires long period of execution and high investment. (Singh 2012.)

Cellular layout is used in for varying product output with low volume production and low WIP production. Cellular layout contains groups of independent workers, machineries and equipment that produce a particular type of product. Cellular layout makes best combination of different types of layouts discussed above. For example, A manufacturing plant that fabricate and assemble parts of varying types will employ cellular layout. Fabrication section can employ process layout, while the assembly section can use product layout. (Singh 2012.)

2.4. Lithium-ion battery manufacturing process

According to Visual Capitalist (2018), the term lithium-ion battery refers to a broad family of different types of batteries and technologies that uses common concept of exchange of lithium-ions between positive and negative electrodes. A battery is made up of electrochemical units commonly referred to as cells. A cell is made up of a positive terminal (cathode), a negative terminal (anode), a separator (permeable insulation material) and an electrolyte. The electrolyte ensures that there is exchange of ions between the terminals while the separator prevent both contacts from having a physical contact thereby preventing a short circuit. (Linden & Reddy 1995.)

A cell can come in different shapes such as cylindrical, pouch or prismatic shape. A cylindrical shaped cell is considered in this research as presented on Figure 3.

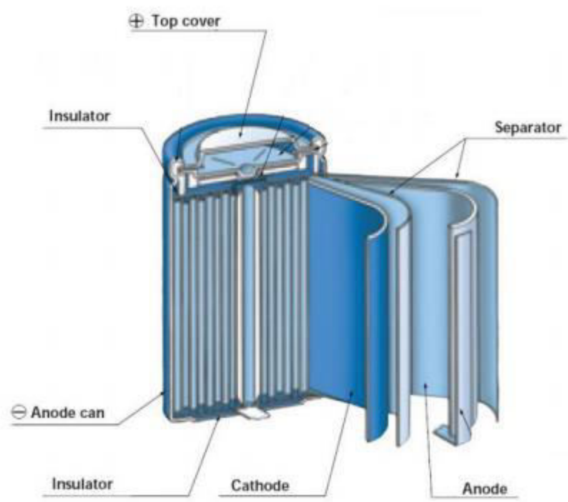

Figure 3. Internal assembly of cylindrical lithium-ion battery (based on EPBA 2007).

In order to produce a single cell, there is a lot of manufacturing stages involved. This is generally categorized into six main stages which are raw material supply, electrode manufacturing, cell assembly, formation cycling, packaging of cells into battery modules and shipping of battery modules from the factory. This section describes all the main categories as well as the different stages in each category which is about twenty different stages as suggested by Sakti, Michalek, Fuchs & Whitacre (2015) presented on Figure 4. A detailed pictorial information of each stage as designed using VC 4.0 is presented in results section of this research.

Figure 4. Lithium-ion Manufacturing stages adapted from ANL's BatPaC. (Sakti et al. 2015).

2.4.1. Raw material supply

For this stage, there are only two sub-stages required which are raw material supply and storage. There are 3 main groups of materials needed for electrode manufacturing. These are cathode raw materials, cathode anode materials and insulation materials. Other required raw materials for this stage are stainless steel pipe, copper foil, aluminium foil, binding and conductive materials and so on. (Hintsala 2018).

2.4.2. Electrode manufacturing

The next stage after raw material supply and storage is electrode manufacturing. In this stage, both positive and negative electrodes otherwise known as Cathode and Anode respectively are produced through different set of sub stages. These sub-stages are slurry mixing, coating, solvent recovery system, electrode calendaring and electrode slitting. (Sakti et. al 2015; Siemens 2018).

i. *Slurry preparation and mixing*

The first thing done in electrode preparation is the mixing of different solid chemical particles of different sizes and shapes in highly viscous media in order to prepare the required slurries for both cathode and anode. A thorough mixing of the slurries must be done at this stage in order to ensure consistent coating and drying operations. The preparation of the slurries for both anode and cathode must be done separately in different mixers and storage tanks. Anode slurry preparation is relatively easy and can be achieved with the conventional mixing techniques. However, cathode slurry preparation could be a bit challenging and it might require a relatively new and advance techniques in order to achieve efficient battery at the final stage. (Liu, Chen, Liu, Fan, Tsou & Tiu, 2014.)

Cathode (positive) electrode uses Aluminum foil and the slurry requires a solvent such as N-methyl-2-pyrrolidone (NMP); an additive, such as carbon black which is used to improve conductivity of the battery, a binding material such as polyvinylidene fluoride (PVDF) (Yoshio, Brodd & Kozawa 2009; Li, Daniel & Wood 2011). The active material such as $LiCoO_2$, $LiNiO_2$, or a three-dimensional material ($LiNiMnCoO_2$) that gives better battery performance in Electric Vehicles (EVs) are used (Zheng, Tan, Liu, Song & Battaglia 2012.)

Anode (negative) electrode uses Copper foil and the slurry preparation uses the same solvent, conductive and binding materials like the case of cathode (Yoshio et al. 2009; Li et al. 2011). But the active material is either carbon or graphite (Yoo, Frank & Mori 2003).

When the mixtures are ready, they are stored in respective storage tanks and eventually transported to the coating section through pipes.

ii. *Electrode coating, drying and solvent recovery*

The prepared slurries from the mixing stage are sent down to the coating machines for coating both the anode and cathode foils on both sides while leaving an extra side uncoated for tab connections later. Depending on the kind of machine used for coating, some machines have additional capabilities of drying and solvent recovery that removes NMP (N-methtyl-2-pyrrolidone) solvent which is considered harmful to the environment and also in some other cases, the solvent is further recycled, and it is ready to be used to prepare another slurry which in turn saves raw material usage. According to Babcock & Wilcox (2018), a world leader in energy and environmental technology solution provider, efficient solvent recovery system can help purify produce and achieve an electronic grade NMP that is reusable on the line. The company also boasts of their proprietary solvent recovery solution that it can achieve a recovery rate greater than 99% which eventually leads to a huge cost savings of $2/kg on the solvent material.

iii. Electrode calendering

Lithium-ion battery is known to have the highest volumetric energy densities as compared to other types of battery. This is because the coated electrodes are pressed through a calendaring machine to achieve two things. One is to reduce the size of the coated electrodes and achieve the desirable thickness and the second thing is to maximize the volumetric energy density of the electrodes. (Gonzalez, Rubio & Beattie 2015).

After the rollers of high pressure from the calendaring machine has pressed the coated electrodes, they are then wound into rolls and ready to be transported to the slitting section.

iv. Electrode slitting

The electrodes from the calendaring stage are too wide to be inserted in a cell case and this is why they must be cut/slit to the appropriate height of 70mm in case of 2170 cells through a slitting machine. The slitting is done for a cylindrical cell and not pouch or prismatic shaped cells in this case. Slitting is a very critical stage that must be properly done and further verified at the control lab to ensure conformity to the required measurements.

The standard method of electrode slitting is through mechanical means through die cutting. However, this method has a number of drawbacks such as high initial capital, non-versatility with varying electrode shapes and wear and tear of the cutting tools within a short while. Laser cutting is currently being investigated as a better alternative with reasonable cost and efficient results. Due to its contactless nature, laser cutting is free from wear and tear and could be easily used on varying types of electrode shapes and geometry with high level of speed. (Kronthaler et al. 2012.)

2.4.3. Cell assembly

This stage ensures that the slit electrodes are reeled together and inserted into an empty case, which will be eventually filled with electrolyte and finally the tabs welded, then the case will be covered and sealed in a controlled environment.

The anode and cathode must have the insulation material in between them during cell stacking stage in order to prevent both electrodes from coming in contact but only having possibility to exchange ions on the long run. At this stage, a separating non-conducting porous polymer film which is usually Polypropylene (PP) or Polyethylene (PE) for exchange of ions between negative and positive electrodes is used (Kronthaler et al. 2012; Liu et al. 2014). A typical electrolyte is a lithium salt, such as LiPF6 (Lithium hexafluorophosphate) in an organic solution (Morishima 2008; Liu et al. 2014).

The electrolyte is infused into the cells with a precision pump through a hole in the cap and then vacuum filled in order to allow the electrolytes to completely fill the spaces between the separating material and the electrodes (Yoshio et al. 2009). The electrolyte must be properly filled because the formation and aging processes depend on it as well as the overall battery performance in terms of capacity, cycle life and safety. There must not be flooding or depletion since this will affect the cell overall performance (Sheng 2015).

After the cells are ready, tabs welded, and case sealed, the cells are pre-packaged by a robot in the vacuum room in order to make storing them in the formation cycling stage easier.

2.4.4. Formation cycling stage, aging and testing.

This is another very important stage in battery production. During manufacturing of lithium-ion battery, the cells are made in an uncharged state. First charging of the cell produces an electrochemical reaction which helps to store electrical energy and forms a solid electrolyte interface (SEI) on the anode when the active material in the electrode films come in contact with the electrolyte. (Yoshio et al. 2009; Lu, Li, Schneider & Harris 2014.)

After the first charge, there must be series of charging and discharging cycles routines to determine the aging of the cells and to identify cells with reduced performance. These routines represent the typical life cycle of cell in a real-life usage application. The performance of cells at this stage determines the durability of such cells when in use. Important parameters considered at this stage are amperage, temperature differences, and pause lengths. The formation, aging and further aging processes requires the most energy, time and space in cell production. (Hettesheimer, Hummen, Marscheider-Weidmann, Schröter, Lerch, Stahlberger & Heussler 2013.) Some lithium-ion battery manufacturing solution providers identify that these stages can be expensive, time consuming of up to 2 - 4 weeks and requires a large storage facility (Siemens 2018). There is different aging solution by different battery manufacturing solution providers such as high temperature aging and ambient aging. (Chromaus, 2018).

The last phase of this stage is charge retention. Charge retention ensures that cells have minimum charges on them when they are finally produced. As a result, battery modules are ready for use with the available charges for the first time. After the cells are ready from the formation and aging stages, they are tested for performance quality and acceptance test by a testing unit and also an important check that must be done is self-discharge rate. The cells that do not meet the requirement are recycled.

2.4.5. Packaging of cells into battery modules and palletizing.

The cells that meet the requirement are ready to be packaged into modules, but cells are wired and connected together first in order to achieve the voltage and current capacity requirements of the battery module. Lee, Kim, Hu, Cai & Abell (2010) argue that battery pack occurs as a result of different levels of hierarchy of connections which involve electrodes-to-tab connection, then cell-to-cell connection for a unit assembly, after that is unit-to-unit assembly for a modular assembly and finally module-to-module assembly for a pack level as clearly indicated on Figure 5.

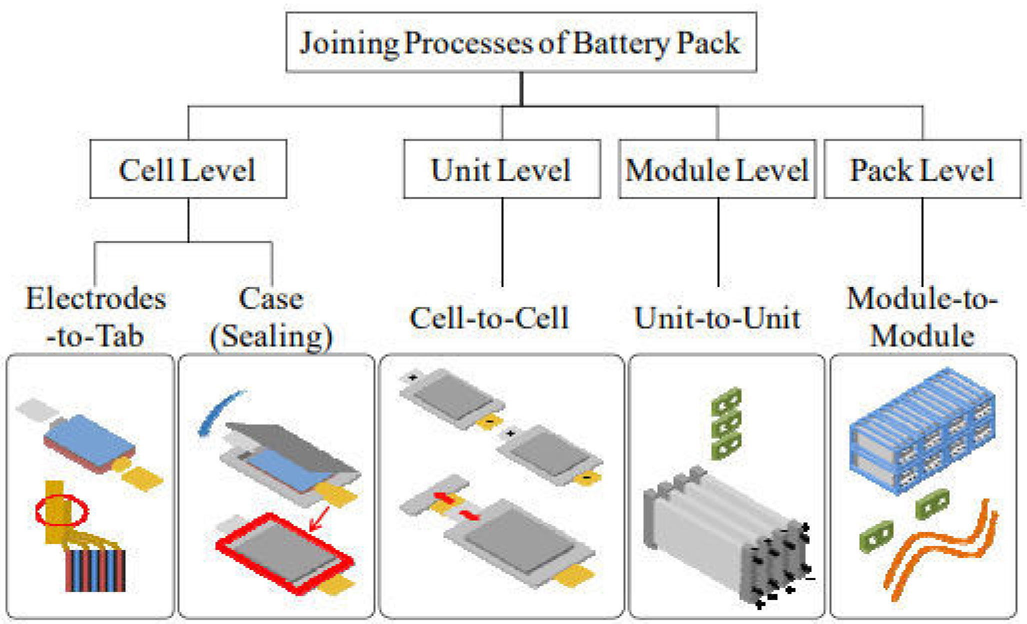

Figure 5. Hierarchy of battery pack manufacturing (Lee et al. 2010).

Lee et al. (2010) further explain that in order to join cylindrical cells there are two methods involved depending on the shapes of the positive/ negative tabs. These two methods are resistance welding for flat tab shaped cylindrical cells and mechanical joining for bolted tab shaped cylindrical cells. Figure 6 represents the two methods explained.

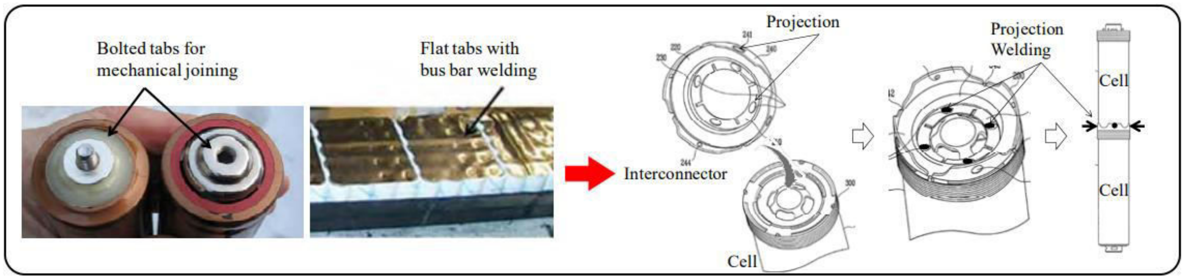

Figure 6. Mechanical joining (Bolted tabbed cells) and Resistance welding (flat tabbed cells) (Lee et al. 2010).

Battery modules casing are typically plastic materials. After the cells are already packed by a packing robot to form a battery module, they are covered and sealed and ready for palletizing. A battery module is made of 385 cells in this case and 10 modules totaling 3850 cells is required for 80KWh Electric vehicle (Hintsala 2018).

Palletizing is the last stage of battery module production; battery modules are palletized on pallets and wrapped by a shrink wrap machine and they are ready for shipping.

2.4.6. Shipping of battery modules from the factory.

The final stage is shipping of the palletized battery modules. Depending on the palletizing pattern, two or more palletized pallets are stacked on top of each other by a stacking machine or a forklift and they are loaded into the truck for shipping.

3. METHODOLOGY

Research methodology is the framework and guideline for the entire research process. Research design is an important part of any research process because it entails the research process that works towards answering the research objectives and research questions at hand (Saunders, Lewis & Thornhill 2016, 163). This chapter contains overall research process used in this study. It entails the research strategies in terms of the time horizon, research purpose, research philosophy, research approach, research tools used and finally the data collection process and how they are analyzed and used in this study to arrive at useful conclusions and answer the research question being studied.

3.1. Overall research process

Research purpose emphasizes the exact way that the research questions are proposed based on exploratory, explanatory or descriptive account and hence answered in any studies (Saunders et al., 2016, 174). This research is exploratory because new insights are discovered on a problem at hand with a limited information based on previous research carried out (Shields & Rangarjan 2013; Saunders et al., 2016, 175). Another reason why this research is considered exploratory is that the problem in this case which is deployment of 3D modeling, 3D simulation and virtual reality methods for efficient planning of LIB manufacturing factory was at the beginning of the project having a bigger overall picture of what the research will look like but as the research progresses a narrower path was defined by the researcher and other stakeholders (Saunders et al., 2016, 175).

Research philosophy entails the system of beliefs and assumption about how knowledge develops over time (Saunders et al., 2016, 124). These assumptions could be based on one’s previous knowledge, or about realities experienced by researchers during their research or about the influence of researchers’ own values on the studies being carried out

(Burrell & Morgan 1979). This research uses pragmatism in its research philosophy. Saunders et al. (2016, 135) proposed five different major research philosophies which are positivism, interpretivism, critical realism, postmodernism and pragmatism. In this research, positivism is considered because the researcher has a value driven research at hand and the researcher also believes that the problem at hand has a practical meaning in business performance and manufacturing planning and improvement. So, the researcher sees a need to initiate and further investigate the use and application of the latest technology in the field being studied in order to achieve new and practical results and solutions. (Saunders et al. 2016, 137.)

Research approach is another important research process that must be thought about well by a researcher. This is because the research approach chosen will determine the pattern of one's research design which will eventually help in categorizing what contribution the results of the research are. Are the research results trying to contribute to established body of knowledge or whether the research results are trying to validate already established theories? Ketokivi & Mantere (2010) generally categorized research approach into three which are deductive, inductive and abductive reasoning. The two researchers propose that deductive reasoning is applicable when a set of premises are the determinants of the conclusions and results of a research. This means there is a form of verification of established theories. The conclusions and results will only be considered true when all the premises are true. On the other hand, Ketokivi et al. (2010) argue that there is no need for a relationship between the conclusions and results of the research and the premises observed. It is enough that the conclusions and results are considered valid once they are supported by the observations being made. On a final note on the last type of approach suggested by Ketokivi et al. (2010), abductive reasoning considers, a 'surprising fact' is simply the rationale behind starting a research. The interesting part is that the surprising fact is considered the conclusion rather than a premise. Based on the conclusion, a set of possible premises are generated and then considered to be sufficient enough to explain the conclusion. (Saunders et al. 2016, 144.) The inductive approach is considered appropriate in this study because the information collected were for specific processes of LIB manufacturing, but they were all combined at the end to generate a general information about the LIB manufacturing factory. More so, the data collected was used to explore the phenomenon and identify themes and pattern that eventually led to inference about the known premises used to generate conclusions and results. (Saunders et al. 2016, 145).

Research strategy is another key component of a research methodology that defines the plan of actions that a researcher will use to achieve the goal of answering the research questions (Saunders et al. 2016, 145). Due to different research traditions commonly practiced by different researchers over years, there have been a number of research strategies evolved over years based on the research methodological choices they have chosen which are qualitative, quantitative or mixed methods. The research strategies are experiment, case study, archival and documentary research, ethnography, narrative inquiry, action research, ground theory and survey. The two research strategies used in this study is experiment and case study hence an experimental case study strategy is inferred. This strategy is discussed better in the next section (section 3.2). Mixed method is used in this research because a number of qualitative data and quantitative data from experts on LIB manufacturing processes were used.

Time horizon of a research can be either cross-sectional or longitudinal in nature. To simply put, cross-sectional is like a ‘snapshot’ time horizon while longitudinal uses ‘diary’ perspective of time horizon. Cross-sectional simply involves discussing a study of a particular phenomenon at a particular time. There is no need to study change and development over time of the phenomenon being studied in cross-sectional study hence this research employed cross-sectional time horizon. (Saunders et al. 2016, 200.)

Figure 7 shows the snapshot overview (blue areas) of the research process used in this study using the research onion proposed by Saunders, Lewis & Thornhill (2015).

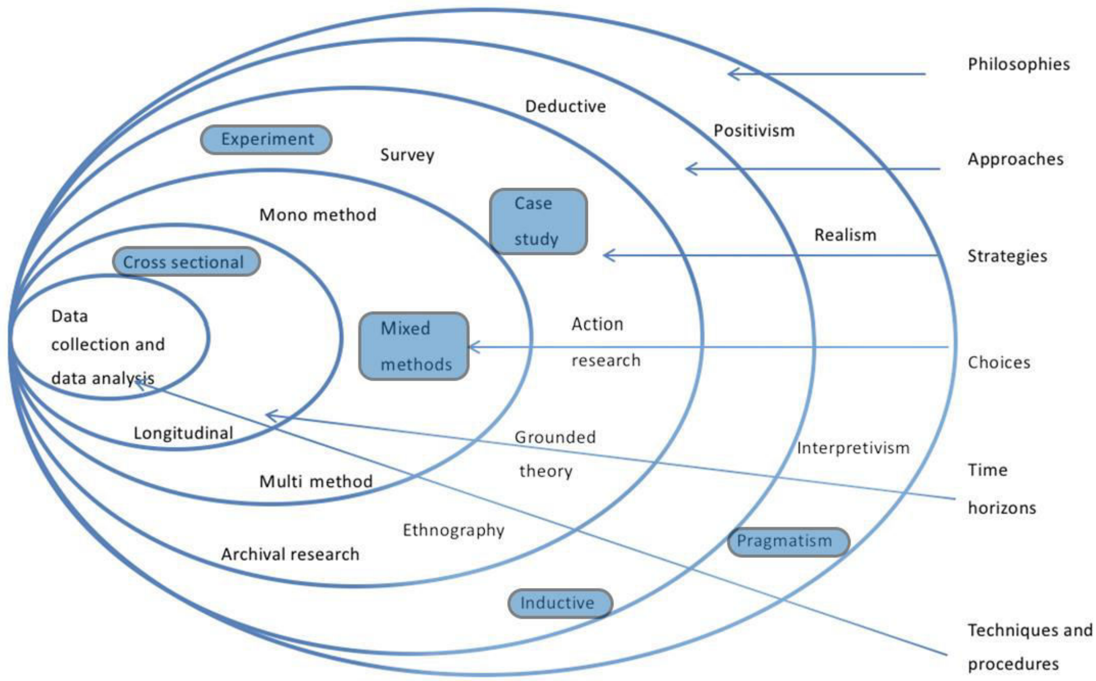

Figure 7. Research onion. (Saunders et al. 2015).

3.2. Research tools and Experimental case-study

This research is a project oriented that is based on experimental case study of designing an automated LIB manufacturing factory in a virtual environment using a 3D simulation software. In this research, VC 4.0 was used for all the simulation while HTC vive VR glass was used for the virtual reality part. This research uses an experimental and case study research strategies because those were considered best fit for this study. The case study part considers LIB manufacturing processes as different cases that could be combined into one large single case of LIB manufacturing factory. A number of researchers consider case study to be appropriate when an in-depth inquiry of the dynamics of a phenomenon being studied can be contextualized (LIB manufacturing in this case) (Yin 2014; Eisenhardt &

Graebner 2007). The experiment part considers adjusting different variables of LIB manufacturing processes to achieve the desirable results of the research such as factory visual layout planning and capacity optimization using a 3D simulation software (VC 4.0).

For clarification purposes on some of the data presented in the results section and as mentioned briefly in the introduction section, this research is one of the bigger research carried out by the University of Vaasa research group. Another researcher (Mikael Hintsala) focus on another area involving the production requirement calculation of the 35GWh LIB manufacturing factory. The entire research group from the university of Vaasa is made up of a supervising professor Prof. Petri Helo, a project coordinator Dr. Rayko Toshev, a project researcher Ebo Kwegyir-Afful and two research assistants Sulaymon Tajudeen and Mikael Hintsala.

3.3. Data collection and analysis

Data can be collected and gathered by a researcher in a number of ways during a research process. The source of the data can be primary or secondary data (Saunders et al. 2016, 316).

For the simulation aspect, some sources of the data are primary in nature because the researcher used raw data based on the calculated requirements by the other researcher (Mikael Hintsala) and then simulated them in the software. Also, some other secondary data such as LIB manufacturing processes and machines (shapes size and capacity) were used in the simulation aspects as well. For the literature review part secondary data was mainly utilized, the researcher ensured the process of collecting and reviewing those data, analyzing and interpreting the data are in line with answering the questions and meeting research objectives (Burns & Bush 2008). In general, for the entire research process, all the relevant information, research papers and articles on LIB manufacturing published on different international journals were used as well in order to achieve a comprehensive and optimized LIB manufacturing factory layout. what kinds of previous studies related to this research were used as well in order to understand and interpret the simulation results.

3.4. Reliability and validity

For any research, reliability and validity of the results are important components. It is an intrinsic aspect of a research process that is present in every stage of a research. The concepts of reliability and validity are observed in process of searching, collecting and even interpreting data used in a research. Researcher's bias and using a weak source of data can interfere with realizing a reliable and valid result for any research.

Saunders et al. (2016, 202) argue that reliability has to do with replication and consistency of results where another researcher can replicate an earlier research and get the same findings. Collins & Hussey (2009) as well suggested an inquiry that provokes reliability of results of a research whether or not the same results can be achieved when the same phenomenon is being observed by another observer at some other point in time.

Validity on the other hand justifies credibility and appropriateness of the measures used in a research. Validity also has to with the accuracy of the results analysis and possibility to generalize the findings of a research. (Saunders et al. 2009,202.) Bryman & Bell (2007) explain validity in a simpler term as to what extent does a research effectively measure what it claims to measure.

In this research, a great detail of attention is paid to the all the sources of data used from earlier literatures, articles, printed books and as well good level of scrutiny of data gotten from the co-researchers as well in order to arrive at reliable and valid results that answer the research questions at hand.

Most importantly, results of this research were also verified in group meetings and with discussions with experts in workshops and technological VR demonstrations for LIB manufacturing experts.

4. VISUAL COMPONENTS 3D SIMULATION SOFTWARE

This section presents the description of the simulation tool used in this research. VC 4.0 is the 3D modelling and simulation tool used to design, model and simulate an automated LIB manufacturing factory for this research. VC 4.0 key features are presented followed by the presentation of the components used for the entire layout.

4.1. Visual Components software

Visual components 4.0 (VC4.0) product family is a software developed by a Finnish company called Visual Components Oy. The company was founded 1999 in Helsinki, Finland and the first software developed by the company was a layout configuration and visualization tool for JOT Automation which is another Finnish company. Over the years, Visual Components have developed several kinds of simulation software such as KUKA Sim Layout (2003), 3D Automate product family (2014) and the latest modeling and simulation software called visual components 4.0 (2016). (Visual Components 2018b.)

Visual Components 4.0 (Premium) was used to design the automated LIB factory in this research and it was the latest release as at the time of carrying out the research. It is an advance 3D modeling and 3D simulation software built on new software architecture and platform. It has a wide range of features ranging from modeling, robot programming, layout simulation, exporting images and videos of a layout and as well exporting animation of the layout which can be viewed in VR glasses with Visual Experience software developed by the same company. (Visual Components 2018a.)

4.1.1. Home Screen

Figure 8 shows an overview of the user interface (Home screen) of VC 4.0 software. The Home screen has important tabs/ tools such as copy, paste, group, delete, measure, selection tool, move tool, PnP tool, cell graph (left) showing the list of components used in the layout, a property panel (right) showing specific properties of the components selected in 3D world, 3D navigation pane towards the bottom (left) and e-catalogue panel (left) showing the list of all the available components in VC 4.0 software.

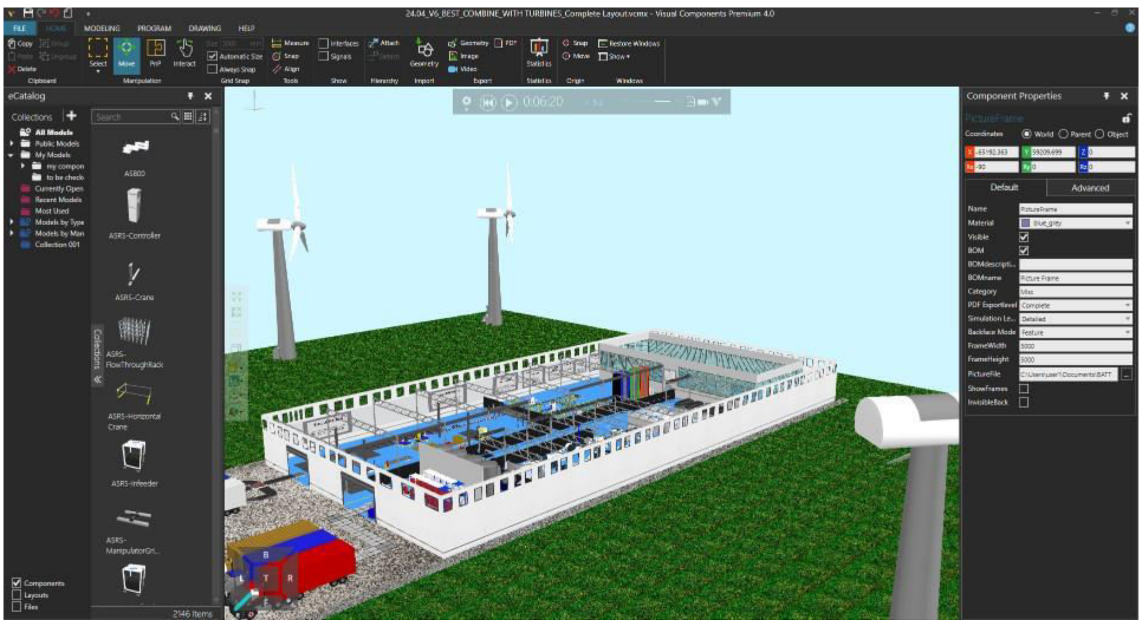

Figure 8. Home screen of VC 4.0 showing the e-catalogue panel and other tabs.

VC 4.0 has a wide range of collection of components built into the e-catalogue of the software. There are over 2000 different types of components by different leading manufacturers. Example of different types of components available in the e-catalogue include but not limited to robots, conveyors, robot positioners, AGV, packaging components, factory facilities, interior facilities, feeders, physics components, controllers, works library components, machine tending, robot tools and so on. According to the company's website, the software is very versatile and can be used to develop, model and simulate any type of manufacturing processes and layouts (Visual Components 2018b).

Some of the key components by ***type*** which are available in the e-catalogue of VC 4.0 are discussed below.

ASRS Components

These are used to carry out tasks related to automatic storage and retrieval of items from process racks. There are 12 different types of components in this group and they are show on **Figure 9**.

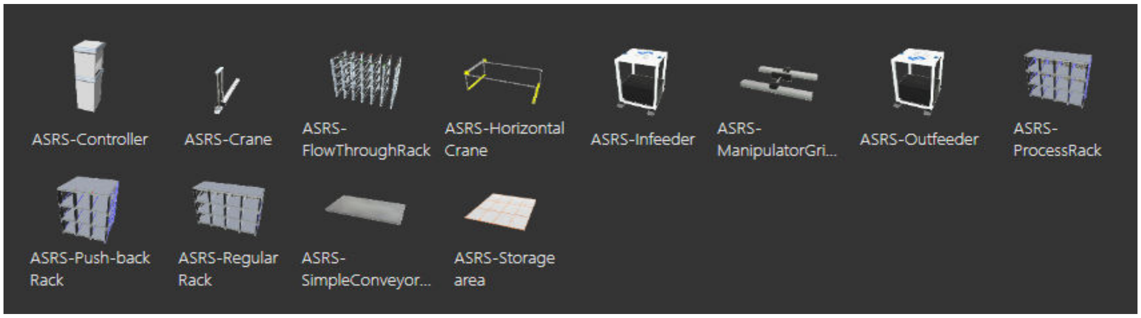

Figure 9. ASRS components (12 items) available from e-catalogue of VC 4.0.

Conveyors

Conveyors are used to transport items from one machine to another in the layout or from one point on a particular machine to another point within same machine. There are different kinds of conveyor types available in the e-catalogue which include straight conveyor, cross conveyor, incline/ decline conveyor, lifter conveyor, converging conveyor and so on. **Figure 10** shows the 44 types of conveyors available in the software.

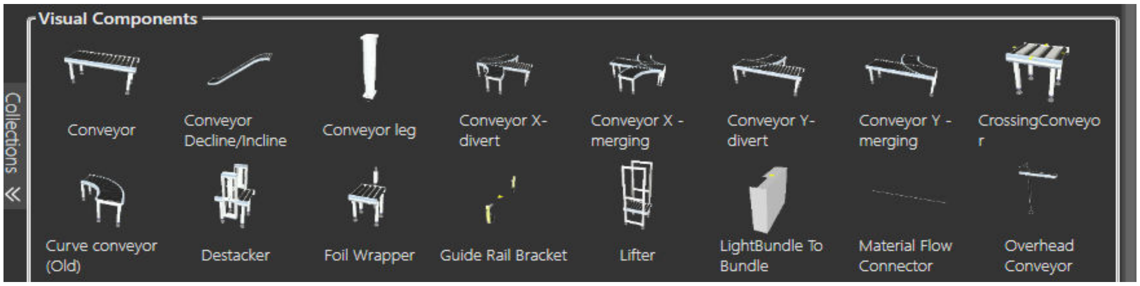

Figure 10. Conveyor components (44 items) available from e-catalogue of VC 4.0.

Factory facilities

Factory facilities components are used to build factory structures in the layout, they include factory wall builder, fence builder, stairway, floor and ceiling builder, pillar builder and so on. **Figure 11** shows some of the 40 factory facilities components available in e-catalogue.

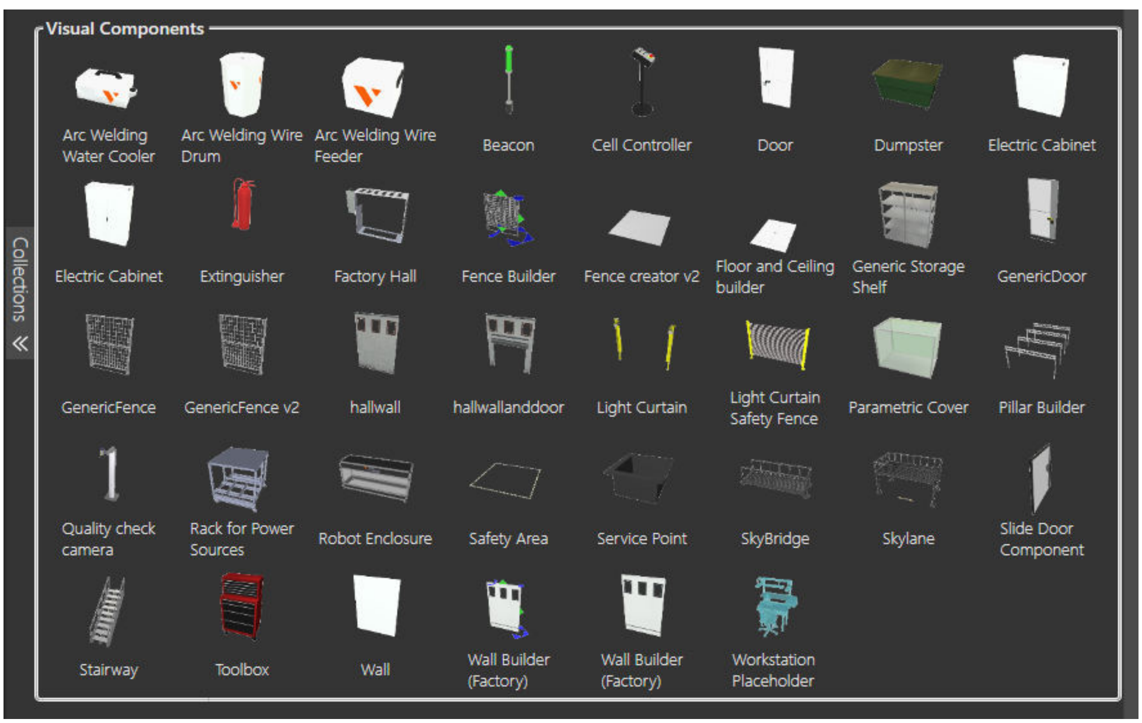

Figure 11. Factory facilities components (40 items) available from e-catalogue of VC 4.0.

Robots

Robots are one of the most commonly found machineries in a modern factory, they are able to carry out variety of tasks such as palletizing, packaging, welding, sealing and so on. In VC 4.0 software, there are 1277 different types of robots from different manufacturers. This wide range of options of robots from different manufacturers make it possible to simulate factory processes whose results are ready to be used in the real-life factory processes. **Figure 12** shows some of the available robots in the e-catalogue.

Figure 12. Robot components (1277 items) available from e-catalogue of VC 4.0.

4.1.2. Modeling Screen

The modeling screen provides different kinds of options for modeling both primitive features and advance geometry. It allows importing of new geometry into the 3D world and it allows newly created geometry to be exported in different varieties of 3D formats and as well as a visual components ***component*** (.vcmx file extension). The modeling screen also allows properties and behaviors of components to be programmed writing python scripts to control a particular component behavior and response to external signals such as sensors. **Figure 13** shows the modeling screen of VC 4.0 and the available tools.

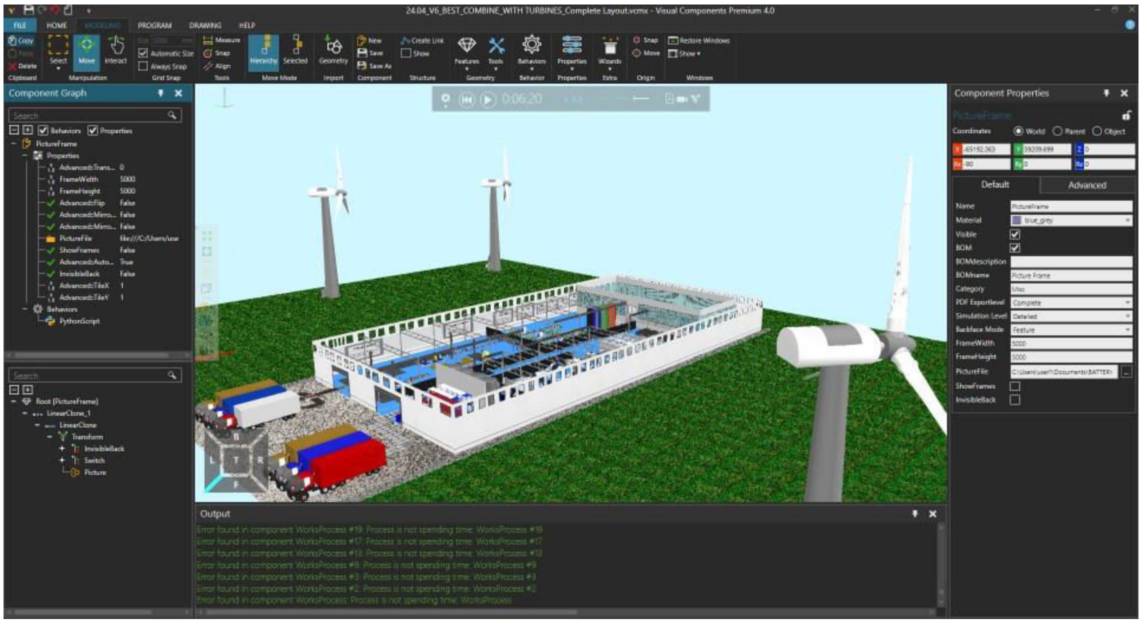

Figure 13. Modeling screen of Visual Components 4.0.

4.1.3. Program screen

Program screen shown on **Figure 14** is meant for programming any robot that is used in the layout. It allows one to jog a robot, set its properties and most importantly program the robot series of actions such as grasping action, input signal, output signal, linear and rotational motions, path tracing in welding operations and so on. It is very important to mention that extended and advance feature such as collision detector option in the programming screen are available as well. When such option is active, the robot is aware of any obstructions along its path and hence trigger an output alarm in the output panel (bottom). This kind of information is very important when there is only limited space for the robot to operate in the real-life factory.

Figure 14. Program screen of Visual Components 4.0.

The other screens on the main menu is drawing and help tabs. The drawing screen is used to generate a 2D drawing of the layout from different views (top, bottom, side and so on) while the help screen has options to visit the company website for tutorials and further help from Visual Components community and forums.

4.2. Components used for the automated LIB manufacturing factory layout

Different kinds of components were used to design the final layout. Majority of the components available from e-catalogue of VC 4.0 were adapted for the project. However, some other 3D geometries were modelled with different 3D modeling software such as SolidWorks, Fusion360, Tinker CAD and so on. Some other components were also downloaded from open-source 3D modeling websites and later edited to suit the purpose of this project. **Figure 15** shows and explains briefly the components from e-catalogue that were used in this project.

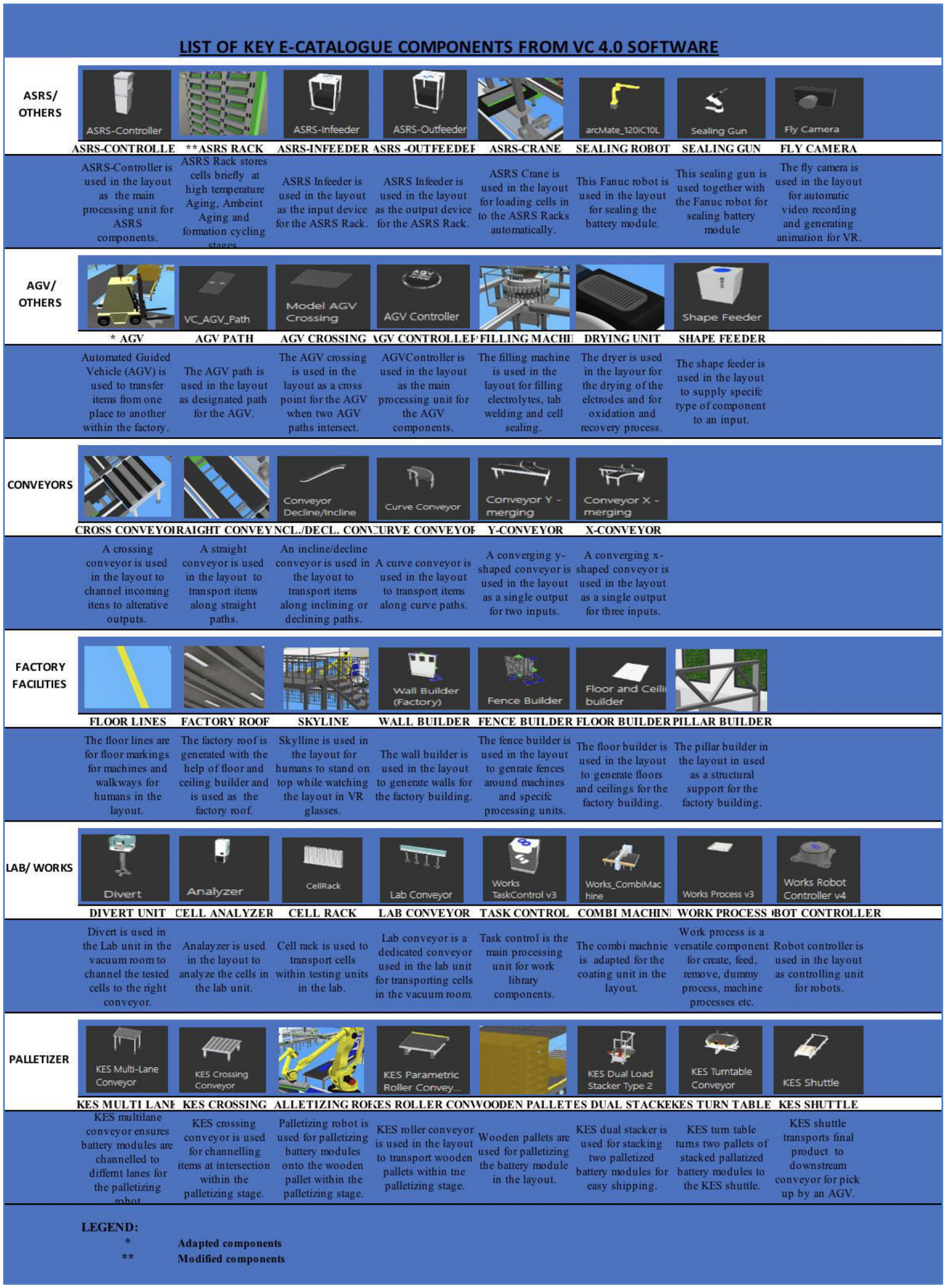

Figure 15. List of key e-catalogue components from VC 4.0.

Figure 16 shows the list and explanation of the other modelled components. Some of them were later edited to suit the need of this project.

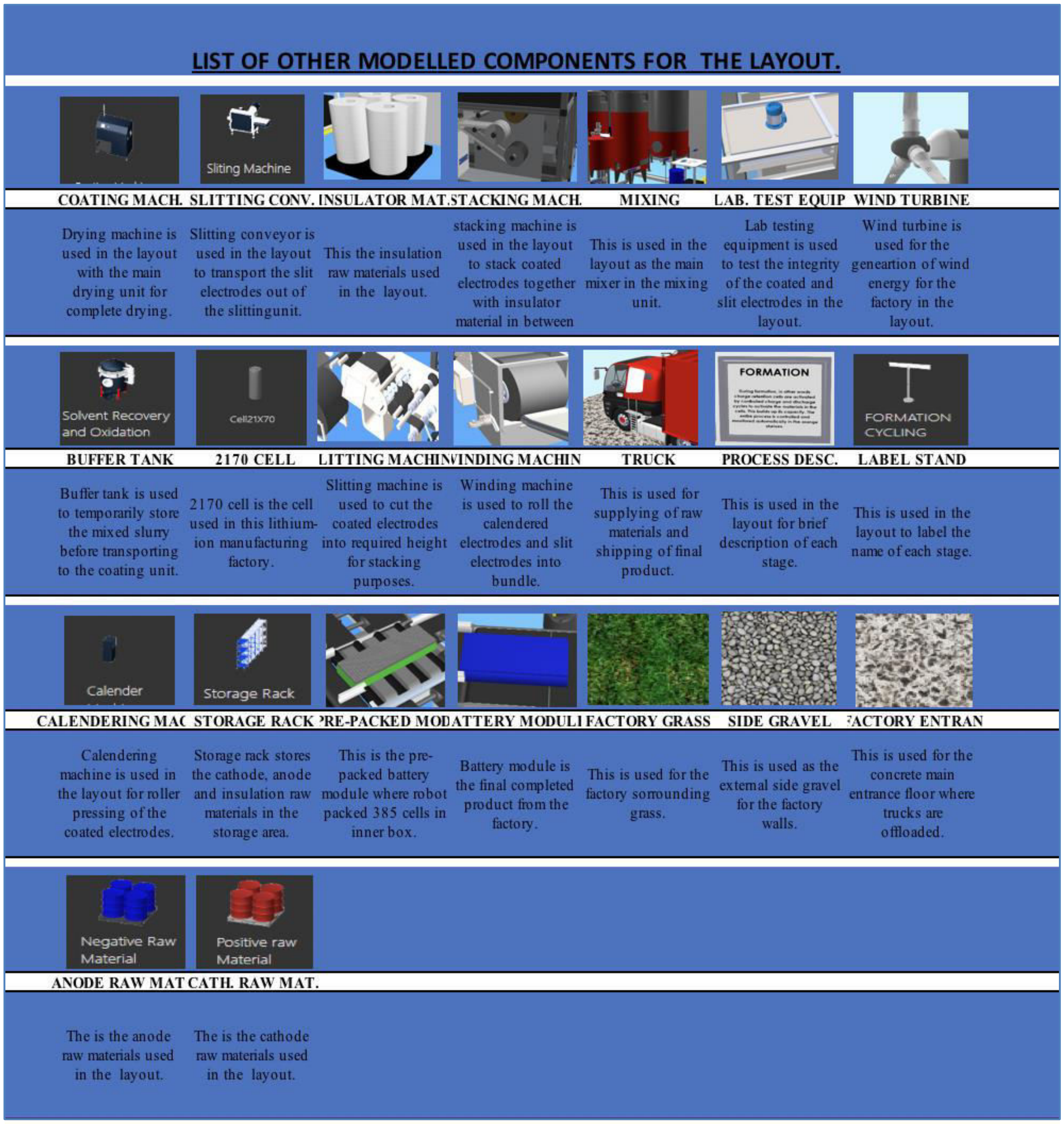

Figure 16. List of other modelled components for the layout.

5. RESULTS

This section presents the results of this research. The entire design process of an automated LIB manufacturing factory using VC 4.0 is presented followed by the VR sessions carried out during the research to identify key areas for possible improvement and optimization. Presentation and dissemination of results of this research using VR headset, video production and website creation for the automated LIB manufacturing factory is the last section presented in this chapter.

5.1. Designing and construction of an automated LIB manufacturing factory layout using VC 4.0

This section describes the manufacturing processes of an automated LIB manufacturing factory that is designed in VC 4.0. There are about 20 different manufacturing processes involved as suggested by Sakti et al. (2015) and the steps provided by Sakti et al (2015) which is presented in the literature review section (Figure 4) was mostly followed in designing the layout in VC 4.0. For some other stages such as the aging and formation processes, relevant sources from different LIB manufacturing solution providers were utilized. Due to limitation in computation power, all the models presented in the results section are only small version (smaller area dimension) of the 35GWh energy LIB manufacturing factory proposed for the project. Due to the computing power limitation, majority of the emphasis is made on the visualization of the automated LIB manufacturing factory. Although the size still considers an efficient factory layout and optimization in mind with a number of size calculation information provided from Hintsala (2018). Such size calculation information is presented in the appropriate sections.

As suggested by Kronthaler et al. (2012), a research on an automated battery production must have three main focus areas. The first aspect must ensure an adequate coating processes is achieved in order to achieve a continuous, homogeneous and smooth electrode compound. The second aspect is that an improved assembly process in terms of an automated design with high performance and quality must be addressed as well. The last aspect is about scrap reduction and quality assurance of the cells. The focus areas mentioned above are given special attention while designing the entire layout of the factory in VC 4.0 software.

Figure 17 shows all the stages of the final layout of LIB manufacturing factory from the right-top view using VC 4.0. All the stages are explained one after the other with detail pictures and explanations afterwards.

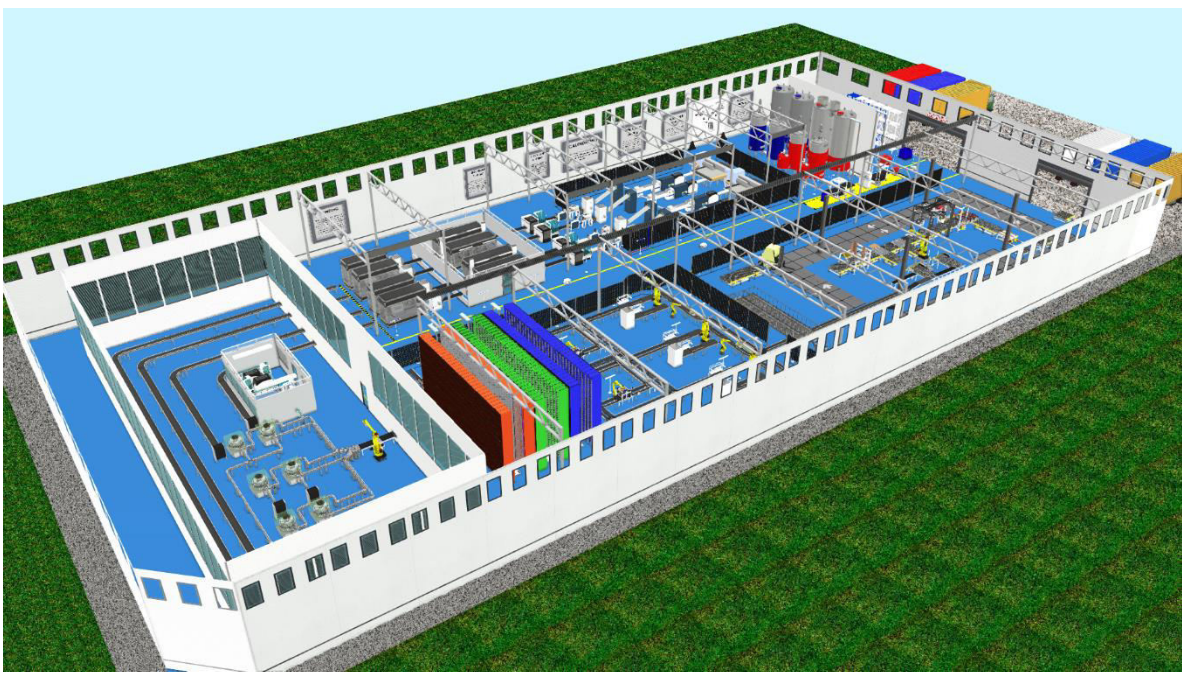

Figure 17. Final automated lithium-ion factory

In the following sections, all the stages of an automated LIB manufacturing as designed in VC 4.0 are presented and discussed in terms of the components used to design them and how they are expected to operate to achieve an efficient and optimized factory layout for an automated LIB manufacturing. It must also be stated that the cycle time and some other key parameters mentioned below are based on the design layout in this research using VC 4.0. The cycle time based on the 35GWh energy production is presented in Appendix 1 as calculated by Hintsala (2018).

RAW MATERIAL OFFLOADING

In the layout, there are three trucks for the main raw material which are Cathode material (Red truck), Anode raw material (Blue truck) and the Insulation raw material (yellow truck) as presented on **Figure 18**. An Automated Guided Vehicle (AGV) automatically offloads the raw materials to the racks in the storage area, as a result, the raw materials are offloaded without human intervention. Other raw materials such as stainless-steel pipe, copper foil, aluminium foil, binding and conductive materials and so on are not shown in this design.

Figure 18. Truck containers with the main raw materials.

Figure 19 shows the left view of the entire factory offloading areas. As seen in the picture, the factory main entrance is designed with concrete so that it can withstand the heavy weights of the entire six trucks including the 3 shipping trucks. From research and from realistic factory construction, concrete is usually a good choice for factory offloading and loading areas in the factory main entrance. In order to reduce the traveling distance of the AGV, the trucks are designed to be close as much as possible to the storage areas as well thereby reducing the traveling time for the AGV and hence more raw materials could be offloaded within a short time. The AGV follows the designated AGV path and AGV crossing to pick up the raw material from the truck and deliver them to the storage area

Figure 19. Left view of truck containers with the main raw materials.

Figure 20 presents an AGV approaching the container to pick up the raw materials that is stacked on a pallet and delivers it to the storage area using the AVG path as show in the picture. The AVG with predefined area (Area 1) determines the paths and directions of the forklift. Both pick up points and drop locations must be defined as well for the AGV to work.

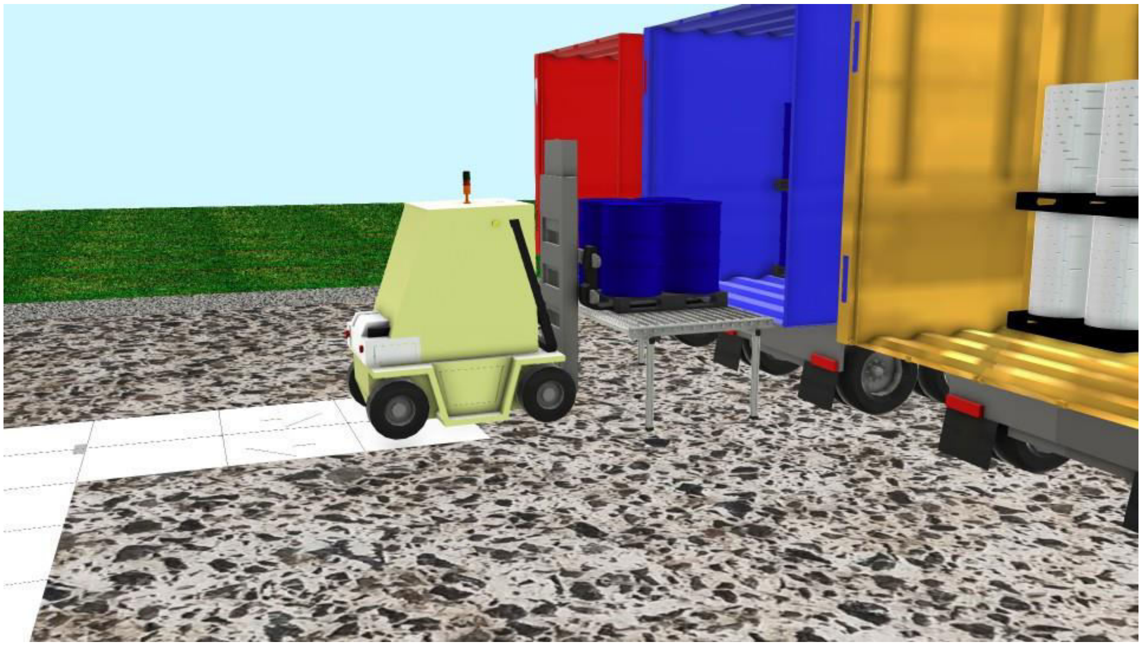

Figure 20. Automated Guided Vehicle (AGV) offloading the raw materials automatically.

As explained above that the AGV automatically offloads the raw materials, **Figure 21** shows a clearer view when the AGV is following the AGV pathways and AGV crossing to deliver the raw material (Anode in this case) already picked to the storage area.

Figure 21. Automated Guided Vehicle (AGV) transporting the raw materials to the storage area via the AVG pathway.

Bill of material (BOM)

The bill of material for this stage consisting of the name of the modeling components, category and unit amount is listed on **Table 1**.

Table 1. Raw material supply bill of materials.

S/N	Name of components	Category	Unit
1.	Truck Container (Anode)	Raw material supply	1
2.	Truck Container (Cathode)	Raw material supply	1
3.	Truck Container (Insulator)	Raw material supply	1
4.	Transporting conveyor	Conveyor	1
5.	Pick location	AGV	1
6.	Drop location	AGV	1
7.	AGV Pathway	AGV	4
8.	AGV Crossing	AGV	3
9.	Raw Material (Anode)	Raw Material (Anode)	1
10.	Raw Material (Cathode)	Raw Material (Cathode)	1
11.	Insulation Material (Insulator)	Insulation Material (Insulator)	1

Specific parameters and calculations

The AGV was simulated to offload and deliver 6 pallets in one minute. The AGV parameters are speed: 1778mm/s, pick height: 700mm AGV Speed: 5000mm/s, drop height: 700mm AGV Speed: 5000mm/s

Table 2 presents the comprehensive amount of trucks and amount of materials in (kg/m^3) required in order to meet the specified 35GWh of energy for the LIB manufacturing factory.

Table 2. Number of trucks requirement for 35GWh Lithium-ion manufacturing factory (Hintsala 2018).

Space requirements for raw material (By default, one-day delivery)		
Backup storage for two days (OPP)	kg/m3	Number of truck loads ordered at once
Graphite (Anode)	1350	4
LNMC (Cathode)	2200	7
Conductive material Super-P (Anode and Cathode)	1800	1
Conductive material KS-6 (Cathode)	1800	1
PVDF binder (Anode and Cathode)	1780	1
NMP Solvent (Anode and Cathode, after recovering)	1000	1
Steinless steel pipe (pipe length 7m. 51 m2 needed)	372	2
Aluminium plates (cell covers)	2700	1
Polypropylene (modules)	910	1
Separator rolls	875	2
Copper foil	8960	3
Aluminium foil	2700	2
LiPF6	1500	1
Dimethyl carbonate	1070	1
Ethyl methyl carbonate	1006	1
Ethylene carbonate	1321	1
Other substances	1000	1
Copper stripes for wiring	8960	0,5
Aluminum for wiring	2700	0,5

MATERIAL STORAGE

In the layout design, the anode, cathode and insulation raw materials are stacked on the racks by the AGV from the previous stage as presented on **Figure 22**. The racks are separated to Anode, Cathode and Insulation raw materials racks. Each rack has 18 slots for pallets which implies (3 rows by 6 columns). The height and width of each slot is estimated to be about 1500mm and 1300mm respectively.

Figure 22. Automated Guided Vehicle (AGV) staking the raw materials on the rack slots in the storage area.

Figure 23 presents the standard Anode raw material. There are 4 drums of anode raw materials weighing approximately 100kg of weight each.

Figure 23. Storage Rack showing the Negative raw material (Anode).

Figure 24 shows the standard Anode raw material. There are 4 drums of cathode raw materials weighing approximately 100kg of weight each.

Figure 24. Storage Rack showing the Positive raw material (Cathode).

Figure 25 shows the standard Anode raw material. There are 4 roll bundles of insulation raw materials on a pallet. Each roll bundle has 13 rolls of insulation materials. This implies there are 52 roll of insulation material on each pallet.

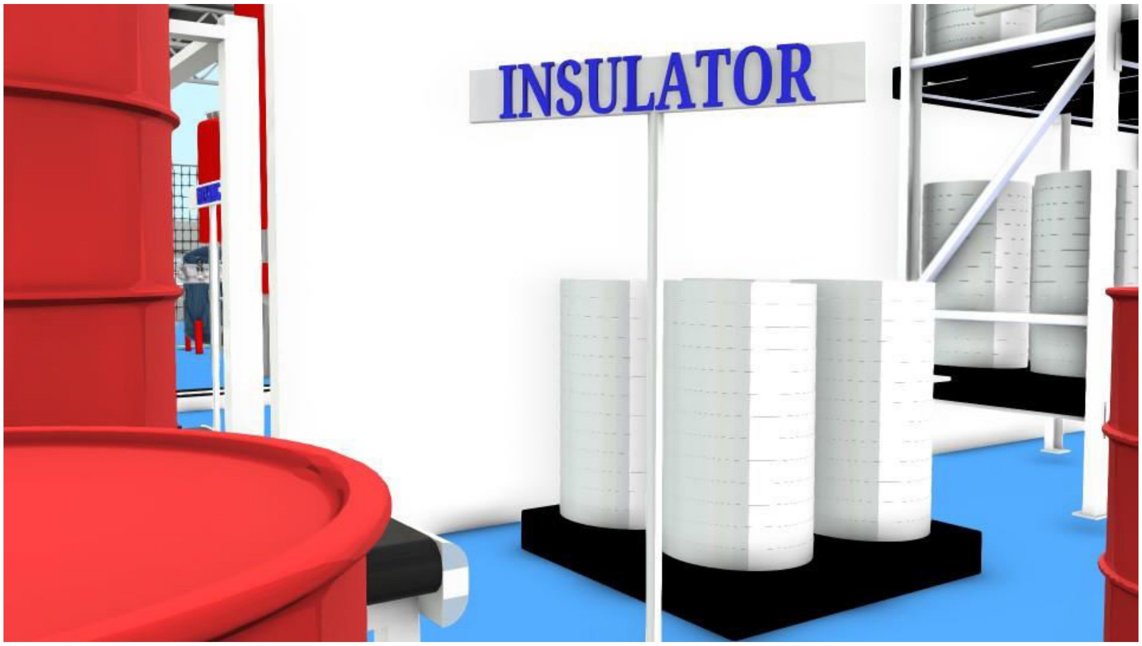

Figure 25. Storage Rack showing the Insulation material (Insulator).

Figure 26 shows the entire storage area arrangement with Anode raw material, cathode raw material and the insulation material. The storage area is designed in such a way that the AGV has enough room to navigate, stack and offload products and turn around as well.

Figure 26. The entire storage area of the factory layout.

Bill of material (BOM)

The bill of material for the storage unit consisting of the name of the modeling components, category and unit amount is listed on **Table 3**.

Table 3. Storage unit bill of materials.

S/N	**Name of components**	**Category**	**Unit**
1.	Raw Material (Anode)	Raw Material (Anode)	1
2.	Raw Material (Cathode)	Raw Material (Cathode)	1
3.	Insulation Material (Insulator)	Insulation Material (Insulator)	1
4.	Storage Rack	Storage unit	3
6.	Works process	Works	3
7.	Process description (Wall frame)	Labels	1
8.	Anode material stand (Label)	Labels	1
9.	Cathode material stand (Label)	Labels	1
10.	Insulation material stand (Label)	Labels	1
11.	Process description (Wall frame)	Labels	1

Specific parameters and calculations

In the layout design, the entire storage can contain 72 drums of anode raw materials, 72 drums of cathode materials and 936 rolls of insulation materials.

Table 4 the comprehensive storage space requirement and amount of materials in (kg/m^3) required in order to meet the specified 35GWh of energy for the Lithium-ion manufacturing factory (Hintsala 2018).

Table 4. Amount of space requirement for 35GWh Lithium-ion manufacturing factory (Hintsala 2018).

Space requirements for raw material (By default, one-day delivery)		
Backup storage for two days (OPP)	kg/m3	Stored material space (m3)
Graphite (Anode)	1350	148,89
LNMC (Cathode)	2200	171,95
Conductive material Super-P (Anode and Cathode)	1800	6,08
Conductive material KS-6 (Cathode)	1800	12,20
PVDF binder (Anode and Cathode)	1780	15,61
NMP Solvent (Anode and Cathode, after recovering)	1000	4,24
Steinless steel pipe (pipe length 7m. 51 m2 needed)	372	281,33
Aluminium plates (cell covers)	2700	17,44
Polypropylene (modules)	910	17,70
Separator rolls	875	104,62
Copper foil	8960	16,52
Aluminium foil	2700	37,08
LiPF6	1500	27,40
Dimethyl carbonate	1070	43,39
Ethyl methyl carbonate	1006	43,12
Ethylene carbonate	1321	35,15
Other substances	1000	35,76
Copper stripes for wiring	8960	1,97
Aluminum for wiring	2700	6,54

MIXING

The raw materials are transported to the mixing unit automatically with the aid of the pot feeder shown on **Figure 29**. At this stage, the raw materials are crushed into a fine powder to prepare the slurry needed for coating the aluminium and copper foils. There are different stages of the mixing process as shown in the layout. As indicated on **Figure 27**, the red tanks represent the positive electrode (cathode) mixing units while the blue tanks represent the negative electrode (anode) mixing units. This colour differentiation helps to easily identify the line of flow for both anode and cathode throughout the entire process.

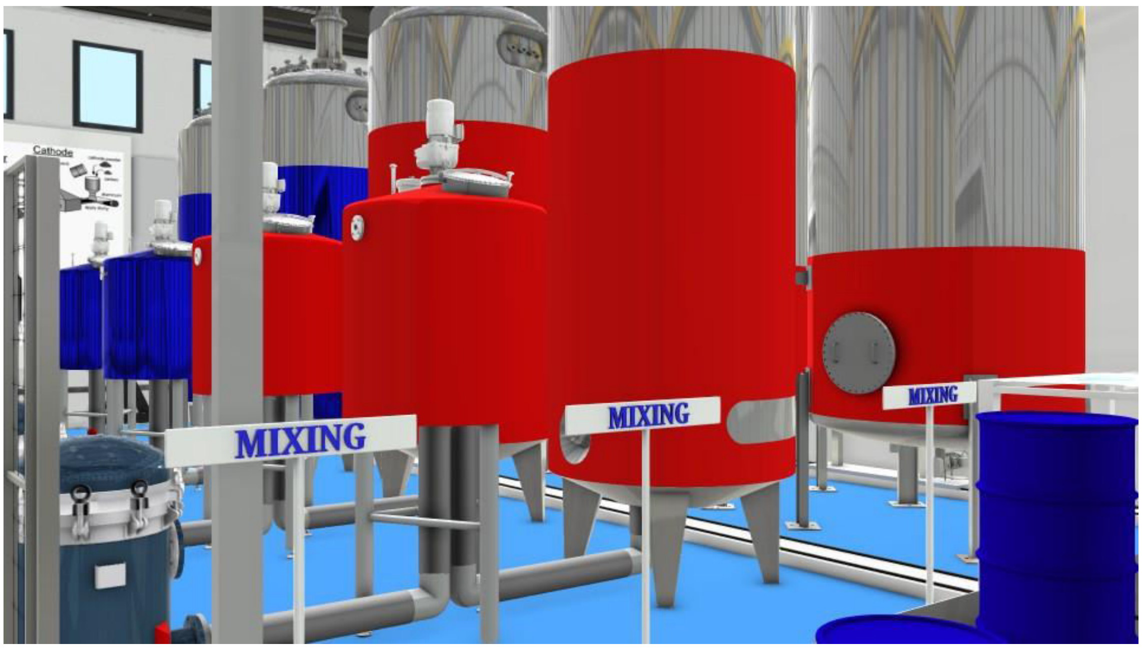

Figure 27. Mixing section overview

Figure 28 shows a clearer view from the front side showing both anode (blue tanks) and cathode (red tanks) lines. Both anode and cathode have two machine flow lines each as indicated in the colour differentiation below. Respective line for either anode or cathode has 2 tanks and two mixers each. The biggest tank is equipped with mixing unit. This is where the raw materials are automatically fed with the automatic pot feeding unit presented on **Figure 29** thereby eliminating the need of manual feeding. When the mixing is ready, the mixed slurry must be transported to the next smaller unit for further mixing. When a consistent mixing has been achieved, the finely mixed slurry is then sent to the next storage tank and is ready to the sent to the buffer storage unit where it will be sent through pipes to the coating machines.

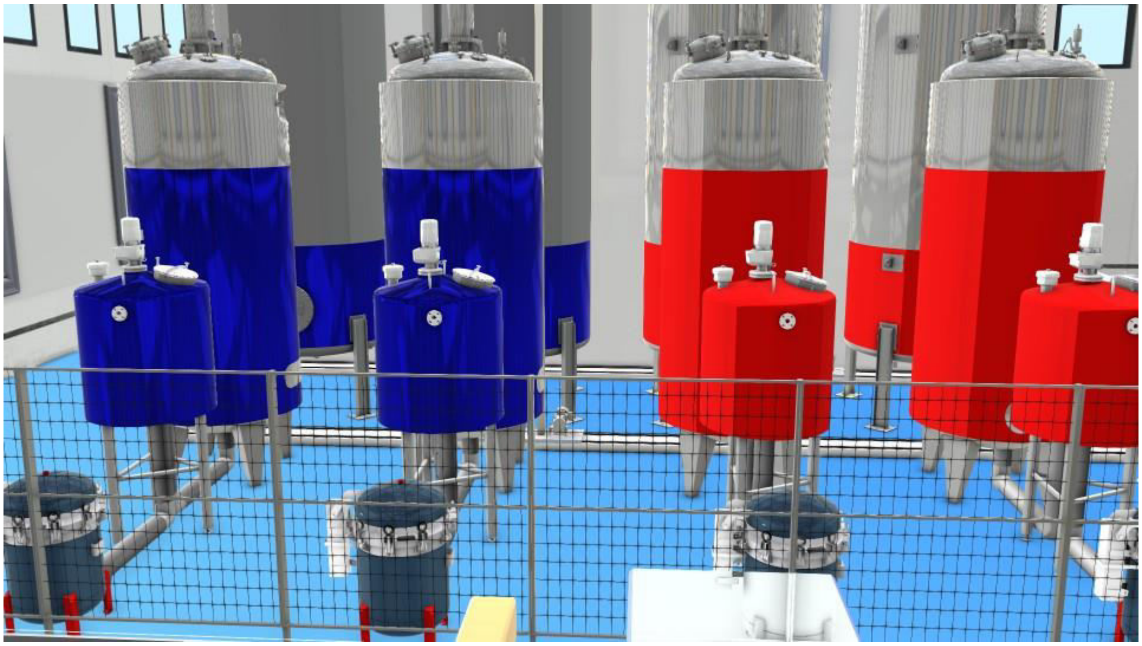

Figure 28. Mixing section with different tanks.

Figure 29 presents the automatic loading of raw material to the main mixer for preparation of slurry meant for coating.

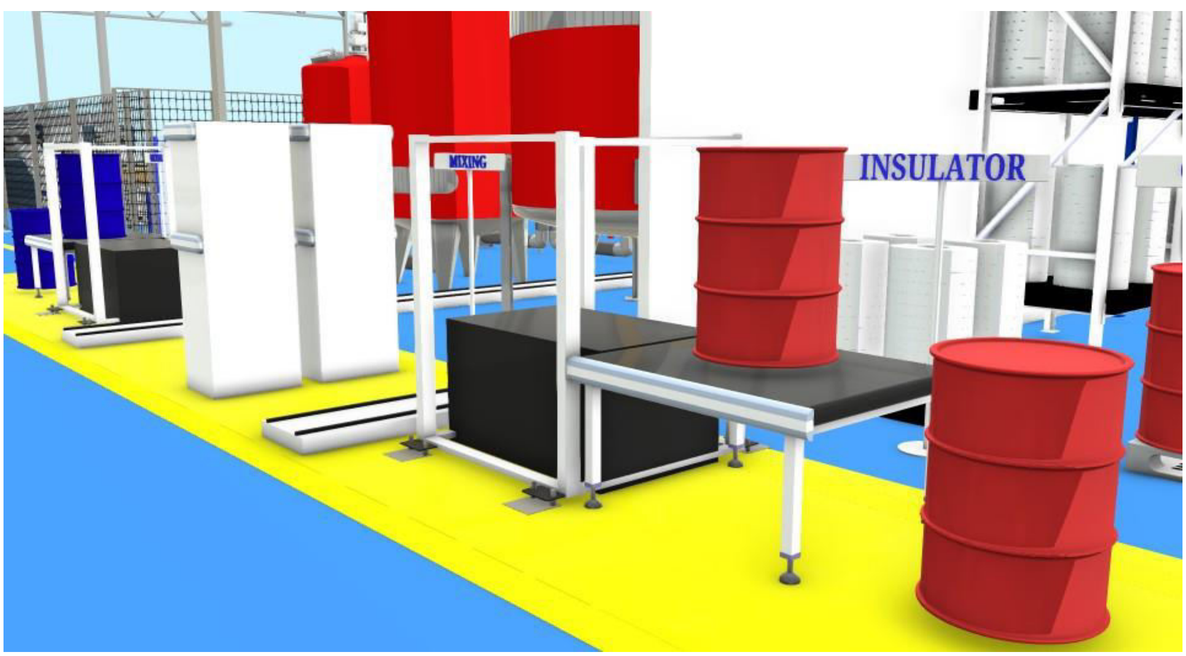

Figure 29. Automatic pot feeder loading unit for mixing unit raw materials.

Bill of material (BOM)

The bill of material for the mixing unit consisting of the name of the modeling components, category and unit amount is listed on **Table 5**.

Table 5. Mixing stage bill of materials.

S/N	Name of components	Category	Unit
1.	Main mixer (Anode)	Mixing unit	2
2.	Main mixer (Cathode)	Mixing unit	2
3.	Auxiliary mixer (Anode)	Mixing unit	2
4.	Auxiliary mixer (Anode)	Mixing unit	2
6.	Main storage tank (Anode)	Mixing unit	2
7.	Main storage tank (Cathode)	Mixing unit	2
8.	Buffer tank (Anode)	Mixing unit	2
9.	Buffer tank (Cathode)	Mixing unit	2
10.	Anode Raw material (drum)	Raw material (Anode)	1
11.	Cathode Raw material (drum)	Raw material (Cathode)	1
12.	Infeed conveyor	Conveyor	4
13.	Restricted area (Floor line)	Interior facilities	2
14.	ASRS-Infeeder	ASRS	2
15.	ASRS-Outfeeder	ASRS	2
16.	ASRS-crane (pot feeder)	ASRS	2
17.	ASRS-Controller	ASRS	2
18.	Mixing label stand	Labels	4
19.	Process description (Wall frame)	Labels	1

Specific parameters and calculations

The mixing stage has important component parameters in this section as ASRS-Infeeder parameters: table length = 1250mm; table width = 800mm; table height = 700mm. ASRS-Crane parameters: length = 14500mm; height = 7800mm; lifter width = 1200mm.

ELECTRODE COATING AND DRYING.

When the raw material slurries are prepared and finely mixed, they are ready to be uniformly coated on the aluminium and copper foils on both sides by the coating machine presented on **Figure 30**. The coating machine is adapted for the design by modifying the Works_CombiMachine from the e-catalogue component of visual components 4.0 (VC 4.0). The Works_CombiMachine (coating machine) can generate non-coated aluminium and copper foils using work process. These uncoated foils are hence coated after the machine has undergone machine process of specified amount of time. For the cathode material, solvent recovery and oxidation must be carried out after the coating as suggested by Sakti et al (2015).

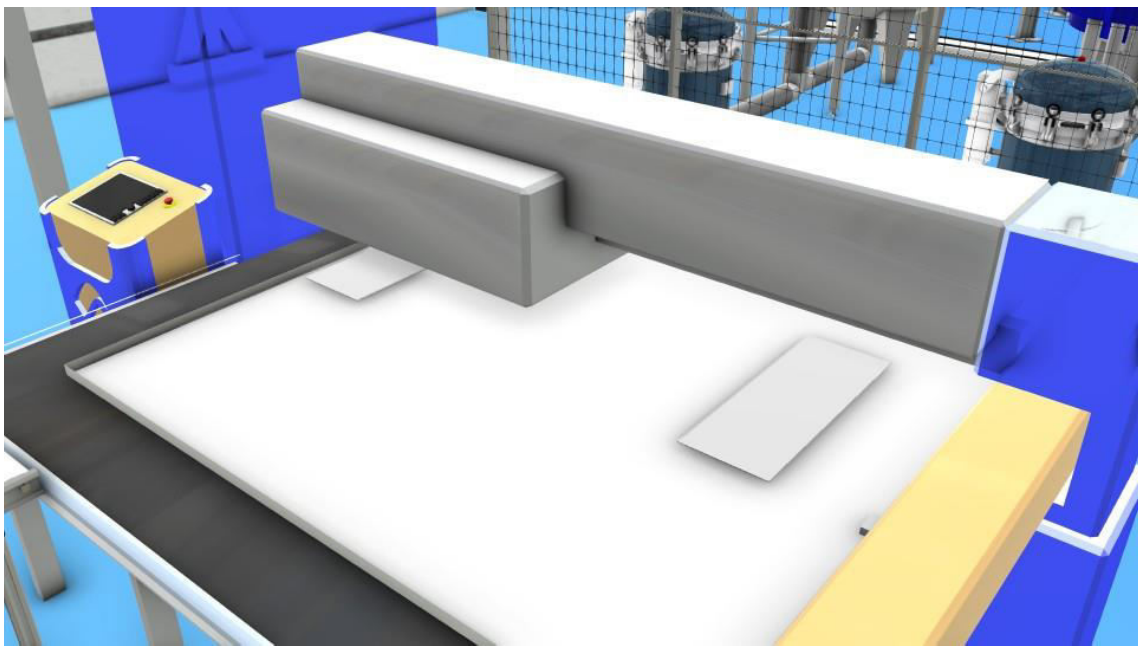

Figure 30. Electrode materials before coating

Figure 31 shows the negative material after coating. Aluminium material is coated in this case and only small side is not coated for tab welding later.

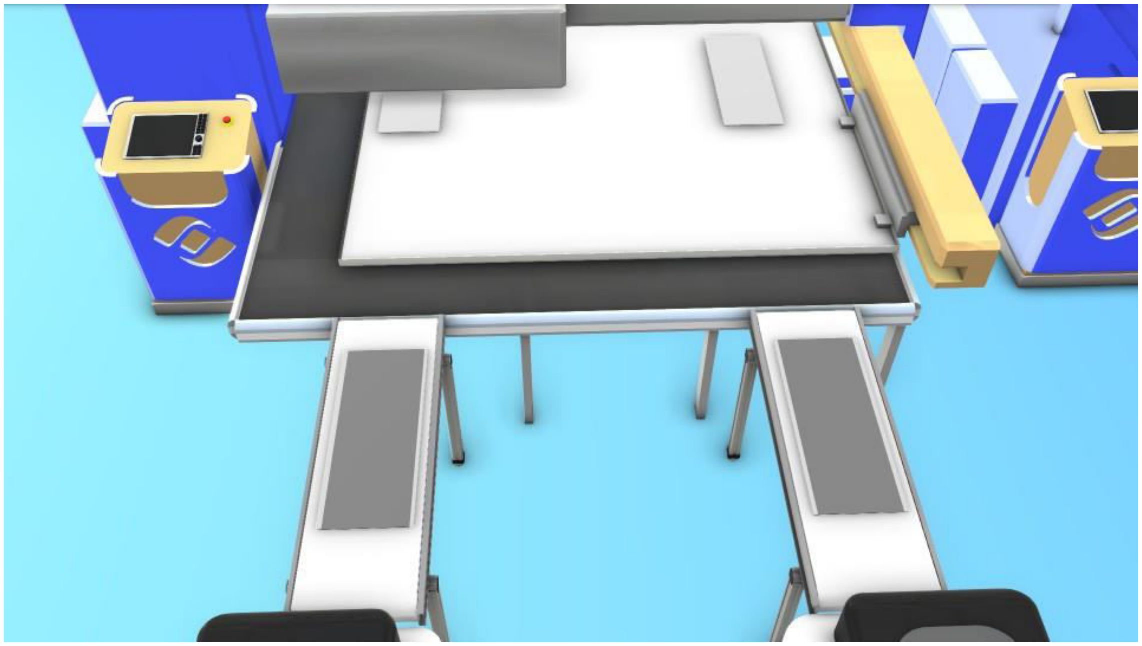

Figure 31. Negative electrode materials after coating.

Figure 32 shows the positive material after coating. Copper material is coated in this case and only small side is not coated for tab welding later.

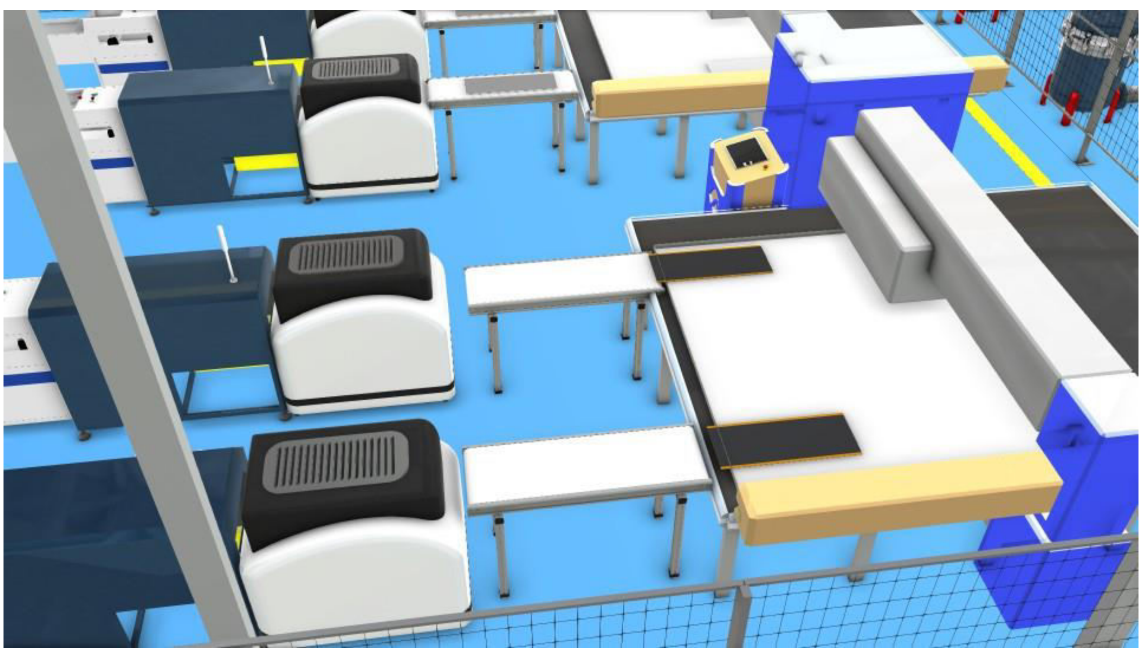

Figure 32. Positive coated electrode.

Figure 33 shows the entire coating section showing two separate lines for both anode and cathode from the downstream section (mixing unit). Each coating machine has two input and output and it can coat two foils at the same time on respective lines (anode line - aluminium or cathode line -copper)

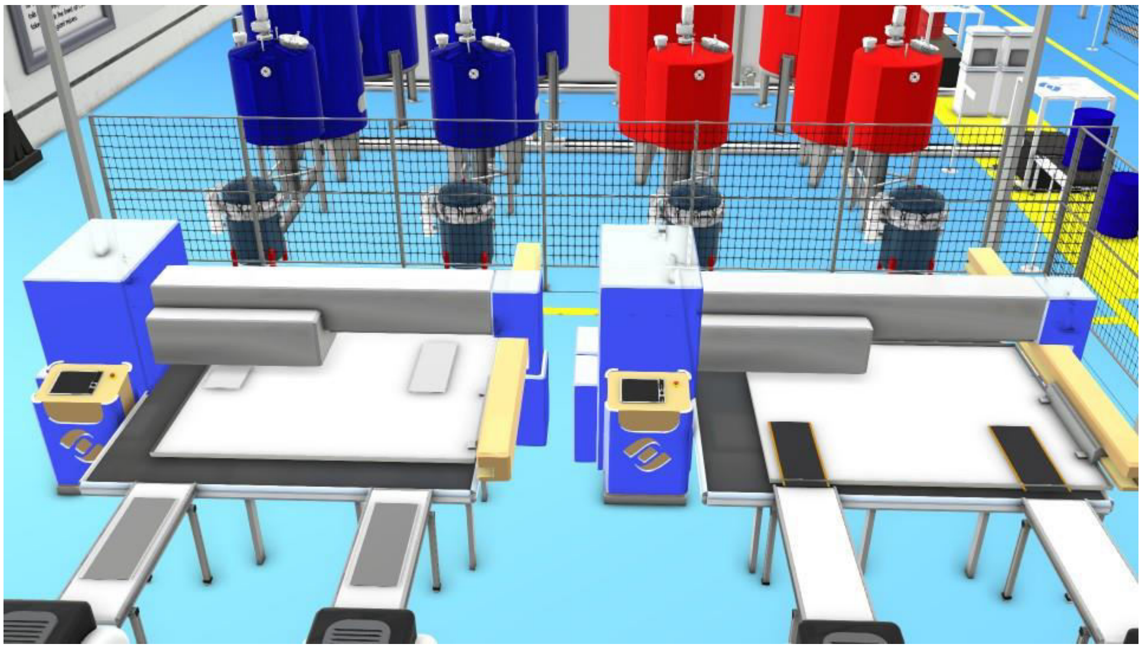

Figure 33. The entire electrode coating section.

Bill of material (BOM)

The bill of material for the coating unit consisting of the name of the modeling components, category and unit amount is listed on **Table 6**.

Table 6. Coating stage bill of materials.

S/N	Name of components	Category	Unit
1.	Aluminium foil (Anode)	Coating unit	2
2.	Copper foil (Cathode)	Coating unit	2
3.	Coated Anode Electrode	Coating unit	2
4.	Coated Cathode Electrode	Coating unit	2
6.	Slurry infeed unit	Coating	4
7.	Outfeed conveyor	Conveyor	4
8.	Works process	Works	2
9.	Works_CombiMachine	Works	2
10.	Coating label stand	Labels	1
11.	Process description (Wall frame)	Labels	1

Specific parameters and calculations

As stated above, each coating unit coat has two sheets of length of 1000mm and width of 400mm at the same time and it can coat approximately 24 sheets in one minute. Other important component parameters in this section are coating machine: maximum sheet length = 2000mm, maximum sheet width: 1500mm.

ELECTRODE DRYING

The coated and calendered electrodes are transported into the drying chamber with the help of conveyors to ensure that all solvent left are removed and dried out. The design in the layout is presented on **Figure 34**.

Figure 34. Electrode drying.

Bill of material (BOM)

The bill of material for the drying unit consisting of the name of the modeling components, category and unit amount is listed on **Table 7**.

Table 7. Electrode drying bill of materials.

S/N	Name of components	Category	Unit
1.	Main dryer	Electrode drying	4
2.	Transporting unit	Electrode drying	4
3.	Auxiliary dryer	Electrode drying	4
4.	Works process	Works	4
6.	Electrode drying label stand	Labels	1
7.	drying label stand	Labels	1
8.	Process description (Wall frame)	Labels	1

Specific parameters and calculations

As highlighted in the bill of materials above, the drying unit has the main drying and the auxiliary drying units consisting of filters, heating units and demisters which help to recover solvent which can be reused again on the line. The focus in the design is to visually represent the drying unit rather than simulating specific parameters such as temperature and so on.

ELECTRODE CALENDARING

The coated and dried electrodes are transported to the electrode calendaring machine with the help of the rising conveyor shown on **Figure 35**. The electrode calendaring machine uses different kinds of hard pressure rollers to press the coated foils into thinner shape. This helps the electrodes to occupy less amount of space in the cell casing and as well improve the of the energy density of the cell. Coated and dried electrodes are transported into the calendaring machine with the help of a work process component. The calendered electrodes are transported out from the calendaring machine to the downstream machines with the help of downward conveyor. The calendaring machine was modelled using Sketchup. The colours of the body of the machine and the rollers were achieved using the modeling tab of the VC 4.0 software. This is presented on **Figure 35**.

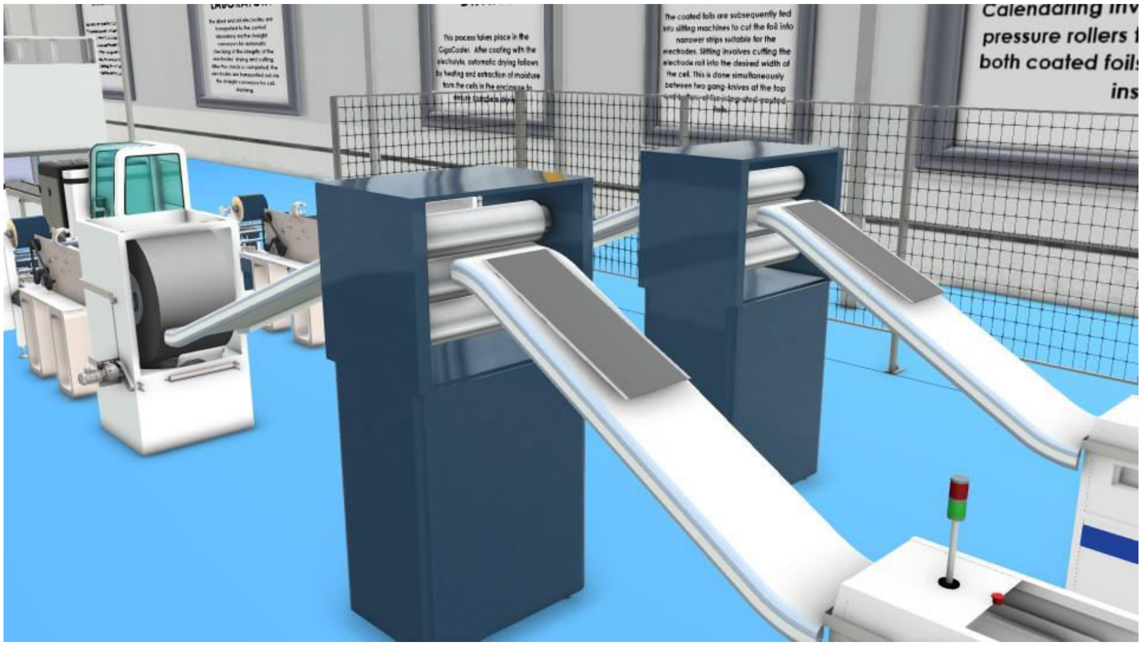

Figure 35. Electrode Calendering.

Bill of material (BOM)

The bill of material for the coating unit consisting of the name of the modeling components, category and unit amount is listed on **Table 8**.

Table 8. Electrode Calendering bill of materials.

S/N	Name of components	Category	Unit
1.	Electrode calendaring machine	Electrode calendering	4
2.	Incline conveyor	Conveyor	4
3.	Decline conveyor	Conveyor	4
4.	Works process	Works	4
6.	Electrode calendering label stand	Labels	1
7.	Process description (Wall frame)	Labels	1

Specific parameters and calculations

The electrode calendering machine can process one coated electrode of length 1000mm in approximately 5 seconds. This implies it can process 12 in one minute. Other important component parameters in this section is the roller pressure speed which is approximately = 200 mm/s.

ELECTRODE SLITTING

The next stage in the layout is electrode slitting. The coated and calendered electrodes are transported to the slitting unit. The electrodes are cut into narrow strips suitable for the stacking purpose with the help of the slitting blades as shown on **Figure 36**. This is measured to a height of 70cm and 21cm in diameter for 2170 cells. During slitting, the tabs are left on the electrodes for electricity transfer to and out of cell as presented on **Figure 36**.

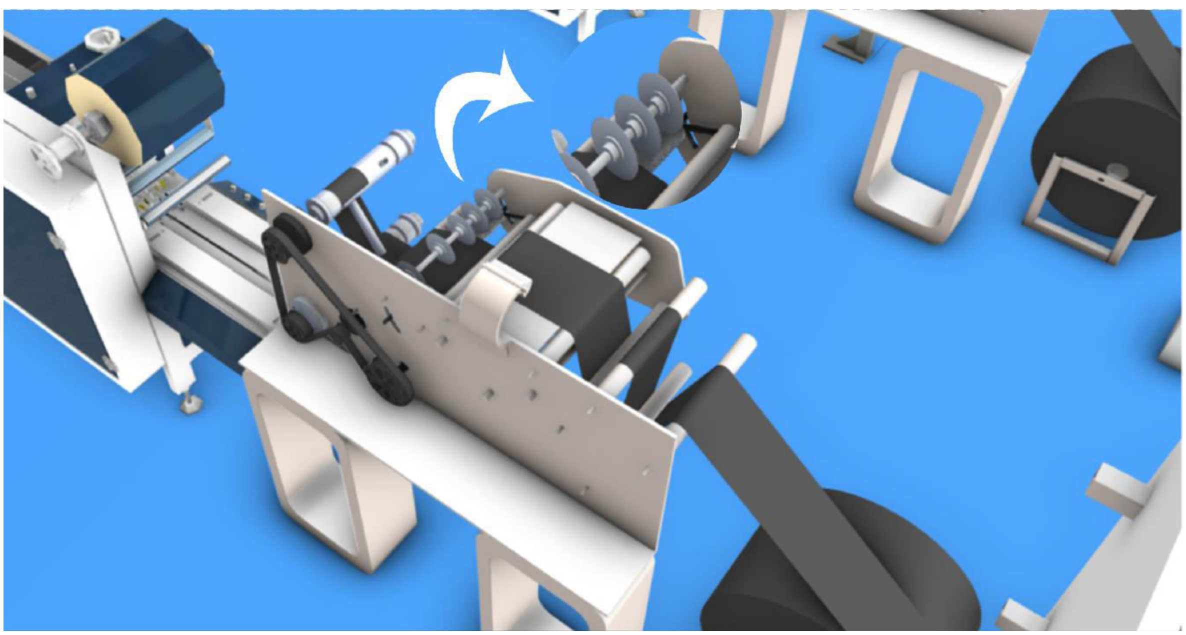

Figure 36. Slitting coated electrodes along the slitting blades.

Figure 37 shows the slit electrodes into 6 equal places with width of 70cm each. The electrode below is the anode, the same goes for the cathode as shown on **Figure 38**.

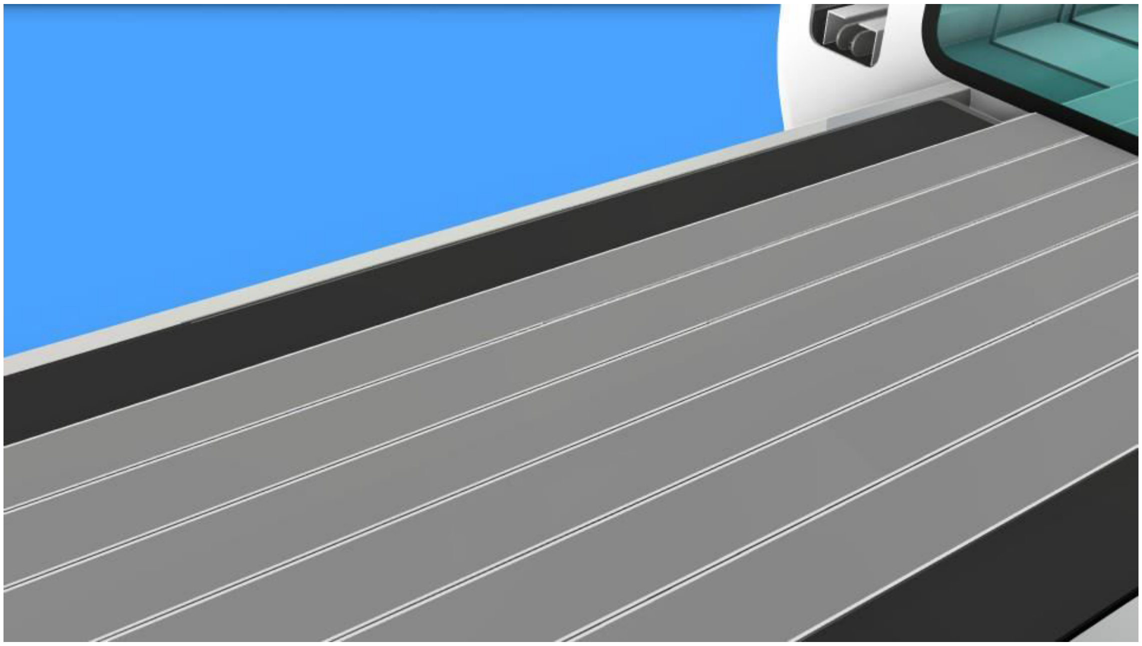

Figure 37. Slit Electrodes (Anode).

Figure 38 shows the slit electrodes of 6 equal parts with width of 70cm. The electrode below is the cathode.

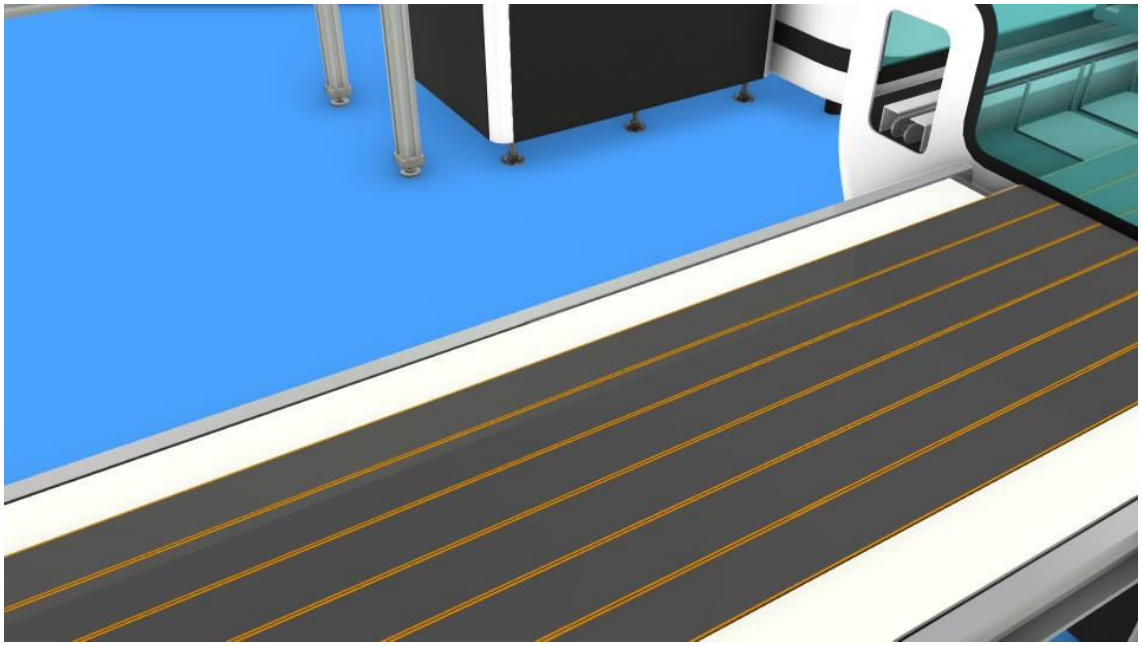

Figure 38. Slit Electrodes (Cathode).

Bill of material (BOM)

The bill of material for the mixing unit consisting of the name of the modeling components, category and unit amount is listed on **Table 9**.

Table 9. Electrode slitting bill of materials.

S/N	Name of components	Category	Unit
1.	Electrode slitting machine	Electrode slitting	4
2.	Transporting conveyor	Conveyor	4
3.	Infeed conveyor	Conveyor	4
4.	Outfeed conveyor	Conveyor	4
5.	Electrode slitting label stand	Labels	1
6.	Process description (Wall frame)	Labels	1

Specific parameters and calculations

In the design layout, the slitting machine can produce 6 slits of width of 70cm and length of 1000mm in approximately 3 seconds since there are 6 slitting blades installed. So, each slitting machine has a performance of 120 slit electrodes of 100mmm length in one minute.

CONTROL LABORATORY

At the laboratory presented on **Figure 39**, specific measurement of quality tests is carried out on the slit electrodes to ensure high quality final product. The slit electrodes that do not meet the quality requirement are scrapped and recycled.

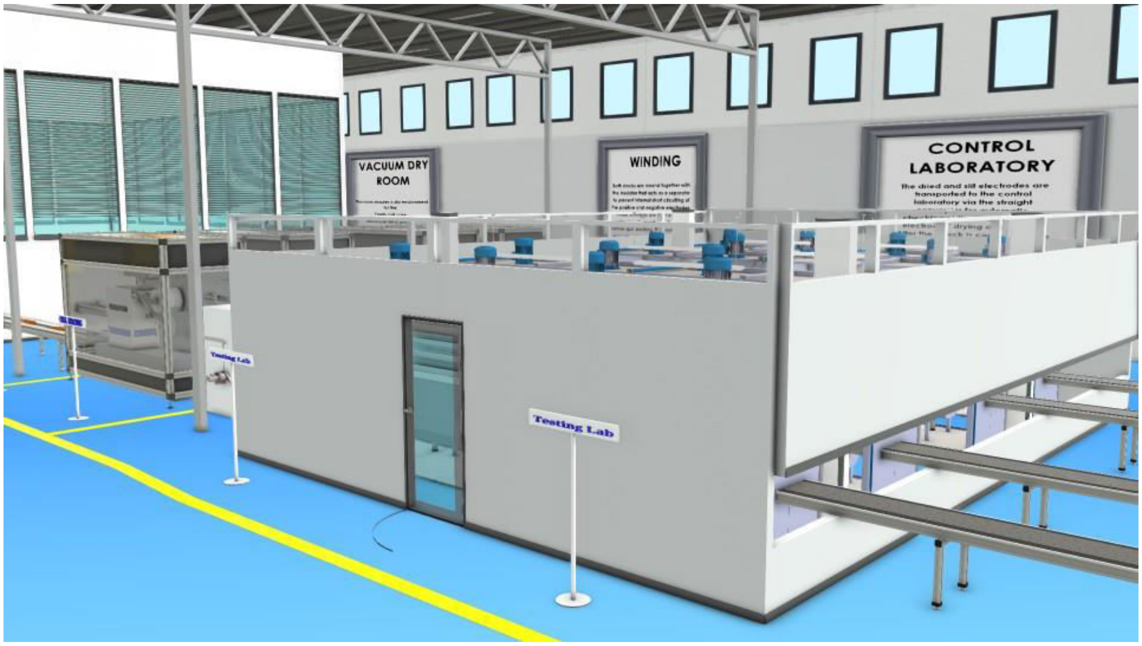

Figure 39. Control lab overview.

Figure 40 shows the inside of the control lab showing the testing machines that electronically measure the dryness, cutting integrity and required thickness.

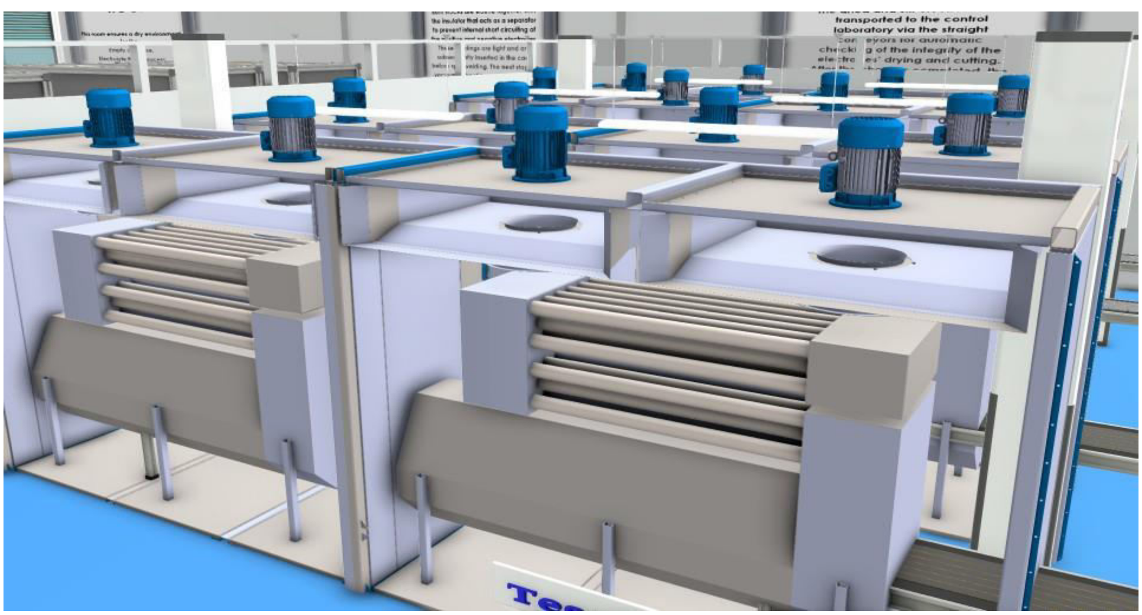

Figure 40. Control lab with internal machines.

Bill of material (BOM)

The bill of material for the control lab consisting of the name of the modeling components, category and unit amount is listed on **Table 10**.

Table 10. Testing lab bill of materials.

S/N	**Name of components**	**Category**	**Unit**
1.	Electrode monitoring machine I	Testing laboratory	4
2.	Electrode monitoring machine II	Testing laboratory	4
3.	Wall builder (indoor)	Interior facilities	14
4.	Infeed conveyor	Conveyor	4
5.	Outfeed conveyor	Conveyor	4
6.	Testing lab label stand	Labels	2
7.	Process description (Wall frame)	Labels	1

Specific parameters and calculations

The control lab unit uses the electrode monitoring machines to ensure that the electrode at this stage are of high quality since that will determine the overall quality of the cells. The focus in the design is to visually represent the electrode monitoring machines and not to simulate the control lab parameters which determine whether the electrodes meet the requirements, or it meant to be scrapped and recycled.

WINDING/ CELL STACKING

The cell stacking/winding stage involves winding both strips of positive and negative electrodes together with the insulator serving as a separator to prevent internal electrodes from short circuiting as presented on **Figure 41**. These windings are tight and are subsequently inserted in the cell case.

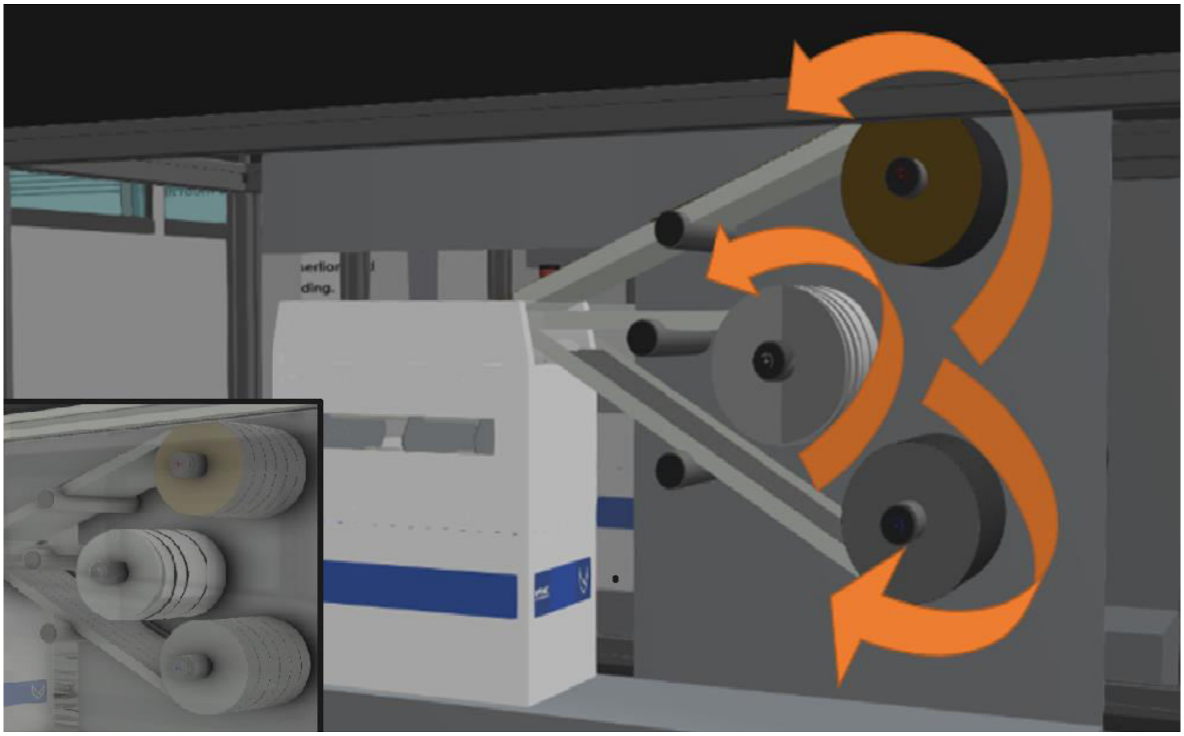

Figure 41. Slit Electrodes (Cathode).

Bill of material (BOM)

The bill of material for the cell stacking unit consisting of the name of the modeling components, category and unit amount on listed in **Table 11**.

Table 11. Winding and cell stacking bill of materials.

S/N	Name of components	Category	Unit
1.	Cell stacking machine	Cell stacking	4
2.	Robot enclosure	Factory facilities	4
3.	Infeed conveyor	Conveyor	4
4.	Outfeed conveyor	Conveyor	4
5.	Cell stacking label stand	Labels	2
6.	Process description (Wall frame)	Labels	1

Specific parameters and calculations

The cell stacking unit was simulated to stack 6 cells at the same time along different lines as observed on the stacking machine. The stacking machine presented here is only meant for visual representation. Other internal rolling processes of electrodes and cutting of electrodes when the number of rolls is achieved are omitted since they are too detailed process.

ELECTROLYTE FILLING AND CELL ENCLOSING

After the tight windings are inserted in the case with already welded bottom cover in the vacuum chamber, tabs are welded in place and the can is filled with an electrolyte which consists of lithium salt such as Lithium hexafluorophosphate in an organic solution. The electrolyte filling and cell sealing/enclosing must be carried out in a vacuum room to prevent electrolyte property loses. **Figure 42** shows the machine that fills electrolyte in the cells, ensures case sealing and tab welding.

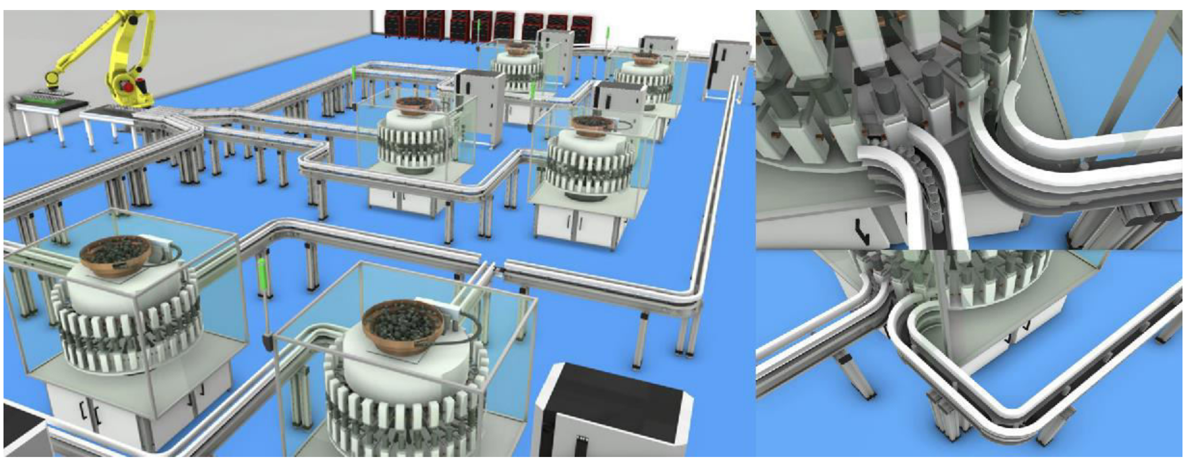

Figure 42. Electrolyte filling, cell sealing and tab welding machine.

After the cells are ready, they are tested individually before the next stage which is formation cycling and aging. Cells that meet the requirement are transported via conveyor to the pre-packaging unit by a robot in the vacuum room. The pre-packaging is very important because it makes storing the cells at formation and aging stage easier. **Figure 43** shows the testing lab unit in the vacuum room that test individual cells and also the robot that pre-pack the cells for the next stage.

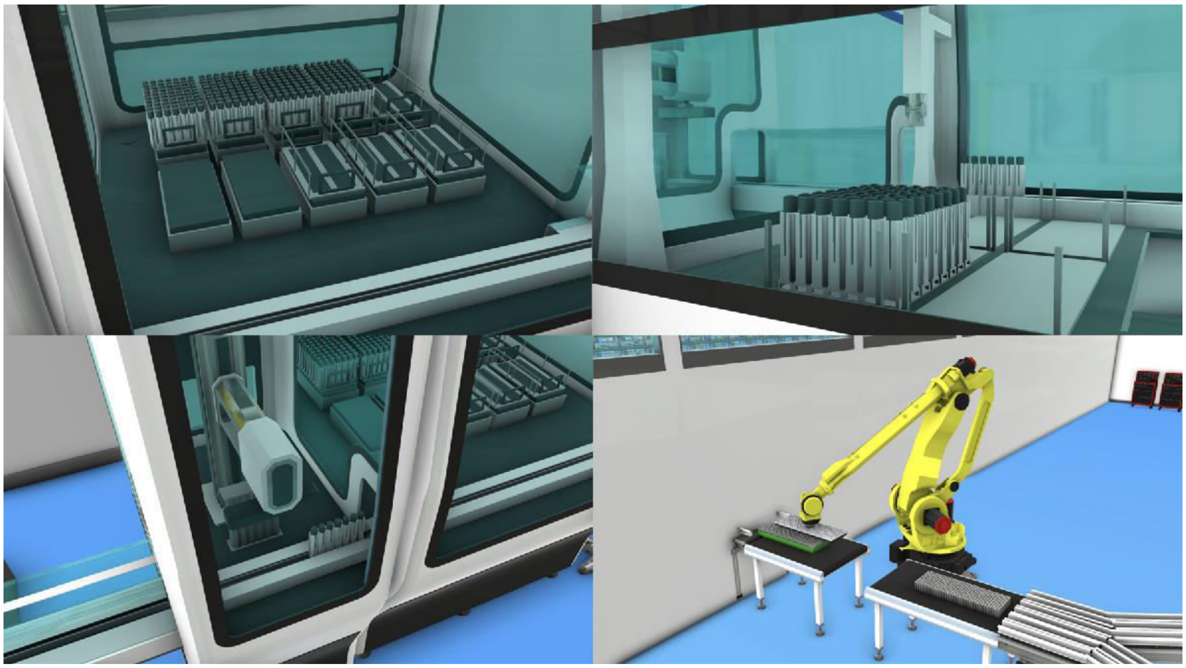

Figure 43. Cell testing lab and cell pre-packaging robot.

Bill of material (BOM)

Table 12 presents the bill of material for the entire vacuum room activities. This includes the electrolyte cell filling, cell sealing, tab welding, testing unit cells and pre-packaging unit for the electrolyte filling and cell enclosing. The stage modeling components, category and unit amount are presented as well.

Table 12. Electrode filling bill of materials.

S/N	Name of components	Category	Unit
1.	Electrolyte filling machine	Vacuum room	1
2.	Tab welding	Vacuum room	1
3.	Cell enclosing	Vacuum room	1
4.	Cell testing lab	Vacuum room	1
5.	Wall builder indoor	Interior facilities	18
6.	Infeed conveyor	Conveyor	4
7.	Straight conveyor	Conveyor	4
8.	Empty cell straight conveyor	Conveyor	50
9.	Curve conveyor	Conveyor	43
10.	Crossing conveyor	Conveyor	1
11.	Conveyor merging -Y	conveyor	1
12.	Lab conveyor	Conveyor	11
13.	Conveyor navigator	Conveyor	1
14.	Lab demo analyser interface	Laboratory	2
15.	Analyzer	Laboratory	2
16.	Lab demo decapper	Laboratory	1
17.	Lab demo centrifuge	Laboratory	1
18.	Main lab input	Laboratory	1
19.	Empty cell shape feeder	Vacuum room	5
20.	Vacuum room label stand	Labels	6
21.	Process description (Wall frame)	Labels	5

Specific parameters and calculations

The vacuum unit has a number of important process as discussed above. All the processes were modelled and optimized based on the provided parameters. The pre-package module box has 385 cells.

Table 13 shows the required calculation for electrolyte production requirement for the 35GWh of energy specification from the Lithium-ion battery factory as provided by Hintsala (2018).

Table 13. Electrolyte production for 35GWh energy for Lithium-ion battery factory. (Hintsala 2018).

Electrolyte production		
Amount for one cell, grams (dried)	7,26	
Amount for one cell (undried), grams, estimate	15	
Dried electrolyte volume for one cell, cm3	4,81	
Undried electrolyte volume for one cell, cm3	9,93	
Number of cells in one liter solvent	100,67	
Mixing time, minutes, estimate	360	
Required Liquid batch size (=tank size), liters	9525,54	
Required number of producted cells in minute	2664	
Actual tank mixing tank size	9600	
Stage capacity in minute	2684	Grams needed
LiPF6 needed for one cell	1,59	
Dimethyl carbonate needed for one cell	2,98	
Ethyl methyl carbonate needed for one cell	2,19	
Ethylene carbonate needed for one cell	2,98	
Other substances	0,20	
Total	9,93	

FORMATION PROCESS

The cells are charged for the first time in the formation stage since during the earlier stages they were never charged. This process makes the cells to get activated by controlled charge and discharge cycles that activate the materials in the cells and thus build up the cell capacity. The entire process is controlled and monitored automatically in the green racks as shown on **Figure 44**.

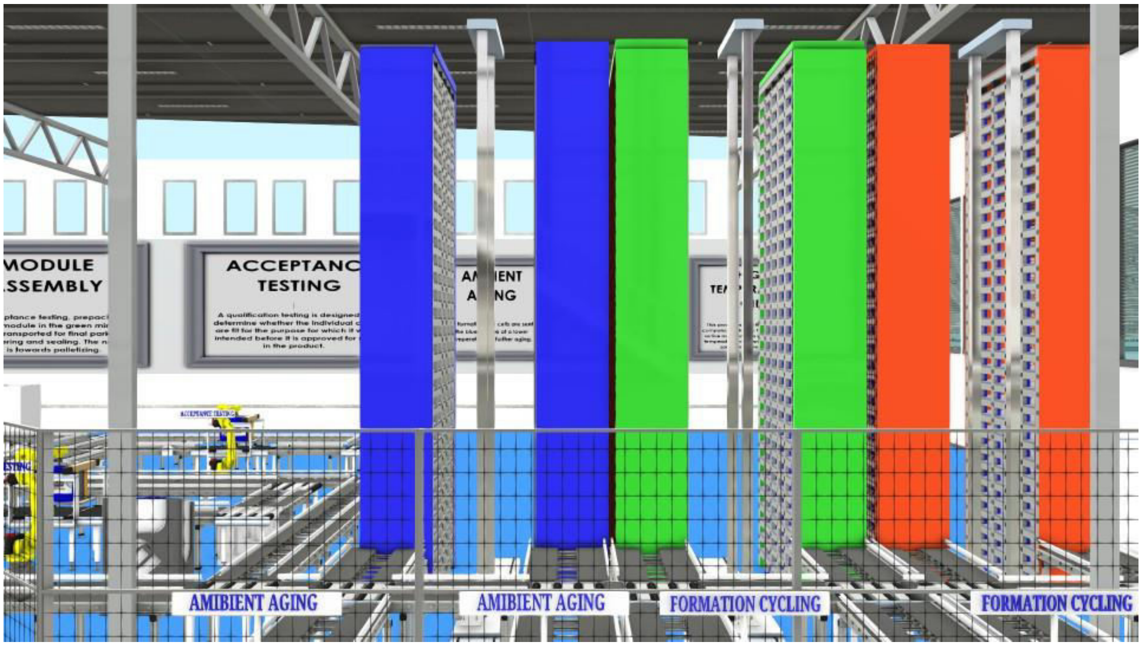

Figure 44. Formation cycling racks.

VR played a major role in the design of this stage. The dimensions of the racks are not intuitive in nature and only the 3D simulation model was not enough to achieve an optimized layout for the racks in this stage. Possible areas of adjustment in terms of rack size and dimensions as well as slot/bay dimesons were only naturally perceived after series of VR sessions. The identified problems were eventually corrected using the 3D software after the VR sessions. At the same time, new and optimized pattern for the racks layout was identified as well. **Figure 45** shows one of the VR sessions in this stage.

Figure 45. VR session for achieving an optimized racks dimensions and layout pattern.

Figure 46 shows the belt sorter conveyors including the cross conveyors supplying the pre-packaged battery modules from the vacuum room to the formation racks (green). The same conveyor mechanism is used for both high temperature aging and ambient aging processes.

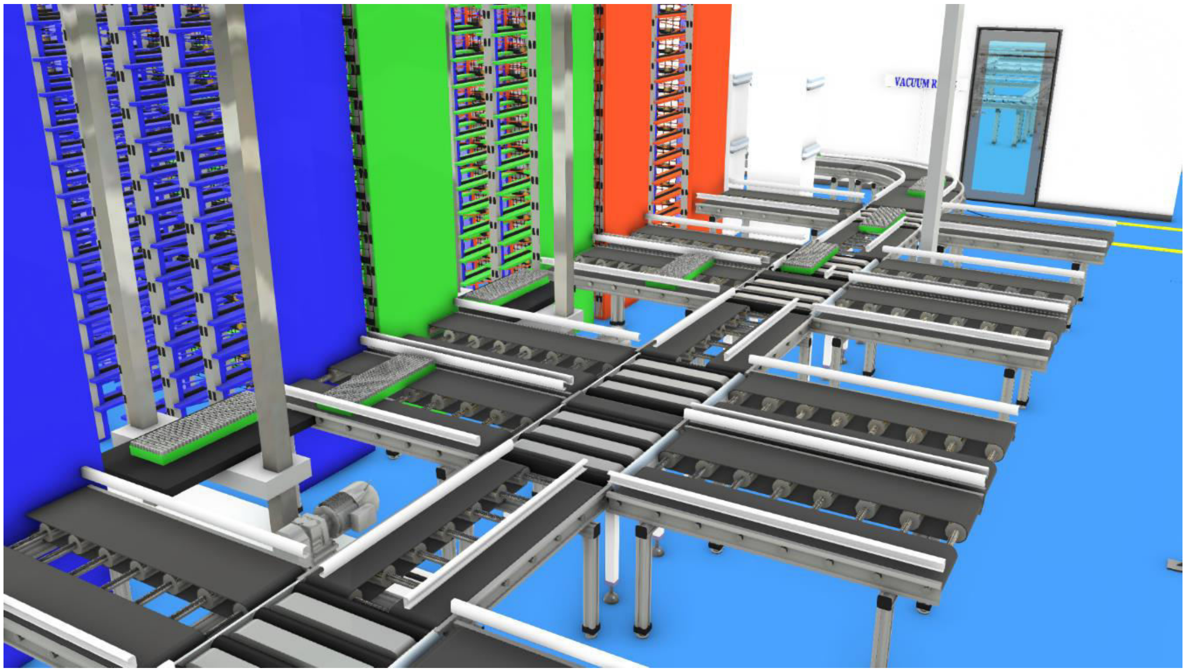

Figure 46. Belt sorter and cross conveyors feeding the formation racks, high temperature and ambient aging racks.

Bill of material (BOM)

The bill of material for the formation cycling unit consisting of the name of the modeling components, category and unit amount is listed on **Table 14**.

Table 14. Formation cycling bill of materials.

S/N	Name of components	Category	Unit
1.	Formation cycling process rack	ASRS	2
2.	ASRS-Crane (pre-package module feeder)	ASRS	1
3.	ASRS-Controller	ASRS	1
4.	ASRS-Infeeder	ASRS	1
5.	ASRS-Outfeeder	ASRS	1
6.	Main infeed conveyor	Conveyor	1
7.	Output conveyor	Conveyor	5
8.	Crossing conveyor	Conveyor	2
9.	Formation cylcing label stand	Labels	2
10.	Process description (Wall frame)	Labels	1

Specific parameters and calculations

The formation cycling stage represented by the two green shelves shown above has important component parameters in terms of capacity, dimensions and so on. The formation racks that can hold 1800 units (pre-packed modules) and has slot dimensions of length = 12000mm; width = 800mm; height = 6200mm while tier height = 200mm and bay width = 400mm.

Table 15 shows the formation stage calculation requirements for 35GWh annual energy for Lithium-ion battery factory (Hintsala 2018).

Table 15. formation stage calculation requirements for 35GWh annual energy for Lithium-ion battery factory. (Hintsala 2018).

Formation cycling and charge retention		
Cells / 1min	2664	
Cells / 1hour	159817	
3 cycles formation time (hours)	6,6	
Cells in stage at once	1054795	
Batch size	2500	
Batches in stage at once	422	3,7V cells are C/1
Stage capacity in minute	3000	
Required Batch in - batch out in every X second	56,3	
Actual Batch in - batch out in every X second	50,0	3 cycles, 6,6h

HIGH TEMPERATURE AGING AND AMBIENT AGING

The cells are stored for a very long time at this stage where the aging is being monitored both in high temperature environment and ambient environment. It requires large amount of space and storage time where the cells can be put to aging tests just like the way they will be used in real device in order to determine the aging process and discharge time rate of the cells. **Figure 47** shows both high temperature aging racks (orange) and ambient aging racks (blue). The sorter conveyors feed the cells into the racks where they will be conditioned to aging environment.

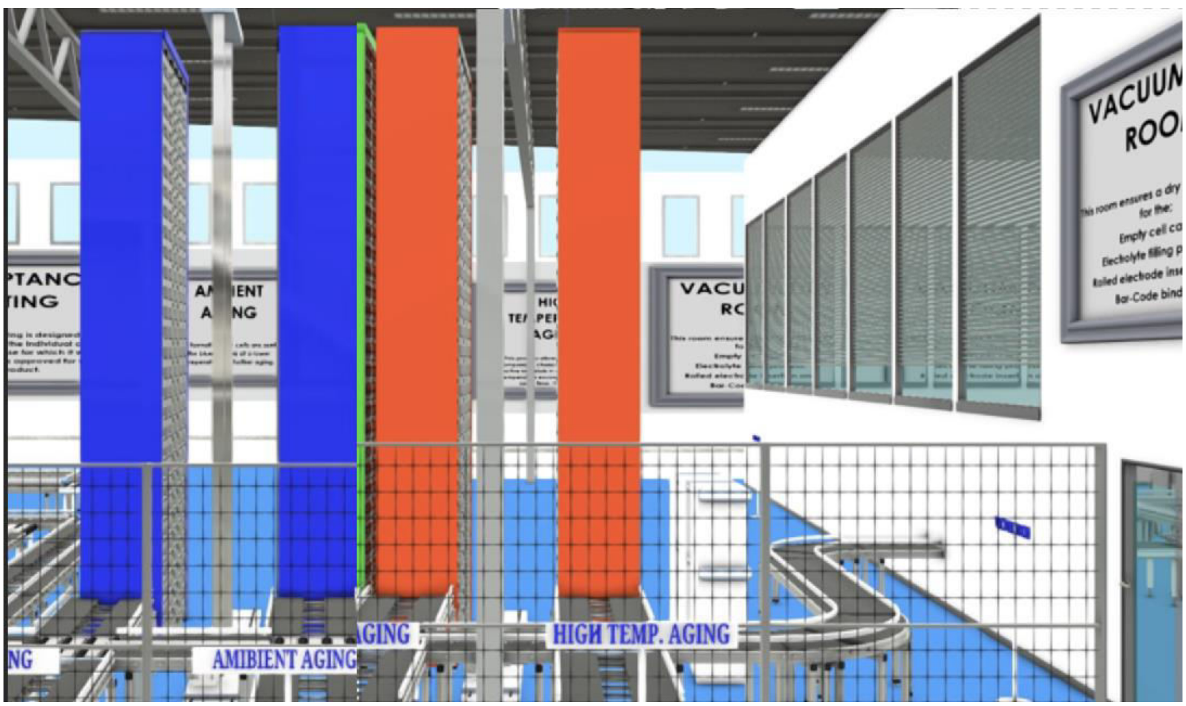

Figure 47. Ambient Aging and High temperature racks.

At a closer look, **Figure 48** shows a clearer picture of the cells being stored in each slot. Both high temperature aging and ambient aging stages have 2 racks each and each rack has 900 slots which implies that the two racks for each stage can hold up to 1800 pre-packaged battery modules.

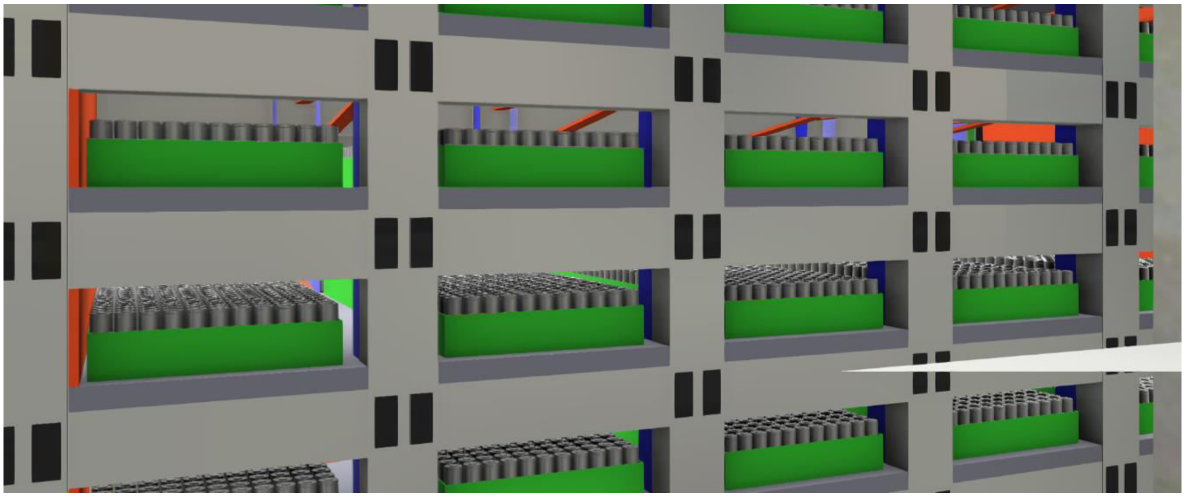

Figure 48. Cells stored in high temperature aging racks.

Bill of material (BOM)

The bill of material for both high temperature aging and ambient aging units consisting of the name of the modeling components, category and unit amount is listed on **Table 16**.

Table 16. High temperature and ambient aging bill of materials.

S/N	Name of components	Category	Unit
1.	High temperature aging process rack	ASRS	2
2.	Ambient aging process rack	ASRS	2
3.	ASRS-Crane (pre-package module feeder)	ASRS	2
4.	ASRS-Controller	ASRS	2
5.	ASRS-Infeeder	ASRS	2
6.	ASRS-Outfeeder	ASRS	2
7.	Main infeed conveyor	Conveyor	2
8.	Ouput conveyor	Conveyor	10
9.	Crossing conveyor	Conveyor	4
10.	High temperature aging label stand	Labels	2
11.	Ambient aging label stand	Labels	2
12.	Process description (Wall frame)	Labels	2

Specific parameters and calculations

The high temperature and ambient aging stages represented by both orange and blue racks respectively have similar parameters as indicated in the formation stage above. They can hold 1800 units (pre-packed modules) each, they both have slot dimensions which is of length = 12000mm; width = 800mm; height = 6200mm while tier height = 200mm and bay width = 400mm.

ACCEPTANCE TESTING

When the pre-packaged modules are ready from the formation and aging stages, they are conveyed to the acceptance testing stage to ensure that they are check for quality requirements. The robot on **Figure 49** checks the module all at once. Faulty cells are isolated and then recycled. It is assumed that all the cells are already connected together. The system is designed in such a way that only one module can be fed into the testing unit at once.

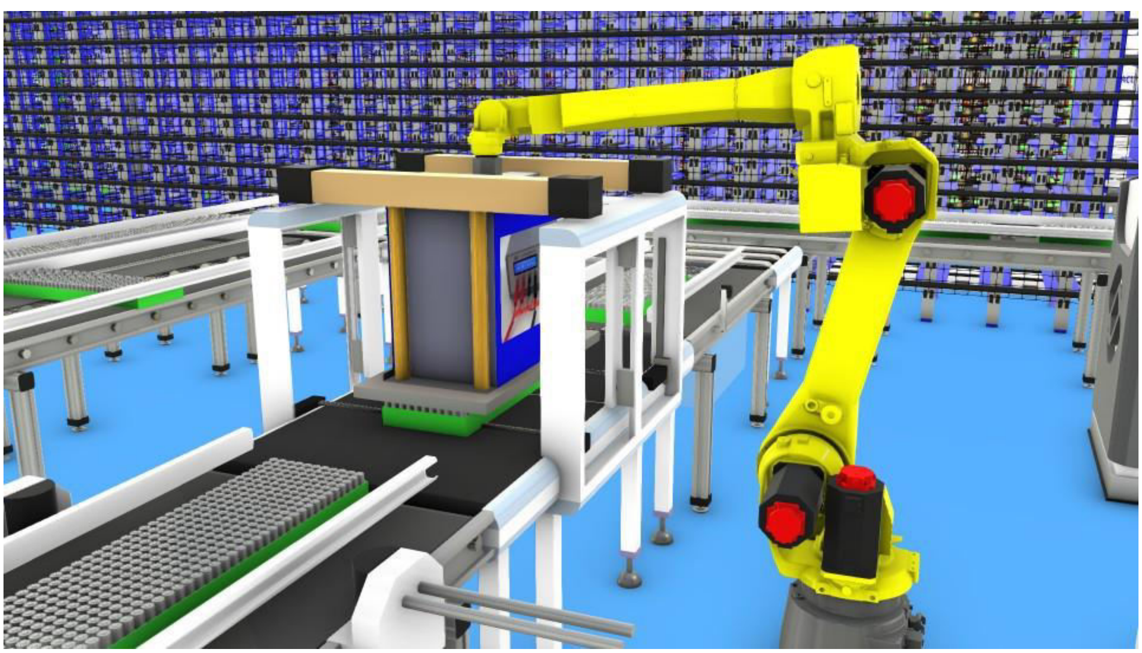

Figure 49. Acceptance testing Robot.

Bill of material (BOM)

The bill of material for the acceptance testing unit consisting of the name of the modeling components, category and unit amount is listed on **Table 17**.

Table 17. Acceptance testing bill of materials.

S/N	Name of components	Category	Unit
1.	Testing robot unit	Acceptance testing	2
2.	Pre-packaged module	Acceptance testing	2
3.	Bladder Stopper	Acceptance testing	2
4.	Conveyor sensor	Sensor	2
5.	Crossing conveyor	Conveyor	14
6.	Main infeed conveyor	Conveyor	1
7.	Straight conveyor	Conveyor	36
8.	Acceptance testing label stand	Labels	4
9.	Process description (Wall frame)	Labels	1

Specific parameters and calculations

The acceptance testing uses sensors to sense when the pre-packaged module is available for testing. Before the testing unit, there is also a stopper to meter the inflow of testing modules into the testing units. The robot checks the current and voltage of the unit. The testing robot in the layout design can check 8 modules in one minute.

Table 18 shows other important requirements for the testing unit timing to achieve the 35GWh annual energy output specification (Hintsala 2018).

Table 18. Final testing time calculation for 35GWh annual energy output specification. (Hintsala 2018).

Final testing	
Cells / 1min	2664
Cells / 1hour	159817
385-Modules / 1min	6,9
Complete Batteries / 1min	0,7
Min / Complete Battery	1,4
Testing time for one module (seconds), estimate	30,0
Modules in testing at once	3,5
Testing stations	4,0
Testing capacity in one minute (modules)	8,0
Testing capacity in one minute (cells)	3080,0

MODULE ASSEMBLY

The next stage is the module assembly. At this stage, the pre-packaged modules that are already tested are packed in the final module box by the packing robot. The packing robot also covers the module as well after packing. The sealing robot is next to the robot as indicated on **Figure 50** and it seals the already packed modules. Each module contains 385 cells each. After the sealing operation, the modules are sent down to the palletizing unit via the conveyors.

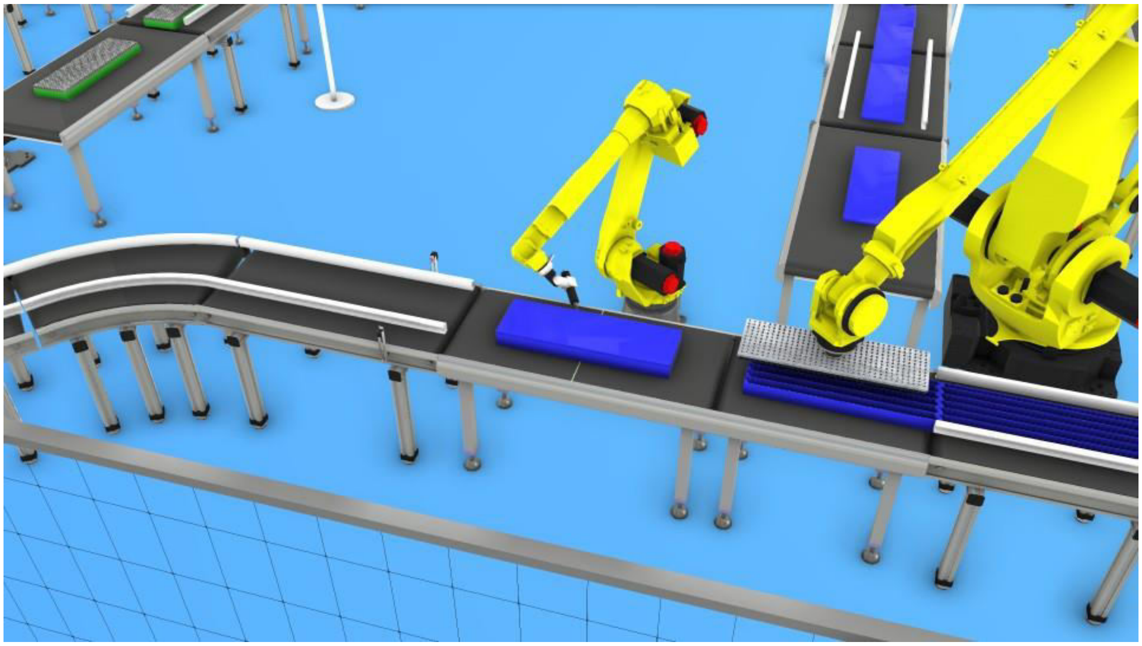

Figure 50. Module Assembly packing and sealing robots.

In order to experience the real dimensions of the module assembly unit and perceive the process work flow, this stage was visualized in VR glass as shown on **Figure 51** and areas of possible improvement were identified and implemented in later design.

Figure 51. Cross referencing the real dimension of module assembly stage using VR glass

Bill of material (BOM)

The bill of material for the module assembly unit consisting of the name of the modeling components, category and unit amount is listed on **Table 19**.

Table 19. Module Assembly bill of materials.

S/N	Name of components	Category	Unit
1.	Packaging robot	Module assembly	3
2.	Sealing robot	Module assembly	3
3.	Pre-packaged module source	Module assembly	3
4.	Module box empty	Module assembly	4
5.	Module box cover source	Module Assembly	3
6.	Conveyor sensor	Sensor	3
7.	Infeed straight conveyor	Conveyor	3
9.	Outfeed straight conveyor	Conveyor	12
10.	Curve conveyor	Conveyor	4
11.	Conveyor merging -X	Conveyor	1
12.	Works process	Works	21
13.	Module assembly label stand	Labels	10
14.	Process description (Wall frame)	Labels	1

Specific parameters and calculations

The module assembly unit uses sensor to sense when the pre-packaged module is available for packing. The robot packs the pre-packaged unit into the final module box and cover it. The packing robot has a load capacity of 140kg and it uses vacuum suction gripper to pick and place objects. It takes approximately 30 seconds to pack and cover a battery module. Fanuc M-410iB/140H was used as the packing robot and it has 5 axes with reach of 2850mm. Fanuc arcMate_120iC10L was used together with a Sealing gun as the sealing robot. It has 6 axes of DOF with a reach of 2009mm and 10kg payload. The sealing robot takes approximately 5 second to seal and glue one battery module.

PALLETIZING

The last stage for the module manufacturing is palletizing. Both empty pallets and assembled modules are supplied to the palletizing robot area. The palletizing robot pick the modules (4 at once) from each of the picking points as indicated on **Figure 52** and then place them on the empty pallets. Two pallets are being palletized as well at the same time. The palletizing robot also places empty sheet of 3mm thickness in between the modules to ensure stability. After palletization is complete, each pallet will have 64 modules (8 on each layer by 8) palletized on it. Afterwards, the palletized modules are moved to the wrapping section.

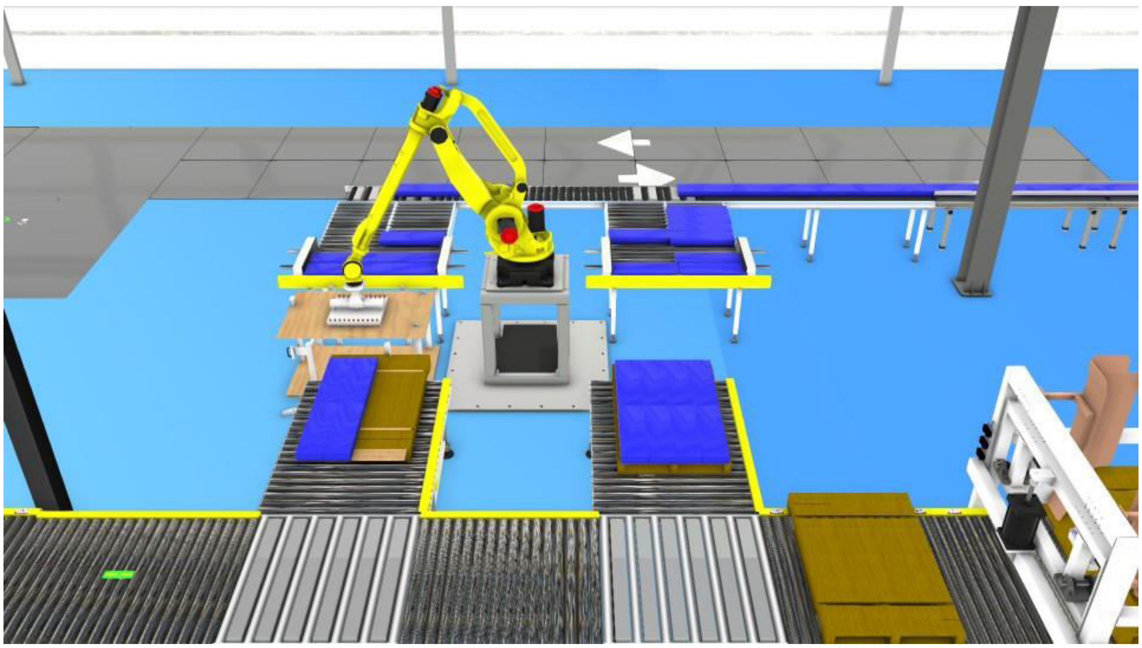

Figure 52. Palletizing Robot.

Figure 53 shows the palletized module being wrapped by the wrapping machine. Afterwards, the palletized modules are sent through the pallet stacking machine to stack them on top of one another in order to ensure easy shipping. The stacked palletized modules are sent to the downstream conveyors where they are ready to be picked up by an AGV and transferred to the automatic loading conveyor systems that loads them to the truck containers for shipping.

Figure 53. Shrink wrapper for the palletized modules.

Bill of material (BOM)

The bill of material for the pelletizing stage consisting of the name of the modeling components, category and unit amount is listed on **Table 20**.

Table 20. Palletizing bill of materials.

S/N	Name of components	Category	Unit
1.	Palletizing robot	Palletizing	1
2.	KES Pallet stack feeder	Palletizing	1
3.	Pallet-GMA 40x48x5.75 wood	Palletizing	1
4.	Cardboard sheet	palletizing	1
5.	KES push gate	Palletizing	
6.	KES palletizer	Palletizing	2
7.	KES K-force Stretch wrap	Palletizing	1
8.	KES dual load stacker	Palletizing	1
9.	KES Pallet dispenser	Palletizing	1
10.	KES turn table pallet conveyor	palletizing	1
11.	KES shuttle	Palletizing	1
12.	Zone capacity controller	Palletizing	1
13.	End zone	palletizing	1
14.	I-beam	palletizing	1
15.	KES multi-lane conveyor	conveyor	2
16.	Straight conveyor	Conveyor	7
17.	Incline conveyor	Conveyor	1
18.	KES roller conveyor	Conveyor	16
19.	KES crossing conveyor	Conveyor	6
20.	Packaged module	Module assembly	1
21.	AGV crossing	AGV	5
22.	AGV pathway	AGV	5
23.	AGV controller	AGV	1
24.	Pick location	AGV	3
25.	Drop location	AGV	1
26.	Loading dock	AGV	1
27.	Palletizing label stand	Labels	4
28.	Process description (Wall frame)	Labels	2

Specific parameters and calculations

The palletizing stage has the supply of already packed and sealed modules from the one input supply and also the supply of the empty pallets from another input supply. The pelletizing robot takes only 4 minutes and 15seconds to palletize one complete pallet of 64 battery modules that implies the palletizing robot has a speed of approximately 14.1 pallets/

hour. Fanuc M-410iB/140H was used as the palletizing robot and it uses vacuum suction gripper to pick and place objects. It has a load capacity of 140kg 5 axes of DOF with reach of 2850mm. The pallet dimensions are also given as approximately of length = 1550mm; width = 1000mm and height = 150mm.

Table 21 shows the required palletizing time to achieve the 35GWh annual energy output specification (Hintsala 2018).

Table 21. Palletizing time calculation for 35GWh annual energy output specification. (Hintsala, 2018).

Palletizing	
Cells / 1min	2664
Cells / 1hour	159817
Cells in one module	385
Current robot speed, modules in 1 minute	6,9
Maximum robot speed, modules in 1 minute	X
Complete Batteries / 1min	0,69
Minutes / Complete Battery	1,45

SHIPPING

When the modules are completely palletized, the pallets well wrapped and stacked on top of one another, the final battery modules are to be sent to auto manufacturing factories where it will be used and fitted into the EVs. An automated loading system was designed in the layout to remove human intervention from manually loading the pallets into the trucks. **Figure 54** shows a already stacked pallets of battery modules being sent into the truck container with the help of the automatic loading system.

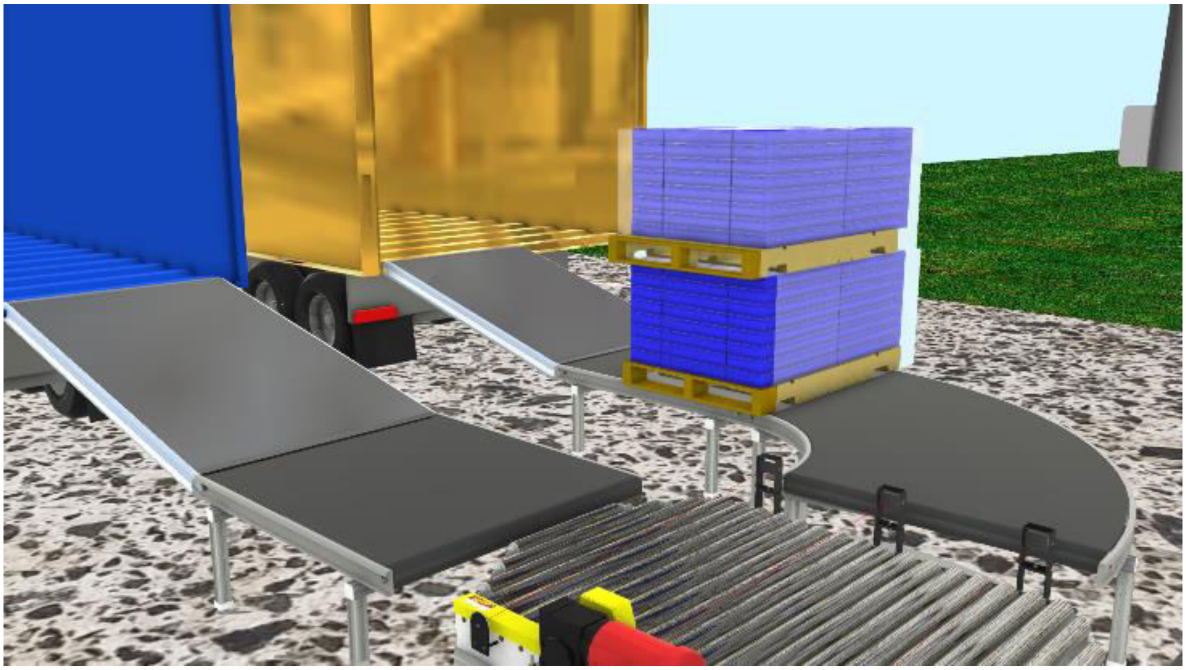

Figure 54. Shipping unit automatic loading conveyors.

Bill of material (BOM)

The bill of material for the shipping stage consisting of the name of the modeling components, category and unit amount is listed on **Table 22**.

Table 22. Shipping bill of materials

Name of components	Category	Unit
KES turn table pallet conveyor	Palletizing	8
Straight conveyor	conveyor	5
Incline conveyor	Conveyor	3
Curve conveyor	Conveyor	2
Shipping containers	Shipping	3
Shipping label stand	Labels	2

Specific parameters and calculations

The most important parameter in this section is that the automatic loading system takes about 1 minute 40 seconds to load two pallets stacked on top of one another with conveyor speed of about 200mm/s. And three 20 feet containers were staged for shipping in the layout.

OTHER COMPONENTS

Figure 55 shows other important components that were used in the layout for important things like floor marking/ factory floor, factory roof, machine fences/ gates, wind turbine, pillar builders, Works task controller to control the works library components and so on.

Figure 55. Other components used in the layout.

Bill of material (BOM)

The bill of material for other components consisting of the name of the modeling components, category and unit amount is listed on **Table 23**.

Table 23. Other components bill of materials.

S/N	Name of components	Category	Unit
1.	Main factory floor lines	Interior facilities	1
2.	Walkway factory floor lines	Interior facilities	6
3.	Fence Builder	Factory facilities	48
4.	Wall builder factory	Factory facilities	38
5.	Wind turbine	Factory facilities	6
6.	Factory entrance	Factory facilities	1
7.	Factory side gravel	Factory facilities	3
8.	Factory grass	Factory facilities	3
9.	Pillar builder	Factory facilities	4
10.	Digital clock	Factory facilities	1
11.	Analog clock	Factory facilities	1
12.	Board display	Factory facilities	1
13.	Extinguisher	Factory facilities	3
13.	Tool box	Factory facilities	9
14.	Floor and ceiling	Factory facilities	1
15.	Work task control	Work	2

Specific parameters and calculations

The most important parameter for this section is the approximate size of the entire factory floor dimensions: width = 46000mm and length = 93500mm. All conveyors speed used in the simulation is approximately 200mm/s

VR SESSIONS

With the help of the VR glass, it was possible to have a virtual walk throughout the entire factory and areas of possible optimization were observed during the VR sessions. The VR glass provided an immersive experience of the entire factory for the researcher where the real dimensions of the entire factory layout and machine sizes in ratio one to one was examined. Some of the important stages that the VR sessions lead to discovery of possible optimization are presented in the next section.

Figure 56 shows the Electrolyte filling machine being examined in the VR glass. During some of the sessions, it was identified that the layout designed at the time did not make effective use of factory space. The VR sessions make it possible to perceive a better layout that can be used to optimize available space.

Figure 56. VR session to examine Electrolyte filling machine.

Figure 57 shows one of the VR sessions for the palletizing stage. It was identified that layout first designed will not deliver fast palletizing result. The feeding conveyor was readjusted and also the pallet feeder and improved performance of the entire stage was observed.

Figure 57. VR session for palletizing stage.

Figure 58 represents how the VR session was used to understand a holistic work flow of 5 stages at one. Starting from the storage to the electrode slitting stage. This kind of global view does not seem natural in the CAD model software because one must keep zooming from one end to another. But in the VR session and due to wider view of human vision, it is possible to experience the entire work flow almost at once because of natural sense of perception of experience by the viewer as if one is in the actual factory. But that was not possible on the desktop 3D simulation software.

Figure 58. VR session to achieve a realistic workflow of multiple stages at once.

Another interesting advantage of having VR sessions on each stage was observed while designing the testing lab unit as represented on **Figure 59**. The cell geometry appeared to be naturally smaller when viewed on the 3D simulation software. But they appear to be of right size during VR session. This is often understood as perspective which is a common misunderstanding of objects size when they are far away and out of focus of the 3D camera of a 3D simulation software. This could lead to layout planning issue sometimes in 3D simulation models. However, the VR sessions helped to correct this kind of misunderstanding.

Figure 59. VR session for testing lab unit.

5.2. Presentation and dissemination of results (VR layout, video production and website creation)

The results of any research must be disseminated in several forms that is accessible for all the stakeholders especially when the research topic is having a case company. The two main deliverables of the project include making the final 3D simulation layout viewable using a VR headset and to also make a video of the entire automated LIB manufacturing factory layout simulation model in great detail of each stage. VC 4.0 makes it possible to record an entire layout and export it into a video of different formats by animating different scenes that the fly camera in the software can move around. A typical code for recording an animated video in VC 4.0 is presented in Appendix 2. Each manufacturing stage was recorded and exported as video format where it was finally edited using a video editing software. A text to speech software was used to add an audio narration of all the stages. All the audio narration of each stage which were derived using text-to-speech converter software was written and provided by Kwegyir-Afful (2018). Two versions of the video were made. A trailer version of about 3.5 minutes was made and a full version of more than 16 minutes with every details of the entire LIB manufacturing process. **Figure 60** shows the cover page of the video uploaded on YouTube with unlisted visibility setting. This setting is used to limit access in search result and only people with the video link can access the video.

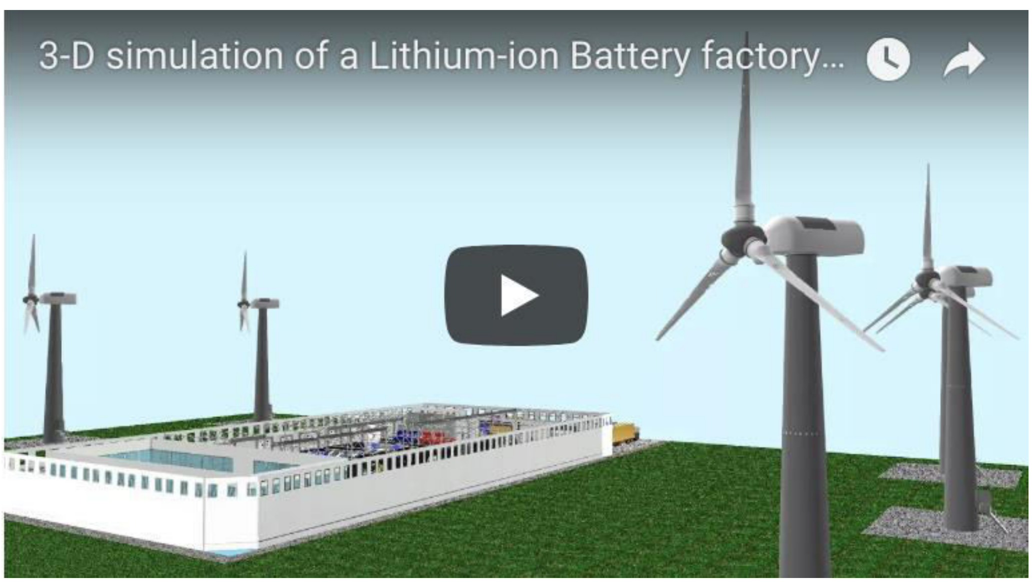

Figure 60. Other components used in the layout.

Another easy way to disseminate information and allow great deal of interaction in great details of all the manufacturing stages is by designing a dedicated website. A website is being created in order to achieve this and the website will entail detail of each stage with short explanation, pictures and video about each stage. **Figure 61** presents a screenshot of the website. The website is still under development at the point of writing this research. So, there might be several changes in the future based on feedbacks received.

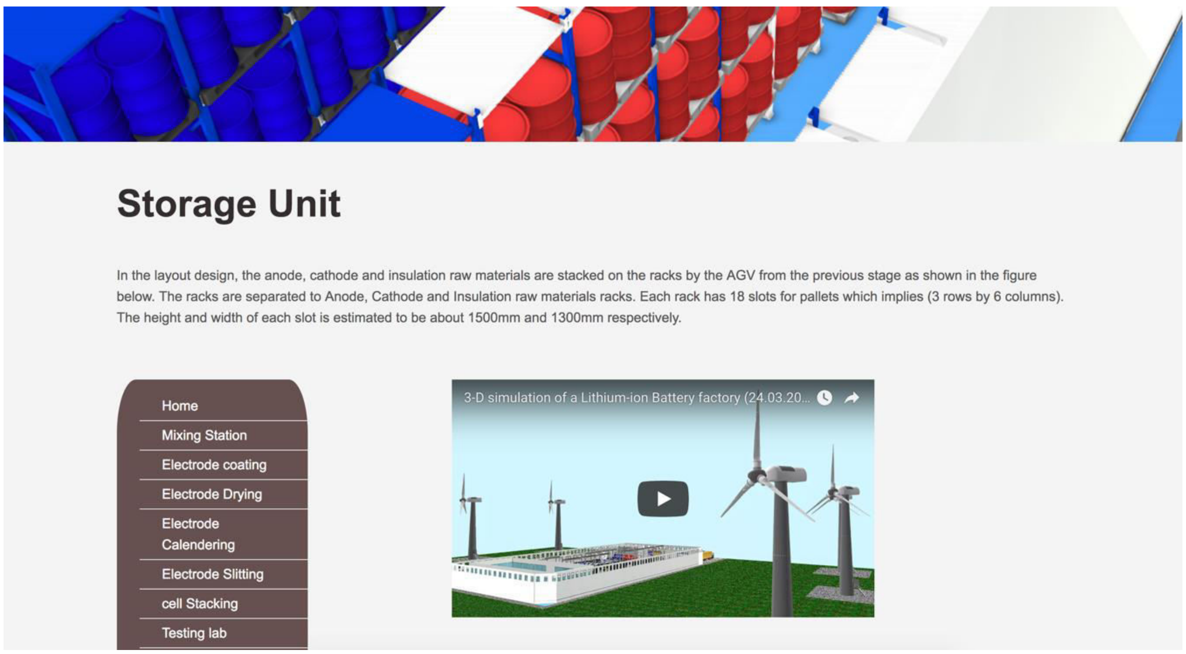

Figure 61. Website development for 3D simulation model of an automated LIB manufacturing factory. (under construction).

6. SUMMARY AND CONCLUSIONS

This section presents the summary of key findings of this research and draw conclusions about the entire research. Towards the last part of this section, managerial implications of 3D simulation in manufacturing were presented, and the last section of this chapter presents recommendations for future research on this topic.

6.1. Key findings of the research

This research was conducted to answer the research questions presented in section 1.3 and ultimately to understand how 3D modeling, 3D simulation and Virtual Reality technology could be effectively deployed as optimization, layout planning and conceptualization methods for an automated LIB manufacturing factory in light of recent advancement in computing power. The results of this research show that the methods above have a huge potential to enhance factory layout optimization, reduce cost and reduce lead time to achieve the final project in real life since possible mistakes and reworks would have been discovered and corrected during the simulation process.

How can 3D modeling and 3D simulation be used for conceptualization of an automated lithium-ion battery manufacturing factory layout?

With reference to the research question presented above, the results showed that a minimalistic concept of a completely automated LIB manufacturing factory was achieved and presented above in section 4.2. It was minimalistic (reduced prototype version) of the 35GWh energy LIB manufacturing factory anticipated because of limited computing power available and also an overload of the software capacity since it was not designed to handle such a large-scale layout (entire factory in a single layout). According to the results of this research, it was discovered that achieving a completely automated LIB manufacturing factory is indeed possible as presented in the results above (section 4.2). The key stages in

LIB manufacturing processes that usually require large amount of human labor were completely automated in the layout using VC 4.0. These include an automated system (AGV) which was developed to achieve raw material offloading to the storage area, an automatic feeding system which supplies the raw material into the mixer was also developed as well to replace the manually operated pot feeders. Finally, an AGV was effectively deployed to supply empty pallets for palletizing and also transfer and stack already palletized battery modules on a conveyor where it was automatically loaded into the shipping trucks via an automated loading conveyor system as presented in section 4.2.

Which factory design layout is the optimal one for an automated lithium-ion battery manufacturing factory using a three-dimensional simulation and virtual reality?

With reference to the research question presented above, the research showed that at the beginning, there was a limitation in term of computing power to build and combine the entire layout of LIB manufacturing stages into one single layout in VC 4.0. However, at the end, a smaller single combined layout but effective and optimized one was achieved considering all the requirements in terms of cost, throughput time, processes integration, synchronization and connections, production constraints, layout optimization and visual representation and optimization (discussed further below) of an entire LIB manufacturing factory using VR glasses. During the simulation project, virtually all the different LIB manufacturing stages where built, tested and optimized individually first in different layout before they were all put together into a single layout where the individual stages could be presented as part of the entire LIB manufacturing factory. The possibility of building individual stages in separate layouts make it possible for effective planning where each layout could be possibly move around like a puzzle in order to realize the most effective one that meet the design specifications.

How can virtual reality be used in design optimization and result dissemination of a 3D simulation model of an automated lithium-ion battery manufacturing factory?

With reference to the research question presented above, the results showed that virtual reality technology using the VR headset is indeed a powerful tool that every simulation engineer must use in their simulation activities to achieve well optimized results. The VR headset was deployed to optimize the smallest detail which could be easily ignored on the 3D simulation software installed on a desktop computer may be due to its size or lack of focus. The VR glass allows non-technical individuals to effectively collaborate and add useful inputs in the simulation process at any stage as well and the VR glass helped in result dissemination since it does not require any technical know to interpreted results delivered through VR headset. This virtual reality method of 3D visualization and optimization has taken 3D modeling and simulation to the next level where every experience 3D simulation engineer must try to catch up in order to take the best advantage of recent technologies to effectively optimize, visualize and present their simulation models to non-technical managers as discussed further in section 5.2 below.

6.2. Managerial implications

For any academic research, many companies and managers look forward to key findings and managerial implications that they can take away to apply on their current investments and make strategic business decisions. This study has gone a long way to achieve a number of useful results. These results among others are the fact that manufacturing industries must consider using 3D modeling, 3D simulation and virtual reality in light of advancement in modern technology and increasing computing power of the 21st century. The result of such approach as presented in this research is that they will prevent unnecessary mistake and they can plan effectively any project even before they are embarked on it in real life since the simulation results will serve as important criteria and inputs to appraise different project scenarios and requirements from which stakeholders and managers can make informed decisions whether or not it is going to be a viable or non-viable project. Another managerial implications of simulation in manufacturing and as presented in the findings of this research is that the old method of using simulation in manufacturing can be improved using latest technology like virtual reality. As mentioned above briefly, old and experience engineer can effectively interact with their simulation models and optimize them using VR glasses. Managers as well can gain direct access to this simulation layouts and add their useful contributions at any stage of the simulation process without any need to interpret hard mathematical equations or read hard legends which they do not understand as in the case of old simulation ways where the simulation engineers are usually the ones that understand those. The mere rendering of simulation results in a virtual environment using a VR glass does not require any technical interpretation but the self-immersion of the non-technical mangers to understand and interpret the virtual world around them.

6.3. Recommendations for future research

During the course of this research, it was discovered that two key areas could be further investigated in the future.

One of them is in the area of understanding and calculating the computing power requirement for this kind of large scale simulation project. In general, computer requirement for 3D simulation is usually a big one and this project is not an exception. In this research, different kinds of computing power were used with the highest having a specification of Windows 64-bit Operating System with processor speed of 3.6 GHz, GPU (GTX 1070), RAM memory of 32GB and intel core i7 processor. However, a number of challenge was encountered such as crashing of the software and freezing of the entire computer several times due to overload of computer memory and as well slow speed of the computer while using the VC 4.0 software with large file size. Finally, there was some rendering problem of large VC layouts (.vcax file extension) with the VR glass as well. Due to the reasons mentioned above, only a smaller version (in terms of dimension area size) of the LIB manufacturing factory was achievable. As highlighted in the challenges encountered with the computing power during the simulation process, it is evident that investigating the computing power requirement is indeed a necessity in order to deliver a realistic size of large models in 3D simulation environments in the future.

The other area of suggestion for future research is to effectively modularize the research about 3D modeling and simulation of LIB manufacturing factory. Modularization in terms of carrying out modeling and simulation research individually on the six major categories of LIB manufacturing or even in a greater detail carrying out 3D modeling and simulation research on each LIB manufacturing stages. There are about 20 different stages involved in LIB manufacturing, this pose a great challenge to modeling and simulating all the smallest details involved in each stage in a single research work. When there is modularization of the research targeted at each stage or in a little bigger extent targeted at the six major categories, the result from each research can then be combined into a larger research comprising of a group of researchers. It is believed that such approach will help achieve a very detailed results of research on LIB manufacturing factory using 3D simulation, 3D simulation and virtual reality.

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8. APPENDICES

APPENDIX 1. One batch production cycle time (Hintsala 2018).

	One batch production time, minutes
Mixing	160,0
Coating and first drying	2,2
Electrode calendering	4,3
Electrode slitting	1,3
Cell rolling and winding	0,1
Assembly	0,1
Increasing the batch size	2,8
Cell filling and aging	0,9
Aging	360,0
Heat drying	180,0
Cap welding and sealing	41,7
Formation cycling and charge retention	396,0
Testing single cells	4,2
Cell packing for modules	0,9
Module welding	12,8
Final testing	0,2
Palletizing and wrapping	6,2
Conveyor belt, time and meters	25,7
TOTAL	1199,3

The figure above represents the cycle time for each of working stages. **Excluding** stages that do **not** affect the total working time have been omitted (solvent recovery, empty cell case production etc.). Conveyor speed is assumed to be 19,8 meters in minute.

Presented time is always for batch. For example, in electrode manufacturing the batch size is one roll (about 130 meters and 2675 cells) and in the palletizing, the batch size is needed time to finish one pallet.

1199 minutes = **19,98 hours**

APPENDIX 2. Animation View Settings.