



CHALMERS
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Conceptual Development of a Battery Swap Management System

A Systematic Approach to Developing a Semi-Automated
Battery Swap Solution for Electric Construction Machinery

Master's Thesis in Product Development

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover picture: Battery Swap Management System placed on construction site.

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Abstract

In order for the construction equipment industry to meet the CO₂ emissions requirements imposed by external regulations and internal sustainability goals, it is moving towards electric machinery. In order for this to be possible, quickly replenishing the energy levels in the electric machines is necessary. Volvo Group aims to have a net zero fleet by the year 2050, which implies that a large percentage of their fleet must become fully electric. This means selling supporting systems that allow the electric machines to operate in the same time frame as current internal combustion engine (ICE) powered machines. The range of the electric machines is limited compared to ICE powered which means additional solutions are needed. Charging large batteries either takes a long time or requires a large amount of energy very quickly, one way to solve this issue is to swap out the batteries inside the machines. In order to keep the machines as efficient as possible on a construction site the battery swap needs to be performed quickly while ensuring operator safety.

The purpose of this master thesis is to develop a concept of a semi-automated battery swap management system that can be used with electric machines designed to have their batteries quickly removed and installed. The thesis will dive deep into what requirements exist on such system in terms of size, capacity, functionality, and mobility. There is also high emphasis on which type of functions are needed in order to make a battery swap management system function. The components needed and how they interact with each other will be a central part of the development of this system. A concept generation and evaluation will be performed using the product development process from Ulrich & Eppinger. Using methods such as brainstorming, morphological matrix, elimination matrix, Kesselring and Pugh matrix, concepts will be screened and evaluated in order to find the best fit for the project. The design of the final concept will be conducted using computer aided design software which also gives the possibility of verifying the mechanical structure using finite element method software.

The final design is a model of a semi-automated battery swap system with the possibility of quickly swapping out batteries for several machines. The battery swap management system is based on a container base plate which means it can be transported using normal truck trailers with ISO container attachment joints. The battery swap management system has been designed to quickly remove and install batteries into machines in order to minimize the time the machine is not operating. This will give Volvo Construction Equipment the possibility of selling electric machines in combination with the battery swap management system and still fulfill the needs of their customers.

Keywords: battery swap, construction equipment, electric machinery, sustainability, energy system.

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Thesis advisor: Anders Ek, CPAC Systems AB

Thesis examiner: Peter Forsberg, Department of Mechanics and Maritime Sciences

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AC	Alternating Current
BESS	Battery Energy Storage System
BOM	Bill Of Materials
BPU	Battery Power Unit
BSMS	Battery Swap Management System
CAD	Computer Aided Design
DC	Direct Current
DFA	Design For Assembly
DFM	Design For Manufacturing
DER	Distributed Energy Resource
ECTS	European Credit Transfer and Accumulation System
FEM	Finite Element Method
ICE	Internal Combustion Engine
ISO	International Organization for Standardization
kW	kilowatt
kWh	kilowatt hours
MG	Microgrid
NDA	Non-disclosure Agreement
NPRA	Norwegian Public Roads Administration
NPV	Net Present Value
POC	Proof Of Concept
PTC CREO	Parametric Technology Corporation CREO (CAD software)
RES	Renewable-based Energy Sources
SF	Safety Factor
SOC	State Of Charge
TCO	Total Cost of Ownership
TTM	Time To Market
VCE	Volvo Construction Equipment

Nomenclature

Below is the nomenclature of the variables that have been used throughout this thesis:

Variables

a	Distance from support to the load point
C_{rr}	Coefficient of rolling resistant
δ	Deflection
E	Modulus of elasticity
F_{rr}	Force rolling resistant
F_N	Normal force
g	Gravitational force
GR	Gear ratio
h	Total height of the cross-section
I	Moment of inertia beam
I_y	Moment of inertia about the y-axis
l	Length of beam
m	Mass of object
μ_s	Coefficient of friction
P	Force applied at point load
r	Radius
$\sigma_{\text{Von Mises}}$	Von Mises Stress
t_f	Thickness of the flange
t_w	Thickness of the web
τ_{static}	Static torque
T_{rr}	Torque rolling resistant
w	Total width of the cross-section
ω	Angular speed of rotating object (rad/s)



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1

Introduction

This chapter introduces the subject and purpose of the master's thesis, providing an overview of the research problem and the rationale behind the study. The incentives for the research are discussed, highlighting its significance within the industry context. Additionally, the chapter outlines the specific aim and objectives of the thesis, along with the key research questions that will be addressed. The scope and delimitations of the thesis are also defined, explaining the boundaries of the research and the factors that fall outside its focus. This includes limitations related to time, resources, geographical area, or specific aspects of the topic that will not be covered. Lastly, the chapter presents an outline of the thesis structure, briefly summarizing the content of each subsequent chapter.

1.1 Background

Volvo Group aims to have a net zero fleet by 2050. This means reducing emissions in their current product offering which for Volvo Construction Equipment (VCE) is expected to be reduced by 30% [1]. This will be done by developing electric machines with the target of making up 35% of Volvo Group sales by the year 2030. The transition to electric machines and equipment by VCE is driven not only by internal sustainability goals but also by external regulatory pressures and broader environmental policies. Governments worldwide are tightening regulations on emissions, with many regions setting ambitious carbon reduction targets that directly impact industries reliant on heavy machinery. For example, the European Union's Green Deal aims for climate neutrality by 2050, with strict interim goals such as a 55% reduction in emissions by 2030 [2].

As a consequence to achieving these goals, more specific regulations are being established aimed towards the construction industry. For instance, the Norwegian Public Roads Administration (NPRA) aims to reduce direct greenhouse gas emissions from construction activities by 55% from 2020 to 2030. The primary approach involves integrating zero-emission machinery and vehicles, as fossil fuels currently account for over 90% of direct emissions at construction sites [3].

NPRA plans to start phasing in zero-emission machinery progressively, with significant increases in requirements and market maturation between 2023 and 2027. By the end of 2027, zero-emission technology will be mandated in all contracts. This transition requires comprehensive energy mapping and planning to ensure the power

supply needs for electrification efforts [3].

While the shift towards electric machinery aligns with global sustainability goals and regulatory demands, the transition is also introducing challenges, particularly from a technical standpoint. One of the most significant concerns with battery electric machinery is the trade-off between environmental benefits and operational efficiency. In industries such as construction, where equipment is expected to run for extended periods with minimal downtime, the limitations of battery technology becomes evident.

Operational capacity, specifically the duration for which electric machines can work before requiring recharging is one of the biggest hurdles as of today. Unlike internal combustion engine (ICE) machines, which can be quickly refueled, electric machinery faces downtime during charging. This results in a unique set of challenges, revolving around optimizing machine performance and minimizing productivity losses.

Solutions offered today by VCE revolves around by having a mobile battery power unit (BPU) in close proximity to the machine [4]. These are available with various capacities ranging from 40, to 396 kWh [5]. These portable units are designed to provide on-site charging for electric machines, allowing them to be recharged without the need to return to a central charging station. This approach provides flexibility, as the BPU's can be moved to different locations on a worksite, reducing the distance and energy-consumption machines must travel to charge and therefore theoretically minimizing downtime [6].



Figure 1.1: Volvo L25 Wheel Loader being charged by an external BPU [6].

However, while this solution provides a level of convenience, it does not fully resolve the underlying problematic of charging time. Even with BPU's promptly available, the time required to recharge an electric machine is still significantly longer compared to refueling an ICE machine.

Additionally, the logistics of deploying and maintaining a fleet of mobile power units adds further complexity to larger construction sites with multiple machines. The BPU's need to be regularly transported and recharged, potentially leading to additional costs and operational coordination challenges.

While electrification is a major focus for VCE, alternative technical solutions are being assessed to address the challenges associated with battery charging infrastructure and logistics. Currently, the next generation electric construction machinery is being developed at VCE and to address this topic, the trend points toward utilizing swappable batteries [7].

1.2 Purpose

The purpose of this thesis builds on the benefits of VCE developing their own battery swap management system (BSMS). Reason behind a BSMS is to ultimately lower stationary vehicle times thus making the electric vehicles more usable and more efficient. This will be done by having a semi, or fully automated battery swap-station where the electric machines will have the possibility to have their battery packs quickly swapped out for a fully charged one, thus being ready to work again rather than standing still and charging. To be able to design and build such a system, understanding system requirements as well as customer needs and wishes will be essential.

This will give VCE stronger product offering due to the fact that they will be able to sell not only the electric machine(s), but also offer a battery swap management system either as a service or as a product itself, making machines run for longer periods with minimal disruption. Furthermore, having swappable batteries gives VCE the future possibilities in the field of serviceability and upgrade-ability of batteries as they will not be integrated as a critical structural component of the vehicle compared to an traditional electric machine. This additionally minimizes potential downtime of in terms of reparations or services if a battery would fail.

1.3 Aim

The aim of the thesis is to research and develop a virtual proof of concept (POC) of a mechanical system with all necessary components capable of performing battery swaps on construction machines including wheel loaders and articulated haulers. Additionally, the thesis will include a high level estimation of the business case and financial aspect. This includes researching the benefits of utilizing a BSMS compared to a traditional ICE fleet as well as research of critical components needed and their relative importance with respect to cost and function.

1.4 Research Questions

At the end of the thesis, the results are meant to answer four specific research questions. These were made to summarize the aim of the thesis. The following questions were outlined:

RQ1: How can the key customer requirements, including metrics such as performance, speed, cost, and size, be systematically identified, prioritized, and benchmarked to facilitate the development of the battery swap system for VCE?

RQ2: What are the components needed in order for the battery swap system to work and what are their relative importance for the POC?

RQ3: How can the system be deployed on construction sites with various sizes and energy requirements?

RQ4: How does the financial viability of the new product, considering profitability, required capital investment, market conditions, and projected customer demand, influence business decisions?

1.5 Delimitations

The thesis is limited by several aspects such as time, information and availability of resources. Firstly, the thesis is comprised of 30 ECTS which is distributed over a period of approximately 20 weeks. This is the outlined time-constraint for which the thesis will be executed. A confidential agreement has been signed between the thesis students and CPAC Systems AB (from here denoted only as CPAC Systems) which means certain information given or conclusions drawn will stay within the organization and might not become available to the public, this will ultimately come down to if CPAC Systems considers certain information sensitive thus it will be hidden from the report in those instances.

Secondly, other aspects of a BSMS such as road infrastructure and grid capacity will not be examined or evaluated to any large extent. This is simply due to the time constraint of the thesis and to focus development on the product rather than supporting functions. The BSMS will chiefly focus on serving wheel loaders and articulated haulers, machines that moves around to a high extent during a work day. This means diggers and excavators will be excluded since their position is more or less stationary in comparison.

Lastly, the manufacturing of a potential physical prototype for the BSMS falls outside the scope of the students' work and will instead be handled by contractors within Volvo Group. However, the virtual POC, represented by a detailed Computer Aided

Design (CAD) model, must be designed at a level of detail and accuracy with sufficient information in order to facilitate manufacturing at a later stage outside of the thesis period. This includes ensuring that the CAD model and all of its unique parts and components can be fully developed and manufactured in a relative short period of time. To support further development, a bill of material (BOM) will complement the CAD model with all necessary information for non in-house developed parts ("off the shelf" standard components) such as data regarding suppliers, vendors, pricing, quantities, etc.

1.6 Approach

The approach will consist of several steps in order to fulfill the aim of the thesis. These steps will entail different areas of the thesis which have milestones that must be fulfilled. Since this technology is still early in its developing phase at VCE and CPAC Systems a wide span of steps must be completed.

- Perform market research as well as competitor analysis to identify current and upcoming trends within battery swap station industry. In combination with the current needs of using battery propulsion vehicles, create a requirement list.
- Perform a literature study to identify the theory behind and the components of a battery swap management system.
- Create a scenario showcasing the energy need on different types of construction sites depending on different types and numbers of machines in order to dimension the battery swap management system as efficiently as possible.
- Perform system analysis and make a functional model to get an understanding of which components are necessary in order to develop a battery swap station and their relative importance related to the requirement specification.
- Conduct a comprehensive product development process involving the generation and evaluation of alternative technical solutions, including the identification and analysis of critical technical challenges, and the verification of key systems using iterative methods such as Pugh, Kesselring, and Morphological matrices.
- Develop a digital mock-up of the battery swap management system to validate the design and create a suggestion for making a physical prototype using off-the-shelf components for CPAC Systems and VCE to build and showcase proof of concept.
- Perform a commercial assessment of the battery swap station to examine the financial viability and business aspects.

1.7 Deliverables

The results at the end of the thesis should contain several aspects in order to fulfill the aim. These are denoted as deliverables of the project and will subsequently incorporate sub-deliverables. The most important ones related to the defined method are listed below.

- Market positioning with concrete value of the product for the customer including a developed framework for requirement specification.
- Assess known concepts and ideas in order to determine a reference solution.
- Generate alternative concepts with the potential for greater customer value.
- Cross-reference the best concepts and select the most promising.
- Final requirement specification for selected concept at customer level.
- Showcase system architecture.
- Mechanical design of prototype.
- Production and product cost estimation.
- Evaluation of business case and commercial assessment.
- Analysis of target fulfillment.

2

Theory

In the following chapter the theory framework will be presented in order to gain a basic understanding of the underlying components of a battery swap management system. The theory is a vital part of developing the system and its incorporated functions and solutions. Most of the mentioned components are common in not only existing battery swap solutions but also others types of mechanical systems, giving a wide possibility of different variants and versions of the same basic components.

2.1 Battery

A battery is a device used to store chemical energy and convert it to electricity through electrochemical reactions. A battery consists of several cells consisting of two electrodes called anodes and cathodes, these electrodes are separated by a chemical material called electrolyte which functions as the transporting element of ions [8]. When electrons move from the cathode to the anode energy is released into the circuit they are moving through. This energy can be used to power electric equipment such as electric machinery.

2.2 Charger

The function of a charger is to restore a drained battery to its fullest possible energy capacity, allowing the battery to be used again. The charging process works by forcing the electrons from the anode to the cathode enabling the chemical reaction in the battery to take place again. During this process, the voltage of each cell is increased until the battery is fully charged and the process of electrons moving will stop. In short, the components inside the charger that enable this are an AC-DC rectifier, voltage regulators, sensors, and a monitoring system.

2.2.1 Power Inverter

Power inverter is an electric device that changes alternating current (AC) to direct current (DC). Firstly it rectifies the incoming signal using diodes or other components which changes the output from alternating directions to a direct flowing one. This output might be rough and contain 'ripples' which using capacitors or inductors is then used to smooth it out and create a more stable voltage signal.

2.2.2 DC-DC Converter

In power management systems, DC-DC converters are crucial components, as they ensure reliable power delivery by maintaining a consistent output voltage despite fluctuations in input voltage or load conditions. These electronic circuits also allow step up, or step down to different voltage levels. This is essential for the battery swap management system as power needs to be distributed from the grid, inside the BSMS and its electrical systems, and also to the batteries [9]. This possibility also needs to exist if the BSMS ever were to become bi-directional, i.e supporting the grid using the batteries when not in use. Voltage needs to be converted the other way around which puts high demands on reliable and advanced DC-DC converters.

2.3 Connector

Connector is an mechanism used to transfer signals or power from one electric component to another. A connector is removable and has insulation that will make sure no moisture or dirt will get inside, but also not creating any hazard for the surrounding area. The standard charging connector for electric vehicles is the SAE J1772 which in combination with DC charging is called CCS Combo 1. Figure 2.1 shows this type of connector.



Figure 2.1: CCS combo 1 connector manufactured by MIDA[10]

2.4 Electric Motors

An electric motor is a device that converts electric energy to mechanical movement. The electric motor consists of an rotating part (rotor) and a stationary part (stator) and the movement is created by letting electrical current go through wire windings by magnets mounted on the stationary part. This creates a magnetic field where the north- and south pole between the rotor and stator will always be close to each

other thus pushing the rotator part which results in the motor output shaft starting to spin [11].

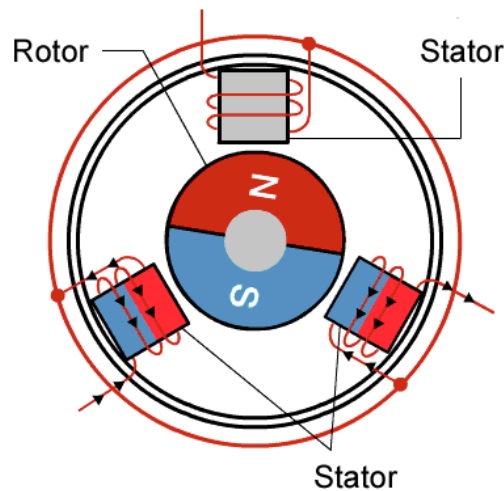


Figure 2.2: Section of a BLDC motor [12].

There are different types of electric motors such as AC-motor, DC-motor, permanent magnet motor, asynchronous motor and synchronous motor among others. Depending on the use case some motors are a better fitment than others because of their characteristic. For an asynchronous motor the magnetic field is created by putting current through the windings which creates induction. This creates a natural slip which is always present in electromagnetic induction. The magnetic field created by the stator will create a flow of current in the rotor which in turn results in a magnetic field of the stator itself.

Asynchronous motors are less costly to make and do not need any rare earth metals for manufacturing the magnets. On the other hand asynchronous motors create more heat and have a lower power density. Synchronous motors have very high efficiency and power density. They are however more expensive to make and it is also necessary to have a starting mechanism since synchronous motors can not start from zero speed. Permanent magnet motors have a simpler design, have low maintenance, and produce relatively high torque at low speeds. On the other hand, they have lower torque at higher speeds as well as risk of demagnetizing the magnets.

2.4.1 Stepper Motor

In order to get accurate control over a small movement instead of a continuous motion, using a stepper motor is a suitable component to achieve it with. A stepper motor works by having teeth around the rotor which interacts with the magnets placed on the stator. Only one magnet will be aligned with the teeth when the motor is standing still. When the motor needs to move, the magnetic field of the next magnet will be induced resulting in one movement which usually corresponds to

3.6 degrees. The amount of degree can vary depending on how many teeth the rotor has [13]. The key advantages of stepper motors are precise control, repeatability, and low-end torque.

2.5 Transmission

Transmissions are fundamental components in mechanical systems, serving as the intermediary mechanism for transmitting power from one element to another. They play a crucial role in the efficiency, performance, and functionality of various machinery and equipment. The selection of an appropriate transmission system is given by various factors such as torque, speed, precision, lifetime and other application or environment-specific requirements.

Transmissions typically involve mechanisms that transfer motion and force between different shafts or elements, ensuring that power is delivered with the desired characteristics [14]. This section will clarify and describe various transmission systems, including spur gears, and chains with sprockets, each of which offers distinct advantages and considerations in engineering design.

2.5.1 Spur Gears

Spur gears, characterized by their straight-cut teeth, are primarily used to transfer motion and torque between parallel shafts. They operate by meshing together in a way that transfers rotational motion and torque. One of their key advantages is their high efficiency in power transmission, with minimal energy loss, making them suitable for applications requiring precision and reliability. They are also cost-effective and easy to manufacture due to their straightforward design. However, spur gears are limited by their tendency to generate noise and vibration at higher speeds, which can be problematic in some environments. An additional important aspect to consider is the presence of backlash, which arises from the gap between gear teeth. This gap is essential for ensuring smooth gear engagement, however this affects rotational accuracy in applications where the shaft changes rotational direction frequently. For assemblies requiring precise alignment, or accuracy, it is important to address this characteristic.

Despite these limitations, spur gears are widely used in various applications, including automotive transmissions, industrial machinery, and consumer products such as power tools. Their durability, combined with the simplicity of their design, makes them a reliable choice for systems requiring efficient torque transmission [15]. Figure 2.3 below shows a spur gear pair.

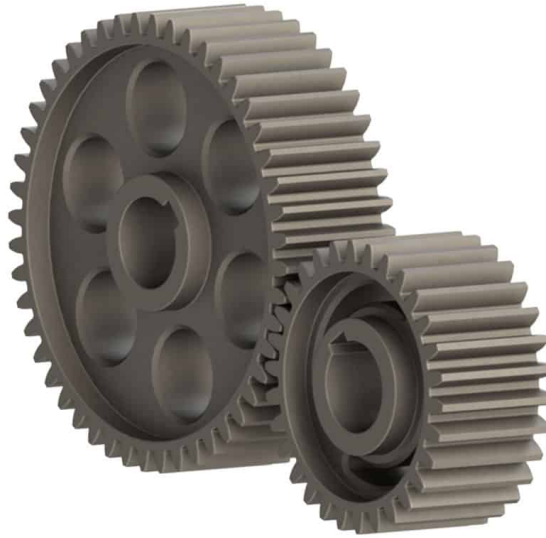


Figure 2.3: Spur gears pair[16].

2.5.2 Chain and Sprocket

Chain and sprocket systems are a robust type of transmission used for their ability to transmit significant torque between two or more shafts over long distances. These systems consist of a metal chain with interlocking links that engage with the teeth of a sprocket which provides a secure connection that minimizes slippage. Chain and sprocket assemblies typically offers a high tensile strength and resistance to wear, which makes them well suited for heavy-duty application [17].

2.6 Actuators

An actuator is a component that outputs a force or torque by converting an electric, pneumatic, or hydraulic input which enables a controlled linear or rotational motion over mechanisms or other devices which the actuator is attached to. The operation of an actuator depends on its type. Hydraulic and pneumatic actuators utilize incompressible fluids, or pressurized air to generate linear or rotational motion. Electric actuators, on the other hand, rely on electrical power to drive motors that produce movement. The choice of actuator type depends on factors such as required force, speed, and environmental conditions. Electric actuators are generally preferred in applications requiring accuracy and minimal maintenance, while hydraulic and pneumatic actuators in general are more robust, and can provide greater forces [18].

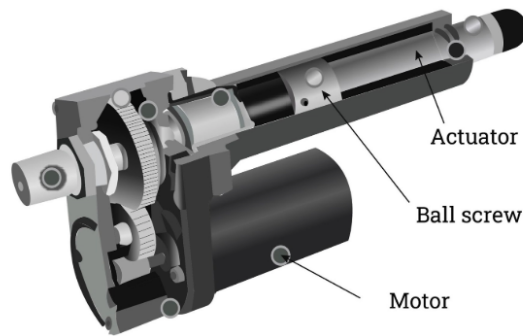


Figure 2.4: Components of an electric actuator [19].

2.7 Hydraulics

A hydraulic system uses an incompressible fluid which gets pressurized by a pump. The pump is then connected with hoses to cylinders which get filled with fluid which in turn pushes on the piston inside, creating movement in the longitudinal direction. The hydraulic piston can move both in and out of the cylinder since a valve block is always installed between the pump and cylinder [20]. The purpose of the valve block is to direct the fluid into needed parts, stop the flow when needed, adjust the pressure of the fluid as well as flow quantity. This results in the possibility of both pushing and pulling parts such as joints, rails, axles and etc which creates a movable system.

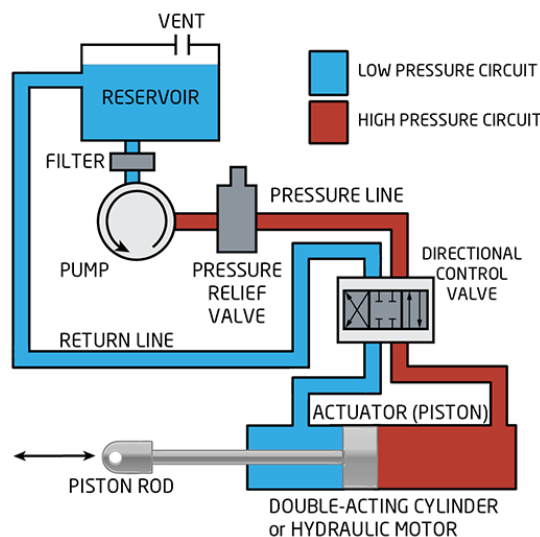


Figure 2.5: Components of a hydraulic system [21].

Advantages of a hydraulic system is the possibility of creating very high torque. The control is also very smooth and linear giving high accuracy, the components usually take up less space compared to a fully mechanical system and can be placed where space is available.

2.8 Positioning System

Components used for positioning of the both battery pack but also moving parts inside the battery swap management system needs to be precise. This means measuring several parameters in order to know where certain parts are at certain times. The battery swap management system always needs to know the exact location of the battery when a machine has parked and is ready for the swap.

2.8.1 Distance Measuring

There are several ways of measuring the position and distance to an object. Depending on environment, available space and cost there are different technologies that could potentially solve the same problem.

- Light amplification by stimulated emission of radiation, Laser for short, is a light emitting device which in combination with a measuring sensor can be used for measuring the distance between two objects. The distance is calculated by measuring the time it takes the laser beam to hit an object and bounce back to the sensor.
- Radio detection and ranging, Radar for short, using radio waves to create an electromagnetic wave which bounces off objects in front of it. A sensor mounted on the radar picks up the energy reflected from the object. Similar to the laser the radar measures the time it takes for the signal to bounce on the object and back, in order to determine the distance.
- Light detection and ranging, Lidar for short. Similar to how radar uses electromagnetic waves, the Lidar uses laser. The distance between the transmitter and the object that the wave hits is measured by the time it takes the wave to bounce on the object and back. This gives the possibility to scan objects from a distance by creating a grid such as terrain.
- A video camera in combination with software can be used to decide the position of an object. Neural network image processing means the software can be trained to recognize the position of objects just by using the camera.

2.8.2 Sensors

Sensors are components used to measure physical properties or changes which is then converted into electrical signals. How the measured value is converted to an electrical signal depends on the environment it is supposed to measure. Resistive sensors will change their resistance based on a physical input such as temperature differences, capacitive sensors will be affected by pressure difference and piezoelectric sensors will generate an electrical charge in response to mechanical stress.

2.9 Mechanical System Calculation

The forces acting on the BSMS will in some instances be very large. This means performing detailed calculations to ensure the system can operate safely across numerous cycles with consistent performance. In order to effectively move parts at specific speeds, the electric motor must possess sufficient performance capabilities. To begin with, the force needed to overcome the static friction by an object, such as trolleys on top of rails, when not in movement is calculated by:

$$F_{\text{static}} = \mu_s \times F_N \quad (2.1)$$

Where μ_s is the coefficient of friction which depending on material is somewhere between 0.6-1.0 and F_N is the normal force calculated by the weight of the trolley:

$$F_N = m \times g \quad (2.2)$$

To get the torque required to turn a driving wheel in the trolley, the radius of the wheel is multiplied with the F_{static} resulting in:

$$\tau_{\text{static}} = F_{\text{static}} \times r \quad (2.3)$$

This is the torque required to turn the axle in a driving wheel. The electric motor will most definitely not have this amount of torque itself but instead combine it with a transmission. Size constraints might also mean the electric motor will not have enough space, thus a transmission becomes necessary.

The gear ratio in the transmission will depend on the torque the electric motor can produce which is found through the following equation:

$$GR = \frac{\tau_{\text{motor}}}{\tau_{\text{wheel}}} \quad (2.4)$$

It also means finding a gearbox with a gear ratio high enough to produce the required torque but also with high enough speed to move the trolley quickly.

When the trolley has started to move, the rolling resistant will be reduced. Depending on the material of the wheel and the surface the value C_{rr} , coefficient of rolling resistant can vary immensely. The force needed to keep an continuous rolling of an component is calculated by multiplying it with the normal force of the component:

$$F_{\text{rr}} = C_{\text{rr}} \times F_N \quad (2.5)$$

Followed by multiplying with the radius of the driving wheel, giving the torque needed to drive the wheel at continuous speed:

$$\tau_{\text{rr}} = F_{\text{rr}} \times r \quad (2.6)$$

Another performance requirement will be the speed, the battery swap should take as little time as possible meaning when parts are moving they need to move as quick as possible. When the torque and the power of the motor is known, using the following formula can give the velocity required by the motor:

$$\omega = \frac{P}{r} \quad (2.7)$$

The velocity at the wheel is then calculated by:

$$\omega_{\text{wheel}} = \frac{\omega_{\text{motor}}}{GR} \quad (2.8)$$

To get the speed of the wheel multiply the radius of the driving wheel with the wheel speed:

$$v = r \times \omega_{\text{wheel}} \quad (2.9)$$

Additionally, determining how fast the trolley needs to move is a necessary step before selecting a suitable motor. By establishing a time requirement for covering a certain distance, we can gain insight into both the trolley's required speed and the duration needed for battery swapping. To calculate the power requirements of the motor, we will need to consider its speed in conjunction with torque, using the following formula:

$$P_{\text{mech}} = \frac{2 \times \pi \times \omega_{\text{motor}}}{60} \times \tau_{\text{static}} \quad (2.10)$$

2.9.1 Structural Integrity

When the battery swap is being performed, the batteries will be hanging outside the BSMS. This means the force equilibrium will change as well as potential risk of deflection on beams hanging outside. In order to make sure all maneuvers will be safe as well as dimensioning chosen components correctly calculating forces and stresses becomes important.

The maximum deflection will occur when the swap station is fully extended and the trolley lifting batteries in and out of the machine is holding both batteries.

In order to calculate the deflection in a cantilever beam, the load, distance from the support to the load point, moment of inertia of the beam and the modulus of elasticity are needed. Using the following beam deflection formula to calculate maximum deflection:

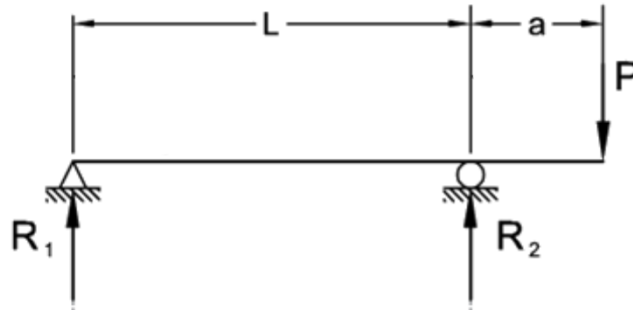


Figure 2.6: Deflection load case [22].

$$\delta_{\max} = \frac{P \times a^2}{6 \times E \times I} \times (3 \times l + a) \quad (2.11)$$

With the following meaning of each variable:

- P = Force applied at load point
- a = Distance from support to the load point
- l = Length of beam
- E = Modulus of elasticity
- I = Moment of inertia of the beam

The modulus of elasticity depends on the material used in the beam, construction steel is usually around 200 GPa. The moment of inertia depends on which type of beam and what dimensions it has, for an I-section the formula for Y-direction is:

$$I_y = \frac{w \times h^3}{12} - \frac{(w - t_w) \times (h - 2 \times t_f)^3}{12} \quad (2.12)$$

With the following meaning of each variable:

- I_y = Moment of inertia about the y-axis
- w = Total width of the cross-section
- h = Total height of the cross-section
- t_w = Thickness of the web
- t_f = Thickness of the flange

A cross section of an I-beam with the corresponding variables is shown in Figure 2.7

2. Theory

following formula:

$$SF = \frac{\sigma_y}{\sigma_{VonMises}} \quad (2.14)$$

To determine the actual stress for the specific design the FEA function of CREO will be used. This software simulates and calculates necessary numbers such as deflection and max von Mises stress, to make sure the values are within safe limits and the design will have a desired safety factor.

2.10 Specific Safety Risks and Mitigation in the Battery Swap Station

The space inside the batter swap management system will not be made accessible when it is operating, this will be done by limiting the possibility of reaching these spaces. The only thing that will be able to enter when operating is a battery. The opening where batteries can travel will be at such height, it will be very hard for a human to reach. For servicing there will be possibility of opening certain areas of the swap station to make sure it meets EU directives [25].

During operation, a trolley carrying a fully charged battery will emerge from the BSMS bringing it to the machine waiting for a swap. This maneuver will be controlled by the driver of the vehicle to make sure the surroundings are safe, the same way the drive must do when driving the vehicle. The swap sequence will be controlled by the driver as well meaning if the button needed to start the swap is not being pressed the swap process will stop. Other safety precautions such as emergency stop buttons will be placed around the battery swap management system.

3

Methodology

This chapter describes the methods and how they will be used in the thesis. The framework of the methodology is derived from the book *Product Design and Development* by Ulrich & Eppinger. The set of methods and attributes are considered well known in the industry and also fits the development process and its objectives of this thesis.

The development process followed in this thesis is organized into six distinct phases: planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up as illustrated in Figure 3.1 below.

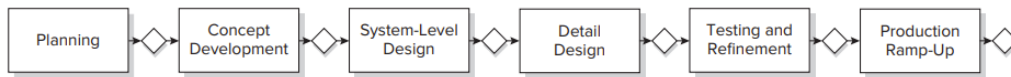


Figure 3.1: The Product Development Process by Ulrich & Eppinger [26].

This methodology ensures that ideas, concepts, and solutions are progressively refined, where each phase in the process serves a critical role in narrowing down solutions and design alternatives while enhancing the end products specificity [26]. For the thesis itself, a significant aspect of this methodology is the second phase, "Concept Development". In the book by Ulrich & Eppinger, this phase is also referred as "The Front-End Process".

The front-end process serves to guide the initial stages of the product development, and is particularly suitable for this thesis due to its structured approach in managing the higher level of uncertainty and open-ended decisions that are typical in the early stages of development. As can be seen in in Figure 3.2, the process revolves around from left to right, focusing on identifying customer needs, establishing target requirement specifications, generating multiple product concepts, selecting and testing the product concepts, and finally plan for the downstream development.

However, the front-end process in practice does not necessarily follow a strictly sequential order. Activities such as identifying customer needs, establishing target and/or requirement specifications, and generating concepts may often overlap, and iteration is frequently required. As shown by the dashed arrows in Figure 3.2, progress in product development is not always linear. In essence, this means that new information or insights at any stage may require the individual, or development team to revisit and refine earlier phases. This repetition of previously completed

activities, known as development iteration, is a necessary and integral part of the process, ensuring that the evolving product concept(s) remains aligned with new findings and potentially changing stakeholder requirements [26].

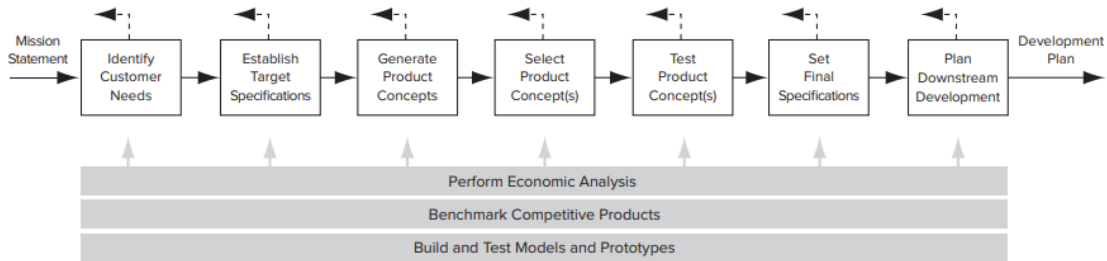


Figure 3.2: The Front-End Process by Ulrich & Eppinger [26].

Moreover, the front-end method emphasizes a thorough exploration of alternatives, including benchmarking competitive products, building and testing prototypes, and conducting economic analysis. These steps are crucial in ensuring that the selected concept is not only innovative but also technically feasible and commercially viable.

By adopting this method, the thesis benefits from a proven framework that systematically addresses the challenges of concept development, making it the most appropriate approach for achieving the research objectives.

3.1 Identify Customer Needs

Establishing the customer needs is an important step in understanding what the product should deliver in order to fulfill customer expectations and desires. This part of the process involves systematically capturing and interpreting both the needs, as well as the main points of the target audience. I.e., a clear understanding of customer needs not only shapes the product’s functionality but also aligns its design and performance with market demands. To outline customer needs effectively, raw data needs to be collected which through for example interviews, observations, focus groups, and identifying trends in the market.

3.1.1 Stakeholders

Outlining the stakeholders is an important aspect of the product development in order to involve and understand the right people. There are usually numerous different stakeholder with different needs and requirements of the product that all will be affected by the product [26]. The customer or end user in this context of this thesis is very important as they are the ones that will be using the product. There are several other entities involved as well such a Volvo Group, VCE, CPAC Systems themselves, technicians and more. This means identifying the different stakeholders and understanding each unique perspective is important for the outcome of the thesis.

3.1.2 Literature Study

In order to gain deeper understanding of a subject, a literature study searches for published information and work already performed. Using the internet in order to find published material such as books, articles, reports, patents, and product information is an effective and efficient way of performing the study. Since the available information is rather extensive, the possibility of finding specific things, gives big advantages of quickly understanding the subject in a comprehensive way.

The internal information and knowledge available from VCE and CPAC Systems on the subject was used during the literature study as well in order to be as efficient as possible. This was a wide variety of text documents, presentations and meetings with people at the office to further deepen the knowledge.

3.1.3 Market Research and Benchmarking of Competitive Products

Part of Ulrich & Eppinger's framework focuses on the benchmarking and market research which meant this became a big part of the early phase of the thesis to understand how mature the technology is, not only at CPAC Systems but in the global market itself. There are several ways of benchmarking different actors in the same market. One way is to create a chart with the customer needs and then comparing different products to each other. Doing it this way gives a customers' perspective of the products and their uniqueness, competitive priorities, and relative performance.

An alternative approach involves conducting a comparative analysis of the metrics associated with different solutions, and presenting the results in a side-by-side chart for clearer visualization. Examples of such metrics are size, capacity, speed, compatibility and deployability.

An additional method for market analysis involves examining patents to gain a deeper technical understanding of both product functionality and potential performance levels. This can be achieved by utilizing patent databases such as Espacenet, Google Patents, or USPTO, providing a comprehensive overview of the pace of technological advancements and identifying key market players. Using the correct keywords and classifications will help to more quickly find the patents closest to the product that will be developed.

3.2 Establish Target Specifications

When the customer's needs have been identified and documented, the target specifications are established that represent the ambitions and aspirations of the development team. These are a direct translation of the customer needs into measurable technical terms where each specification is linked to a metric, which in turn has an ideal value as well as a margin. However, as these specifications are established before the constraints of the product technology are fully known, some needs might

fail to be met, while others can be exceeded depending on what product concept is chosen further downstream in the process. This is why the target specifications need to be revised after a concept has been chosen, which is illustrated in Figure 3.2.

3.3 Generate Product Concepts

Creating the concept of a product is a way of showcasing how it will look, function, and give value to the customer. There are several different steps in which this can be done in order to do a thorough screening and evaluation.

3.3.1 Functional Model

A functional model is a way to break down the system into smaller subsystems or components to more easily understand functions and processes. This increases the possibility to discover opportunity, information needs, but also to act as a basis for calculating costs. For current products a functional model can be used to analyze specific components or to understand which components could potentially be removed completely to develop a better design. For completely new products this can be used to give an overview of what needs to happen inside the product for it to function as desired.

3.3.2 Brainstorming

One of the most widespread and simple ways is internal searching, also called brainstorming. In this instance team members and individuals work together with their previous knowledge to generate new ideas. This activity should be open-minded and creative following certain guideline in order for the ideas to flow freely such as: suspending judgement, sketching a lot of the ideas, welcome ideas that might seem infeasible, generate as many ideas as possible and building physical models can all attribute to creating the most ideas.

Combining these ideas with information gained from patent searches and market analysis can be used to design solutions for each function. These sub-solutions can then be put into a morphological matrix with each sub-function listed in the left column and respective sub-solutions in the rows. This technique gives an overview of each generated solution to each function which in turn can be used to generate concepts. Using software such as 'Morpheus' [27] which combines all functions with all solutions and produces all possible concepts that could be generated, is a useful starting tool. After that follows a process of putting constraints or simply sorting out unfeasible concepts that have been created, which otherwise might result in thousands of concepts needing individual evaluation. This will most likely narrow down the total amount of concepts to an amount that can be evaluated more thoroughly.

3.3.3 Screen Product Concepts

To screen out and evaluate concepts, several different techniques can be used. After the matrix is created in 'Morpheus' there will possibly still be many alternatives. Putting the concepts into an elimination matrix will give further screening by checking if the concepts fulfill the requirements. The simple method is to check each concept one each requirement. If just one requirement is not fulfilled the concept will be eliminated. Doing this method not only screens out concepts but also makes sure they will be viable for the requirements that were set from the beginning of the project. This is also an effective way of narrowing down a huge number of concepts to a smaller amount that can be handled in the following matrices.

The next step in the screening according to the methodology is the Pugh Matrix which is a structured approach to evaluated concepts more thoroughly. The purpose of this phase is to rapidly narrow the amount of generated concepts and subsequently improve them. Additionally, this type of decision matrix not only evaluates each concepts but also compares the concepts to each other.

The first task involves preparing a selection matrix where concepts are placed in a grid alongside evaluation criteria from the requirement specification. One of the concepts are chosen as a reference, i.e. a benchmark design, to serve as the basis of comparison.

Concepts are then evaluated relative to the reference using a simplified scoring system. Ratings are assigned as "+" (better than reference), "0" (same as reference), or "-" (worse than reference) for each criterion in each cell. Important to note is that the reference concept is always rated as "0" for all criterion. Following the ratings, concepts are ranked based on their aggregate scores, which is noted in the last row of the matrix.

After this step, the next task involves evaluating whether the concepts can be improved or combined to create enhanced alternatives. If feasible, these newly improved concepts, formed through the combination of existing ones, are incorporated into the matrix and rated alongside the original concepts. The matrix is then re-evaluated with the updated set of concepts, using the same rating and ranking process as before. To exemplify, Figure 3.3 below shows an illustration of a generic Pugh matrix.

Criteria	Alternative 1	Alternative 2	Alternative 3	Baseline
Safe	-	-	0	0
Durable	+	0	-	0
Weight	-	-	+	0
Easy to assemble	+	0	-	0
Reliable	-	-	-	0
Cost	+	0	+	0
NET SCORE	0	-3	-1	
RANK	1	3	2	
CONTINUE?	Yes	No	No	

Figure 3.3: Generic example of the Pugh Matrix [28].

The last step in the evaluation process is selection method called "Kesselring Matrix". In contrast to the Pugh Matrix, an ideal concept is created instead of using an existing concept as a reference. In addition, each criteria is assigned a weight factor based on their relative importance. Each criterion is scored on a quantitative scale, ranging from 1 to 10 and these scores are then multiplied by the assigned weight factor for each criterion, emphasizing the importance of critical criteria in the overall assessment.

The weighted scores for all criteria are summed to provide a total score for each concept. Concepts are then ranked based on their total scores, with higher scores indicating closer alignment to the ideal concept. This process not only allows for a more nuanced evaluation of the concepts but also helps to prioritize those that balance the most critical factors effectively.

3.4 Test Product Concepts

Once one or more concepts are selected, they generally follow the process of concept testing, which is a structured method used during the concept development phase to evaluate whether a product concept aligns with customer needs and resonates with the target market. This process involves gathering feedback from potential customers in the intended market segment to assess the viability and interest of the proposed concept. It is an important step in narrowing down design alternatives and refining concepts before advancing further in the product development process.

The method is closely related to prototyping, as concept testing often requires some form of product representation, such as sketches, models, or working prototypes. However, it can also be represented through verbal descriptions depending on the type of product, stage of development, and the goals of the test.

In certain cases, concept testing may be disregarded due to practical constraints. For example, if the product category has very short life cycles, or if the cost of testing

is disproportionately high compared to the cost of launching the product, a team may choose to not pursue with this method. However, when applied appropriately, concept testing provides valuable insights that has a high potential of enhancing the likelihood of developing a product that meets customer expectations and achieves market success [26].

3.5 Plan Downstream Development

The final activity in the concept development phase, in the front-end process focuses on establishing a comprehensive plan to guide the later stages of product development. This methodology involves the creation of a detailed development schedule which outlines key milestones and activities that are required to bring the product from concept to realization.

A central element of this part of the process is the creation of a project documentation tool, referred by Ulrich & Eppinger as a "contract book". This document consolidates the outputs of the front-end activities into a single, organized source. It typically includes the mission statement, customer needs, details of the selected concept, product specifications, economic analysis, development schedule, staffing plans, and budget allocation. The contract book functions as a formalized agreement between the development team and the organization's senior management as well as other stakeholders which helps to ensure alignment on project goals, deliverables, and resource commitments.

3.6 Supporting Activities

In addition to the core activities of the concept development phase, i.e., the front-end process, the stated activities below plays an important role in ensuring successful product development and product refinement. According to Ulrich & Eppinger, these activities include economic analysis, benchmarking of competitive products, and the development and testing of models and prototypes.

These activities are iterative and ongoing, which helps to provide insights and furthermore guiding decision-making throughout the process.

3.6.1 Perform Economic Analysis

Economic analysis is a critical supporting activity that helps justify the continuation of the development and informs decision-making on trade-offs between development costs, manufacturing costs, and other financial factors. Important to note is that the economic analysis is not restricted to the concept development phase, but can and should begin before the project starts and subsequently be revisited periodically as the product evolves over time. Similarly to other parts of the concept development process, this element is also iterative, which increases the likelihood that decisions are based on the most accurate and current financial projections.

3.6.2 Benchmark Competitive Products

Understanding competitive products in the specified market is an integral part of concept development as it supports the strategic positioning, market entry, and the design of a new product. According to Ulrich & Eppinger, product benchmarking involves a detailed analysis of competitor offerings to gain insights into their strengths, weaknesses, and design approaches. This activity is particularly valuable and important during early stages of development since it helps to identify opportunities for differentiation and improvement.

3.6.3 Build and test Models and prototypes

Modeling and prototyping are integral to every stage of concept development, as its providing a hands-on approach to explore and refine product ideas. Various forms of models and prototypes can be chosen depending on the specific objectives of the development phase and are as follows:

- Proof-of-concept models: These models demonstrate the technical feasibility of a design and help validate critical functions.
- Form-only models: These models focus on the physical appearance of the product and are often used to evaluate ergonomics, style, and customer preferences.
- Spreadsheet models: These models are utilized to analyze technical trade-offs which offers a quantitative base for decision-making.
- Experimental test models: These models are developed to set and validate design parameters which can help to ensure the performance under real-world conditions.

4

Results

4.1 Market Analysis

The current market for battery swap systems is very much evolving. From a world-wide perspective, the Chinese market is paving the way as of 2024 with big companies such as SANY, XCMG, Foton and NIO. All of the mentioned companies have a finished prototype or working product that has been showcased. Depending on the type of product or market, the solutions vary in how they solve the battery swap problem. The following sections will go over the mentioned companies and their currently known solutions.

4.1.1 SANY

SANY Heavy Industry Co., Ltd. is a Chinese construction equipment company offering a wide variety of construction machines. In recent years SANY has developed electric machines such as the SANY EV490-20, which is a fully electric truck [29]. This truck was developed with the battery pack sitting behind the driver's cabin with the possibility of easily removing it. In 2022 SANY presented their automated battery swap station using the same truck as the vehicle to showcase their solution. The swap station removes the battery pack by lifting it straight up and to the side, then placing the battery pack inside the building to then pick up a fully charged battery which moved over to the truck. This whole process takes around 5 minutes and the swap station can store up to 8 batteries. One of the main downsides to this solution is the physical size. The swap station is essentially a building which means the mobility of it is essentially non-existent. It also requires the machine to drive inside the station meaning very precise maneuvering is needed and the risk of hitting the station is greatly increased. Figure 4.1 shows this solution.



Figure 4.1: SANY Battery Swap Solution [30].

4.1.2 XCMG

Xuzhou Construction Machinery Group Co., Ltd is a big Chinese construction company making various construction machines. Similar to SANY they have developed electric machines with the battery pack located behind the driver's cabin. XCMG have also presented a battery swap solution which is more mobile than SANY's. Instead of having all components in a building, XCMG have created a trailer which can be placed in many different locations. This solution can hold up to 9 batteries and it takes around 5 minutes to perform a battery swap. Since this swap station requires the truck to be parked next to the battery that is fully charged inside the swap station there will most likely be requirements on how precise the parking needs to be which is not obvious. The batteries can only slide in from the side of the truck meaning the whole vehicle needs to be built around this type of battery swap in order for it to work. Figure 4.2 shows this solution.



Figure 4.2: XCMG Battery Swap Solution [31].

4.1.3 Foton Motor

BAIC Foton Motor Co., Ltd. is also a Chinese company manufacturing trucks, busses and sport utility vehicles. Similar to SANY they have made a battery swap station for trucks as a whole building, the truck drives inside and the battery is lifted straight up and moved inside the building to then be replaced by a fully charged one. The swap takes around 3 minutes and the swap station can hold 7 battery packs. Similarly to SANY this swap station is essentially a building which means mobility is non-existent. The reason behind this is most likely because it is supposed to be a permanent installation where trucks drive in to swap and then continue their journey, similarly to a petrol station. Figure 4.3 shows this solution.



Figure 4.3: Foton Motor Battery Swap Solution [32].

4.1.4 NIO

Nio Inc. is a Chinese automobile manufacturer. Nio only makes passenger cars as compared to the other companies mentioned previously but have developed their battery swapping station for several years. Since Nio's vehicles all have their battery packs mounted from underneath, the vehicle needs to be raised, the battery pack lowered and then moved to the side and replaced with a fully charged one. Each station can hold up to 23 batteries and each swap takes around 2.5 minutes. This swap station yet again is a building, it does have large capacity and quick swap times. It also requires the vehicle to be lifted in order to reach the battery place underneath. As of 2024 Nio operates over 1300 swap stations. Figure 4.4 shows this solution.



Figure 4.4: NIO Battery Swap Solution [33].

4.1.5 AMPLE

AMPLE is a San Francisco based US company developing battery swapping technologies with the focus of being able to offer one solution for many different manufacturers. They have swap stations for both passenger cars and trucks which through their own batteries makes it possible to swap between different brands. Similar to Nio the swap station raises the vehicle to then lower the battery pack and swap in a fully charged one. AMPLE have developed interfaces for each vehicle which is installed and then gives them the ability to use the same battery pack supplied by themselves in all vehicles coming into the swap station. Having the same battery for different types and makes of vehicles is a very flexible approach, the swap station similarly to NIO requires the vehicle to be lifted during the swap since the batteries in these vehicles are located on the underside. Each swap takes around 5 minutes and the swap station can hold several batteries at the same time. Figure 4.5 shows this solution.



Figure 4.5: AMPLE Battery Swap Solution [34].

4.2 Patent Search

In order to deepen the understanding of current solutions a patent research was performed. Several companies with different kinds of solutions exist. This gave further possibilities in the development of the thesis not only to improve but also innovate solutions not yet in existence. In order to narrow the search down terminology such as 'Battery swap', 'Battery replace trailer' and 'swap station' was used. Combining this with focusing on trucks or construction equipment made the search focused on the right type of patents.

A company mentioned in the previous section which reoccurred in the patent search was XCMG. As a contrast to the many truck swap solutions XCMG has filed patent *CN117486105A* named 'Mobile battery replacement equipment and battery replacement method there of' Figure 4.6. This patent uses just a truck as the swap station compared to a full trailer, with space for only two batteries. It is still fully mobile and it has the possibility to swap batteries on construction machines such as excavators. As can be seen in the figure below it needs to extend legs behind it in order for it to allow the battery pack to reach the machine in need of a battery swap.

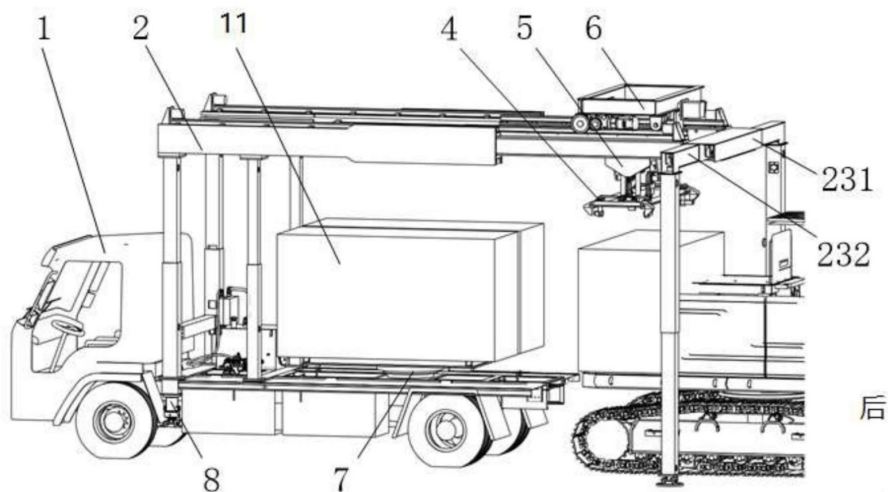


Figure 4.6: XCMG Mobile battery replacement equipment and battery replacement method [35].

The next type patent which entails a swap station as a trailer had several applicants. One of them is the company Tanbo Tech Shanghai CO LTD with the filed patent *CN113895300A* named 'Mobile truck battery replacing device' Figure 4.7. The truck in need of a fully charged battery drives up side by side to the swap station, then the battery is slightly lifted up and out of the truck and moved inside the trailer. When a battery has been brought inside a stacking robot will move the battery into available spot and then return to the truck with a fully charged one.

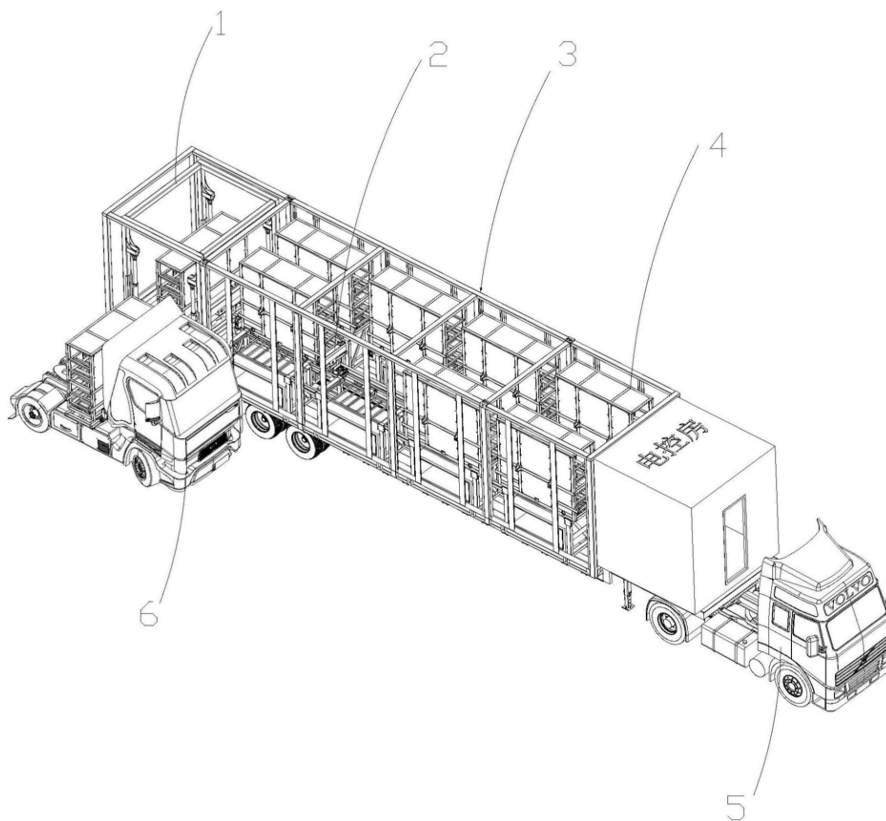


Figure 4.7: Tanbo Mobile truck battery replacing device [36].

Another example of using a trailer as a swap station is patent *CN116061749A* named 'Mobile battery replacing station' Figure 4.8 filed by the company Langu Wisdom Beijing Energy Tech CO LTD. Similar to the Tanbo patent the battery is lifted up and moved inside the trailer where several batteries exist ready to be swapped. The difference between the patents is the positioning of the truck. In this one the truck is parked behind the swap station which means the battery is always correctly positioned in relation to its charging spot. It also means the trailer is smaller since there is no need for the battery to rotate before it can be placed in its spot thus saving space inside the trailer.

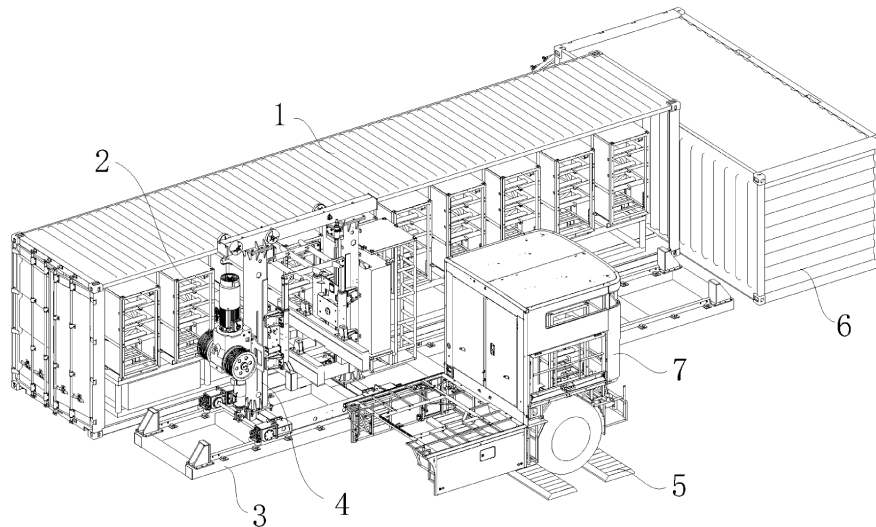


Figure 4.9: Westwell and Kewe Integrated Vehicle Battery Swap System, Method and Device, and Storage Medium [38].

Other types of patents use a completely different approach. The company Three One Heavy Industry Share LTD has filed patent *CN216636218U* named 'Mobile battery replacing station' Figure 4.10. This consists of several trailers connected to a pulling vehicle. In this patent the swap system is divided by its different functions such as charger, battery storage and a battery replacing device. Since the battery replacing device is behind the batteries and placed on a separate trailer it needs to somehow move alongside the trailer to be able to reach the batteries and swap them into the machine in need of one. It is a bit unclear exactly how this part of the swap works but one can assume the pulling vehicle is supposed to drive this battery replacing device around. Another aspect of this patent is the possibility of holding a fully charged battery while removing the low-charged battery. This would mean the swap time is reduced since there is not step of the process where the removed battery needs to be transported and placed into storage before the fully charged battery is picked up and swapped into the machine waiting for a battery.

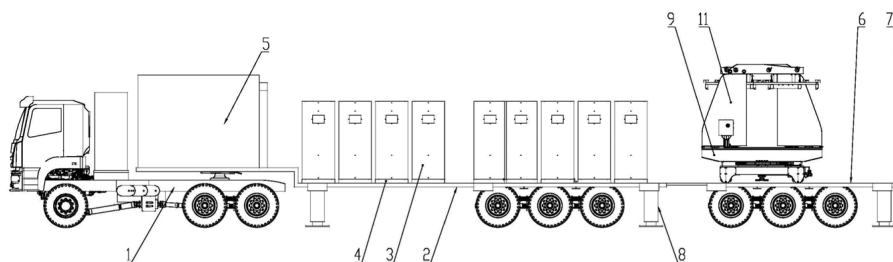


Figure 4.10: Three One Heavy Industry Share Ltd Mobile battery replacing station [39].

4.2.1 Summary of Patent and Market Research

The patent and market research revealed a variety of innovative battery swapping solutions, primarily focused on increasing efficiency, mobility, and compatibility with different vehicle types. A common theme among the patents is the use of one-way systems, where the depleted battery is first removed and placed at a designated charging spot, followed by the retrieval and installation of a fully charged battery. While this approach simplifies the technical requirements of the swap process and the station itself, it significantly increases the time needed for a complete swap as the system must handle each battery sequentially.

Many patents focus on mobile and compact designs, particularly for use in construction equipment and trucks. Companies like XCMG and Tanbo Tech have developed mobile solutions, such as truck-mounted or trailer-based systems, that allow for deployment in remote or variable locations.

Efficiency remains a central concern, with most systems achieving swap times between 2.5 and 5 minutes. However, the limitations of one-way swapping restrict the ability to further reduce these times. However, one solution stands out which is the solution by Three One Heavy Industry which is an attempt to optimize the process by allowing components to simultaneously handle depleted and fully charged batteries. This bi-directional approach could dramatically decrease swap times and highlights a potential area for innovation.

Finally, standardization and compatibility are emerging as important factors in the development of battery swapping technology. As an example, AMPLE's universal interface allows for cross-brand compatibility, which showcases the potential for greater flexibility and broader adoption of swapping systems.

4.3 Functional Analysis

To get an understanding of what functions the overall system should be able to fulfill, and what potential solutions to be used for those, a functional model as well as the schematics of the battery swap management system was developed.

4.3.1 Black Box

The purpose of the black box is to show what inputs and outputs a system will have. The functions inside are neither shown nor examined. For the battery swap management system the input will simply be machines with batteries low on charge and a 400 V AC connection from the grid. Then the functions inside the black box will solve the necessary tasks in order for the output to be a machine with a fully charged battery. Figure 4.11 shows the black box model for the BSMS.

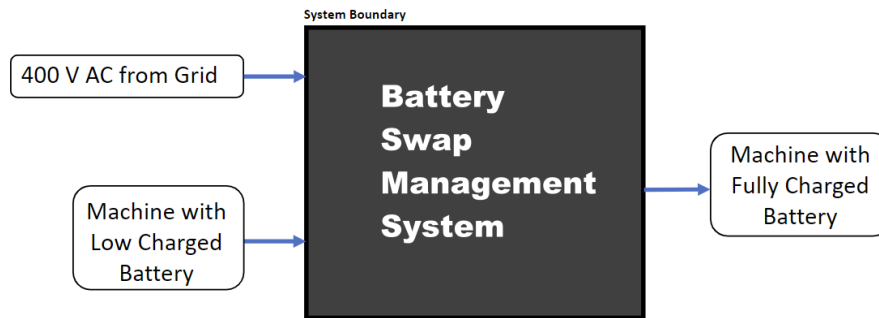


Figure 4.11: Black Box for Battery Swap Management System.

4.3.2 Functional Model

A functional model was developed with the aim of systematically decompose and breaking down the main function into more manageable sub functions. The primary function is to reduce vehicle charging downtime and even out peak power demand. The corresponding solution is the development project itself, a battery swap system. In line with this analogy, six sub-functions to the battery swap system was identified. These are essential for ensuring the desired functionality of the system and that the primary objective can be fulfilled. These sub functions are as follows and is depicted in Figure 4.12 below. The same functional model in the form of a tree diagram is attached in Figure ??.

- **Swap Batteries:** This sub function plays an important role in the context of the battery swap system as the main solution for reducing vehicle charging downtime. Swapping batteries is a direct alternative to recharging batteries hence significantly minimizing the time a vehicle is out of operation. The sub-solution for this function is associated with a mechatronic system, which has the capability, and facilitates the semi-automated process of swapping batteries with minimal human assistance and intervention. The mechatronic system

itself is expected to include a variety, and a combination of mechanical, hydraulic, and electrical components as well as software and sensors. The sub sub functions includes actions such as unloading and loading batteries from the vehicle and the system itself, transporting the battery to be swapped to a designated charging point within the swap station, and also being able to store the battery in a secure way. The corresponding solutions to these functions (sub sub solution) are for instance a crane, robotic arm, or some form of sliding rail system to unload and load the batteries.

To ensure efficient transport of the batteries from the unload stage to the designated charging point, and vice versa, systems such as conveyor belts, overhead cranes, or rail systems can be employed considering the weight of and size of the batteries. Finally, to facilitate charging without human intervention and storing the batteries securely, racks, stackable trays, or rotating storage bins can be used.

- **Transport Assembly:** In the battery swap system, this sub function exists to ensure the mobility and deployment of the system itself. The ability to transport the entire battery swap assembly to various locations, such as construction sites or other work environments, is critical for its demands of a flexible and mobile product. The sub-solution for this function involves using a mobile platform, which aims to provide the structural and mechanical support required to move the system from one site, or location to another. This platform must be robust and versatile, whilst also complying with road and traffic regulations.

The sub sub function of the above includes providing mobility, which is facilitated by solutions such as a trailer, roll-off flatbed, or even self-propelled system such as truck. These platforms enable a safe and controlled transportation of the battery swap system, ensuring that it can be rapidly deployed where it is needed without excessive setup time or need of external machinery.

- **Distribute Energy:** This is a necessary sub function to manage how energy is handled and transferred throughout the battery swapping system. The sub-solution to address this is an energy management system, which oversees power distribution across the storage part of the system, state of health (SOH), state of charge, and temperature of the batteries to ensure safe and efficient charging cycles. Key sub sub functions here include charging batteries and power system, i.e. the energy needed to make the systems itself operate. The sub sub solutions for these tasks involve devices like on-board chargers to re-charge batteries, and DC-DC converters to maintain proper voltage levels, ensuring that batteries are charged as efficiently possible and ready to be deployed quickly after each swap.
- **Communicate Battery Status:** Communicating the battery status is an important sub function that ensures operational efficiency for not only the battery

swap system, but also for the operator running the electric machines. This is presumed to be managed via cloud connectivity as the sub-solution, enabling real-time data exchange between the system and operators. The sub sub function here is to facilitate operations, which is enabled through telematics solutions. These will provide updates on battery charge levels, and operational readiness, meaning essentially when at what point in time a swap of the battery is most favourable depending on external circumstances such as how many machines are expected to perform one or more swaps during the day, or at what rate the machine(s) are depleting their energy. This real-time communication allows for predictive battery swaps, ensuring the battery swap system runs efficiently by reducing potential queues and keeping downtime minimal.

- **Carry Parts:** This sub function is necessary in term of ensuring that all components within the battery swap system's power unit are securely positioned and supported both during operation as well as transport. It solely serves the purpose of connecting and uniting the sub solutions of the Mechatronic system to the sub solution "Mobile Platform", i.e. the solutions of "Un/load", "Transport", and "Store" the batteries. The sub sub solution is thought out to be a stable and robust frame structure constructed using beams, bracket, clamps, and other components that ensures the mechanical structural integrity of the system.

In addition to securing components, this sub solution also involves the sub function of cover parts to protect the internal systems from external environmental factors. Inside components and parts needs to be protected from dust, moisture, and potential physical impacts, and by that increasing the durability and reliability of the battery swap system.

- **Compliance with Safety and Legal Regulations:** Compliance with safety and legal regulations is a highly important aspect as and thereby a subfunction to ensure that the battery swap system operates within industry standards and guidelines. The sub solution to meet these requirements is a battery swap safety system, which incorporates several measures to guarantee safe operation within the external and internal perimeters of the system. Key sub sub functions include allowing for emergency shutdowns and hindering catastrophic failures. These are achieved through shutdown buttons and fire suppression systems respectively, which are necessary to react quickly in case of malfunctions or hazards, preventing accidents. Additionally, systems equipped with visual indicators and sensors provide continuous monitoring of the environment. These systems informs the operators to mitigate any potential risks, ensuring that safety standards are consistently upheld.

4. Results

Main Function	Main Solution	Sub Function	Sub Solution	Sub Sub Function	Sub Sub Solution
Reduce Vehicle Charging Downtime and Even out Power Demand	Battery Swap System	Swap Batteries	Mechatronic System	Un/Load Batteries	Crane, Robotic Arm, Sliding rails
				Transport Batteries	Conveyor Belt, Overhead Crane, Rail System
				Store Batteries	Racks, Stackable Trays, Rotating Storage Bind
		Transport Assembly	Mobile Platform	Provide Mobility	Trailer, Roll-Off Flatbed, Self-Propelled
		Distribute Energy	Energy Management System	Charge Batteries	On-board Charger
				Power System	DC-DC Converter
		Communicate Battery Status	Cloud Connectivity	Facilitate Operations	Telematics
		Carry Parts	Frame Structure	Hold Parts	Frame
				Cover Parts	Cover
		Compliance with Safety & Legal Regulations	Battery Swap Safety System	Allow Emergency Shutdown	Shutdown Buttons
				Hinder Catastrophic Failure	Fire Suppression System
				Inform User reg. Surroundings	Visuals
				Detect Hazards	Sensors

Figure 4.12: Functional model for the Battery Swap System.

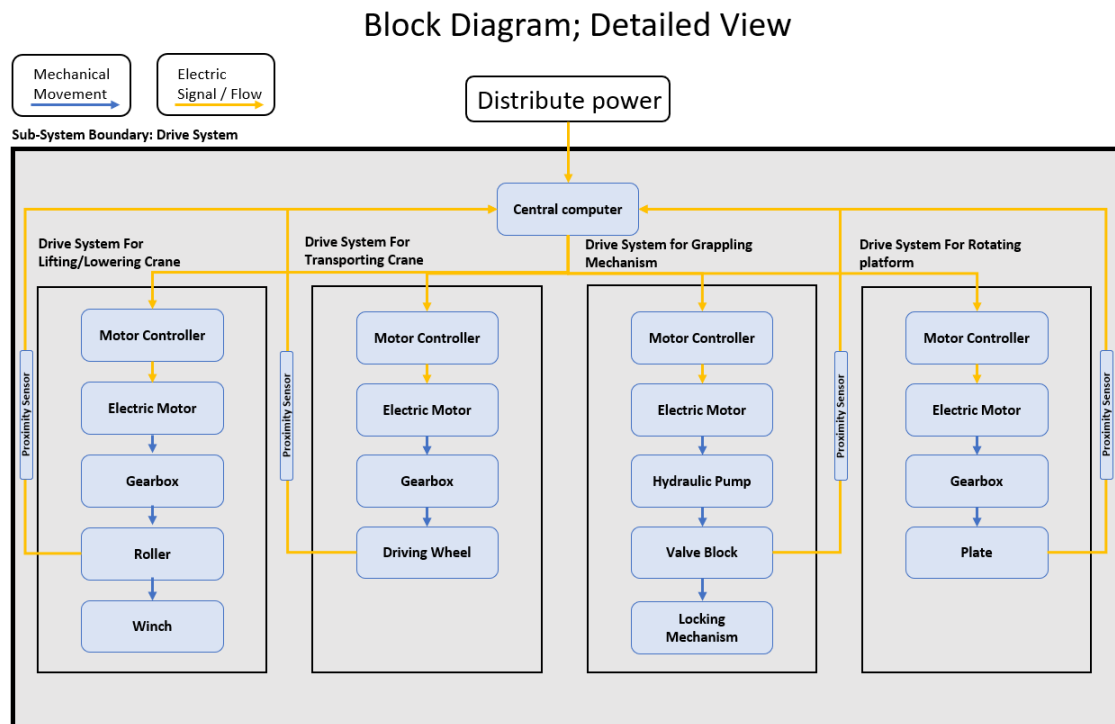


Figure 4.14: Detailed view of the block diagram of the Battery Swap Management System.

4.4 Idea Generation

Early idea generation stemmed from inspiration provided by CPAC systems and VCE. Previous documentation and ideas gave insight of what a swap system could look like. Continuing upon this, doing the market and patent analysis deepened the understanding of which components would be needed and possible layout of a BSMS. Since emphasis was put on having a mobile platform this deepened the search even further. After the basic understanding of what a BSMS could look like, the main functions were written down thus creating the functional model. During this process, brainstorming was executed on several occasions in order to broaden the possible sub-solutions.

4.5 Concept Generation and Evaluation

The sub-functions created during the idea generation were used in the software "Morpheus". This software helps create all possible combinations by cross matching all the sub-functions inserted, which resulted in 5400 solutions. The software does not automatically take into consideration what the incompatibilities are or feasibility of each sub-solution. This meant looking at each correlation between the different sub-functions and deciding what would be possible or not. Taking cost, technical feasibility and practicality into consideration the solutions was then reduced from 5400 to a total of 135 concepts. This was mainly done by defining incapacibilities

between different sub-solutions where some functions would have been made redundant if combined. An example of this was combining a robotic arm with storing batteries in trays along a trailer. These solutions would be unnecessarily complicated to develop and more efficient ways of using each sub-solution existed. Other examples where sub-solutions were simply disabled in the matrix were having a 'self-propelled' battery swap management system. Not only the cost of manufacturing such a product but also for the customer to have essentially a truck just standing around would not have been efficient.

After the concepts were generated in the morphological matrix they were moved into the elimination matrix. As mentioned in subsection 3.3.3, each one of concepts would be analysed to see if it fulfills the most important criterias from the requirement specification. This resulted in either receiving a '+' or '-' depending on if the criteria was fulfilled or not. If just one criterion was not fulfilled the concept was deemed unfit for the battery swap project and therefore removed. The final outcome of the elimination matrix was 18 concepts.

What became apparent during the concept generation phase was one main aspect that split the final outcome into two groups. The two groups were either taking the previous VCE solution into consideration or doing it completely unconstrained. The reason behind this decision to partly take notice of previous work was the focus on creating value for CPAC systems and VCE. Suggesting a completely brand new version for the BSMS might be considered too complicated or expensive thus continuing with two groups of concept parallel during the final part of concept generation was decided upon. Keeping the options viable as long as possible could give advantages in the future when more information has been gained.

The next step consisted of putting each group of concepts into a 'Pugh Matrix'. There, one of the concepts would act as an reference and the others would be compared to understand if some concepts are less suited than others. The comparison would simply be how well each concept fulfills the criteria from the requirement specification. Discussions around each sub-function graded each concept either better, worse or the same as the reference concept. The reference concept was then changed two times before evaluating if any of the concepts was consistently worse than the others and therefore would not be developed further.

The last step of the concept evaluation process was the 'Kesselring Matrix'. Instead of using one of the existing concepts as a reference the ideal concept was made. Using the criterias yet again but putting a 'weight' on each criteria where the ideal concept would have highest possible scoring and each of the concepts would be analyzed to see how well the criteria were fulfilled. The final outcome was concept number 2941.

This concept consists of an overhead crane that will roll on the top beams of the structure. This will be version of a trolley that at the bottom of it will have a rotating plate, named 'Horizontal Rotating Bin' during the concept evaluation. The

overhead crane will not only move inside the battery swap station but also be able to extend outside the structure in order for it to reach the machine the needs the battery swap. This means one component will solve two different problems, both moving the battery into and inside the BSMS. When placed inside, the batteries will be locked in place using guide rails. There will also be a fixed connector at the side of the battery which can be moved and adjusted depending on the size of the battery and location of the connection. It is through this connector the batteries will be charged. All these components will be placed on a container base plate. This will give the possibility of placing the whole BSMS on a standardized truck trailer which will maximize the mobility.

4.6 Final Design

After the concept evaluation was performed, the actual development of the chosen concept began which resulted in the final design. As the thesis aims to develop and showcase a POC, it was highly important to taking the financial aspects, Design For Manufacturing (DFM), and Design for Assembly (DFA) into consideration from the beginning. The result of this approach is a lower volume of in-house manufactured parts leading to lower cost, less complexity, and a minimized Time To Market (TTM).

By sourcing standard components and off the shelf parts, less time was spent on specific design and development of parts already existing. Parts and components not available on the market or meeting the established requirements have been designed in-house using the CAD software PTC Creo together with the complete assembly of the BSMS.

Additionally, to verify the structural integrity including stress, strain and deformation in the various sub frames the BSMS, the Finite Element Method (FEM) was employed using the built in workbench in PTC Creo.

The final design represents the culmination of all concept screening and evaluations conducted throughout the development process. As mentioned in 4.5, the concept that emerged superior to the others, designated as Concept 2941, was selected for its alignment with the project's objectives and includes the following features described and illustrated below:

- **Load / Unload Batteries: Overhead Crane**

Solving the problem of lifting the batteries in and out of the machine will use an overhead crane. This will translate on rails mounted on top of the BSMS which eliminates the needs for having supporting legs standing on the ground and potentially becoming an obstacle for the machines when maneuvering.

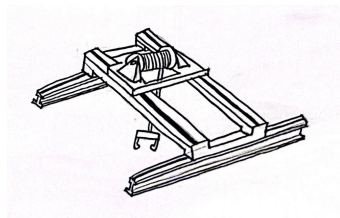


Figure 4.15: Illustration of Overhead Crane.

- **Horizontal Rotating Bin**

To minimize the swap time a rotating bin will be used. This will give the possibly of not only holding two batteries at the same time during the swap but also installing one battery without having to bring the other one back into

the BSMS.

- **Transport Batteries to Charging Location: Overhead Crane**

Transporting the batteries inside the BSMS will use the same overhead crane as for unloading and loading the batteries as seen in Figure 4.15. This means one sub solution will solve two different problems.

- **Store Batteries in Swap Station: Guide Rails**

Locking the batteries in place will be achieved by utilizing guide rails which the battery slides into when lifted into its charging spot. This not only means the need for a locking mechanism is redundant but also guides the batteries into their exact designated location.

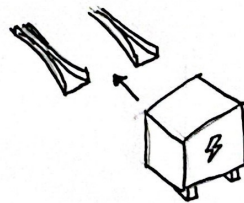


Figure 4.16: Illustration of Guide Rails.

- **Enable interoperability across diverse battery interfaces: Fixed Connector**

When the battery is placed in its charging spot the connector will be positioned in a fixed location relative to the battery which also simplifies manufacturing of the charge pad base plates. If the swap station will be used with batteries from other manufacturers, this can be reconfigured with a small effort.

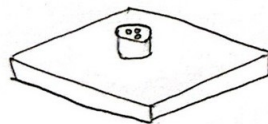


Figure 4.17: Illustration of Fixed Connector.

- **Provide Mobility: Trailer**

Providing the mobility for the BSMS will have been chosen to be a standard 40 ft container truck trailer. This is not only a very cost-effective solution, but also means attachment points will be the same as standard 40 foot containers, meaning transportation by other means such as sea, train or ship will

be facilitated. The approach of having a de-coupled design also results in the BSMS having an ability to stand on its own after being placed in the correct position eliminating the need for the trailer when parked.

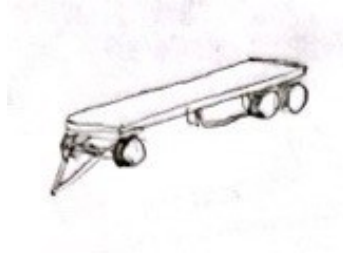


Figure 4.18: Illustration of Trailer.

As described above, this concept consists of an overhead crane that will roll on the top beams of the structure. This will be adaptation of a trolley that underneath is equipped with a rotating plate capable of lifting two batteries individually at the same time. The benefit of this solution is to minimize the swap time since loading and unloading the batteries can be performed without the need of dropping of a battery in between.

The overhead crane will not only move inside the battery swap station but also be able to extend outside the structure in order for it to reach the machine the needs the battery swap. This means one component will solve two different problems, both lifting the battery into and out of the swap station as well as moving it inside the swap station.

4.6.1 Final Design Mechanical System

Using the software PTC Creo the final design was created taking the selected sub-solutions and cross functional aspects from the idea generation. The final result is shown in Figure 4.19.



Figure 4.19: Rendering of final CAD model of the BSMS.

The complete CAD assembly consists of several sub-assemblies that fulfill the different functionalities. To structure the design work, these have been divided into five separate entities according to DFA and DFM, and are as follows:

- **Trailer and Base plate**

The foundation of the BSMS is the base plate and this is the main structural assembly holding all parts and components together which is shown in Figure 4.20. This also serves as the interface to the trailer making the BSMS transportable, and has the exact same dimensions and connections as a standard 40 feet long container. The reasoning behind this choice is to make the swap station as transportable as possible which, using a standard truck trailer means no specialty vehicle needed to transport and move the swap station around. In the corners of the base plate are ISO standard corner castings which means they can be placed and locked in the same way as a normal container.

As mentioned previously, the trailer seen in Figure 4.19 is a standard container truck trailer only existing for visualization purposes. This has not been designed by the master thesis students, but used with permission from the 3D Library site "GrabCAD" [40].

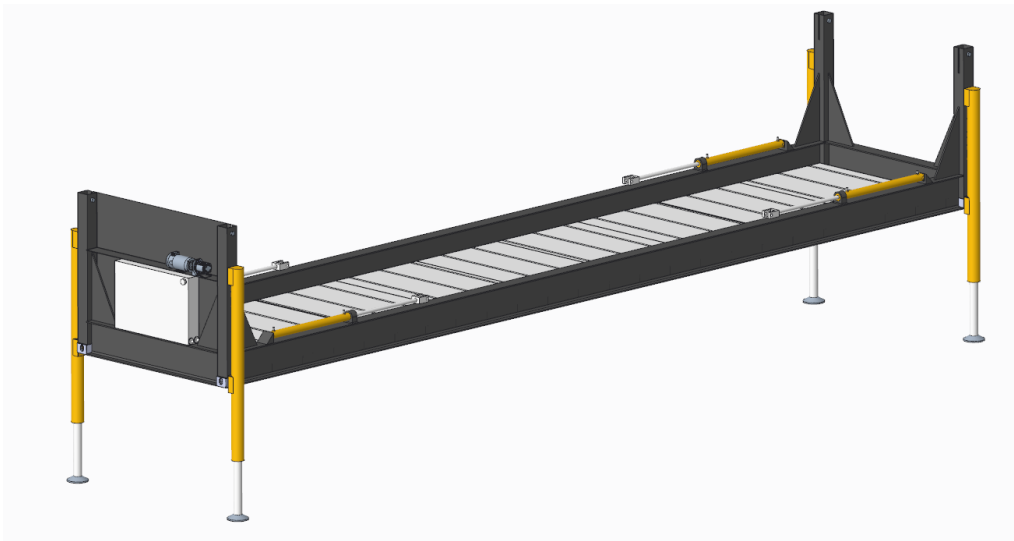


Figure 4.20: Rendering of base plate.

- **Frame**

One of the main limiting factors of the battery swap station is the requirements for being able to be transported on a public road. The maximum recommended height is 4.5 m in Sweden, above this height there is no guarantee of not hitting signs or overpasses [41]. A standard truck trailer usually ranges between 1.3-1.5 m in height which gives the swap station 3 m of height to build upon. Therefore, the placement of the batteries have been set to as low as possible since a battery needs to be able to travel above the ones already placed inside. This approach also helps with a low center of gravity increasing the overall robustness of the system.

In order for the swap station to meet the height requirement during transport as earlier mentioned as well as being able to lift the batteries in and out from the machine, the frame needs to be able to be lifted and lowered in the Y-direction. This means having a system raising and lowering the top part of the swap system in order to meet this requirement. The reason behind not making the swap station low enough to meet the height requirement on public roads is the previously mentioned requirement of two batteries being able to move above one another, this did not leave enough space for the base plate and trolleys above to fit. The system designed for performing this movement is referred to the lower beam frame, and consists of hydraulic cylinders pushing on diagonal beams supported by a rotational joint and rollers resulting in 500 mm raise or lowering capability.

In all corners there are sliding square steel profiles that can be locked into position with rigid pins when raised to correct height. Performing this maneuver not only gives enough space inside the swap station when operating but also solves the height requirement for being able to be transported on a public road. The lower beam frame is shown in Figure 4.21



Figure 4.21: Rendering of lower frame.

The upper part of the swap station is referred to the upper beam frame, and supports a large translatable system of I-beam which gives the functionality of extending outside the swap station in order to reach the machines standing behind it. This system of beams can extend 4.5 m outside the swap station in order to give the operator of the machines waiting to swap a battery a higher possibility of positioning the machine correctly.

This frame has to be able to counter hold large loads at the very end without deflecting or moving in any direction. There are extra pair of trolley wheels placed on the underside of the lower upper beam in order to prevent lateral or vertical displacement. The dimensions required for the big I-beam has been matched through calculations to withstand the maximum loads applied during a battery swap. The upper beam frame is shown in Figure 4.22.

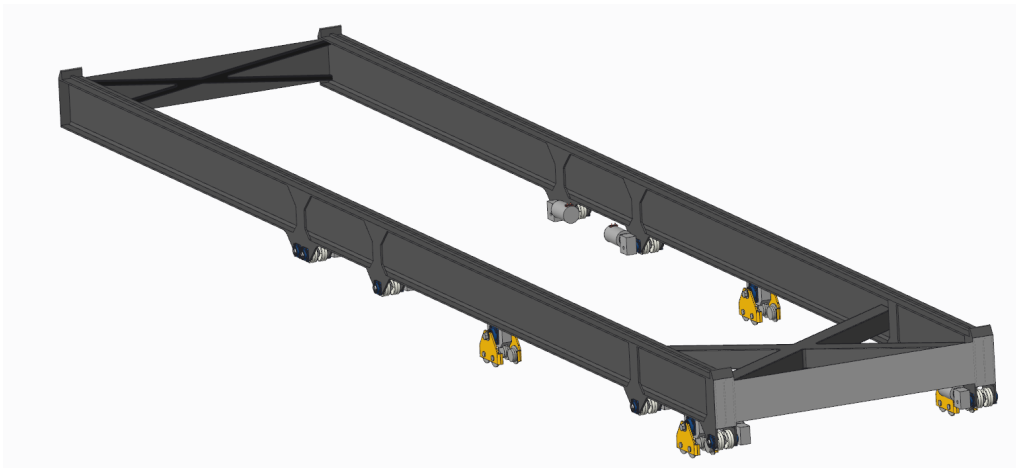


Figure 4.22: Rendering of upper frame.

- **Trolley**

The upper most part of the swap station consists of the trolley where the function is to perform both the transportation of batteries as well as lifting the

batteries in and out of the machines. This trolley has the ability to translate along the swap station on the upper section of the frame which will give it the ability to pick up batteries inside the swap station and move them to the machines waiting for a battery swap.

The trolley is able to hold two batteries at the same time, meaning it will be able to bring a fully charged battery with it when moving out of the swap station to perform the battery swap on the machine. This means swap time is being reduced since the bottom part of this trolley has a rotational function as well meaning the low charge battery will be lifted out of the machine, the trolley rotates the fully charged battery into place and then lowers it into the machine.

Located below the rotator are two winches that individually can raise and lower one battery each. This approach allows the system to move in all directions, and removes the requirement of an exact positioning of the machine below. The operator is therefore able to position the machine somewhere within the borders of the swap area. The trolley is shown in Figure 4.23.

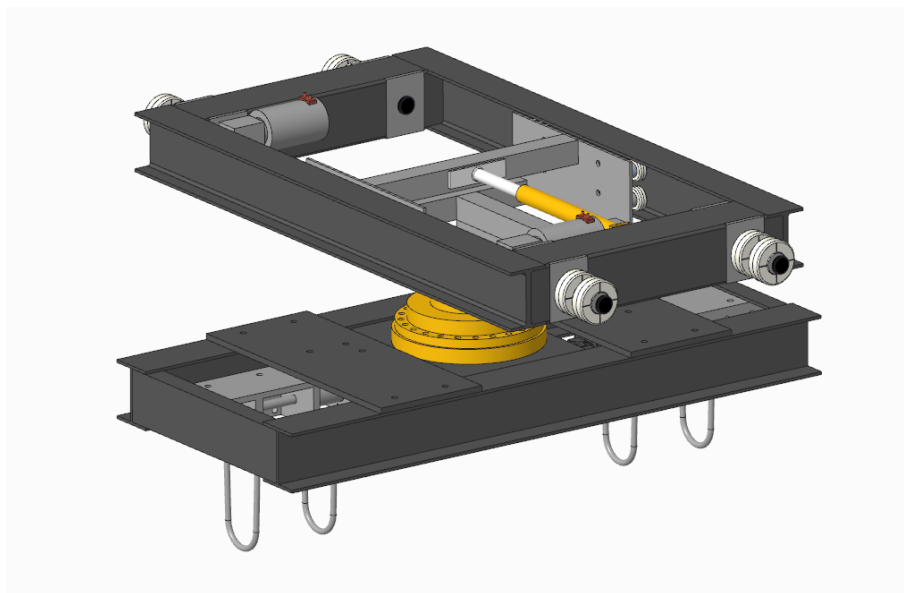


Figure 4.23: Rendering of trolley.

- **Attachment Plate**

Attached to the winches on the trolley, there exists an attachment plate to easily attach and de-attach individually to the batteries through electric actuators. The attachment plate is shown in Figure 4.24.

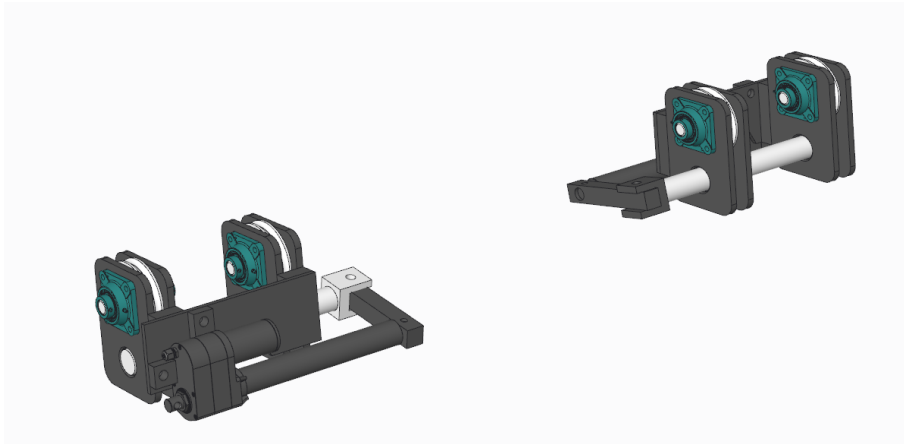


Figure 4.24: Rendering of the attachment plates.

- **Battery Charging Infrastructure**

Inside the BSMS; batteries, the storage solution (guide rails), and fixed chargers are positioned onto the base plate and in total, the BSMS can hold up to 7 batteries at the current size and configuration. The storage solution and fixed charger is shown in Figure 4.25.

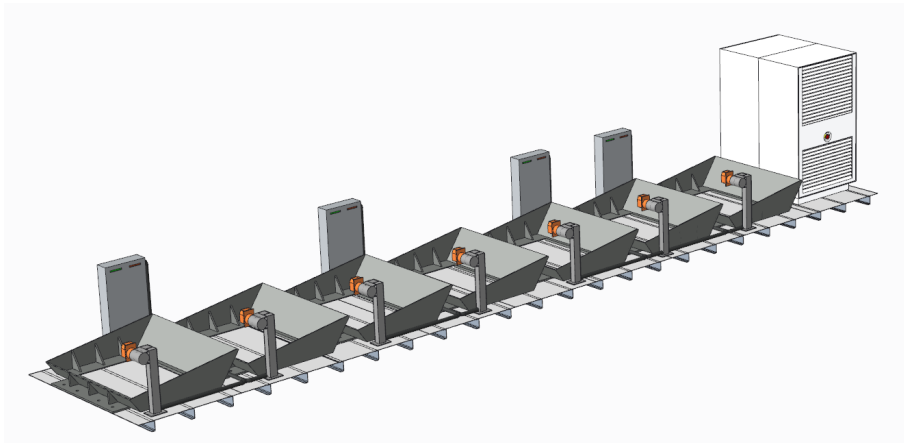


Figure 4.25: Rendering of the charging infrastructure.

4.6.2 Verification of Final Mechanical Design

The mechanical integrity of the BSMS was thoroughly analyzed to ensure its reliability under operational conditions. One of the key components requiring verification was the upper and lower beam frame, which is critical for supporting the loads associated with the battery swapping itself. This system must be able to withstand significant loads at the very end of the beam during operation, without deflecting over the requirements nor exceeding the yield strength of the materials used.

Verification of the mechanical design was conducted through iterative simulations utilizing the FEM workbench in PTC Creo. These simulations provided detailed in-

sights into the stress, strain, and deflection behavior of the upper and lower system of beams, and associated components under maximum load conditions. The results confirmed that the upper frame and its underlying support (the lower frame system) are capable of safely handling the maximum loads without exceeding material limits or experiencing unacceptable deformation. The detailed results of the simulations are presented below.

4.6.2.1 Structural Simulation of Upper Beam Frame

In the figures below, the results of the simulations are presented for the upper beam frame, including maximum displacement δ_{\max} (seen in Figure 4.26 and Figure 4.27) and the Von Mises stress $\sigma_{\text{Von Mises}}$ (seen in Figure 4.28). The maximum displacement is approximately 18.6 mm, which occurs at the outermost end of the I-beam under full load conditions. The maximum Von Mises stress is calculated to be 2.119×10^5 kPa, equivalent to 211.9 MPa.

This stress is below the typical yield strength of structural steel, which ranges from 250 MPa to 355 MPa depending on the grade used [24]. With this result, the design has a safety factor (SF) of approximately 1.18 to 1.68 which is calculated according to the formula below:

The SF is calculated as follows:

1. For the minimum yield strength:

$$SF_{\min} = \frac{250}{211.9} = 1.179 \approx 1.18$$

2. For the maximum yield strength:

$$SF_{\max} = \frac{355}{211.9} = 1.675 \approx 1.68$$

It is important to note that the maximum Von Mises stress is not concentrated on the I-beam itself but rather on the supports connecting to the rollers as shown in Figure 4.28. This indicates the criticality of these connections and the need for reinforcement to avoid potential failures under load.

The boundary conditions applied during the simulations are depicted in all the figures below. The blue arrows represent the rollers connected to the frame, which are modeled as simply-roller supports under a concentrated in-plane load. The yellow arrows denote the point loads applied to the frame section in the negative Y direction, representing the trolley carrying the maximum weight of the batteries during operation. These boundary conditions were chosen to closely replicate the real-world operational scenario of the battery swap station, providing a realistic assessment of the structural behavior.

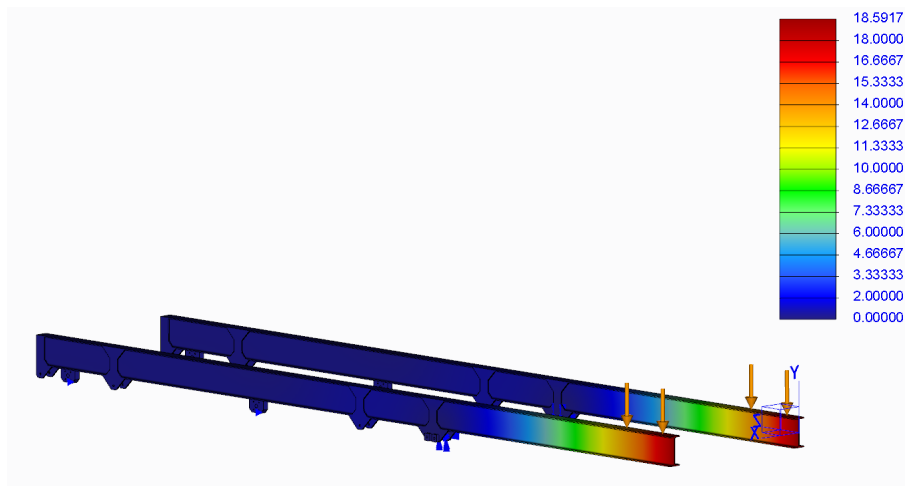


Figure 4.26: Maximum deflection δ_{\max} with the whole beam in perspective.

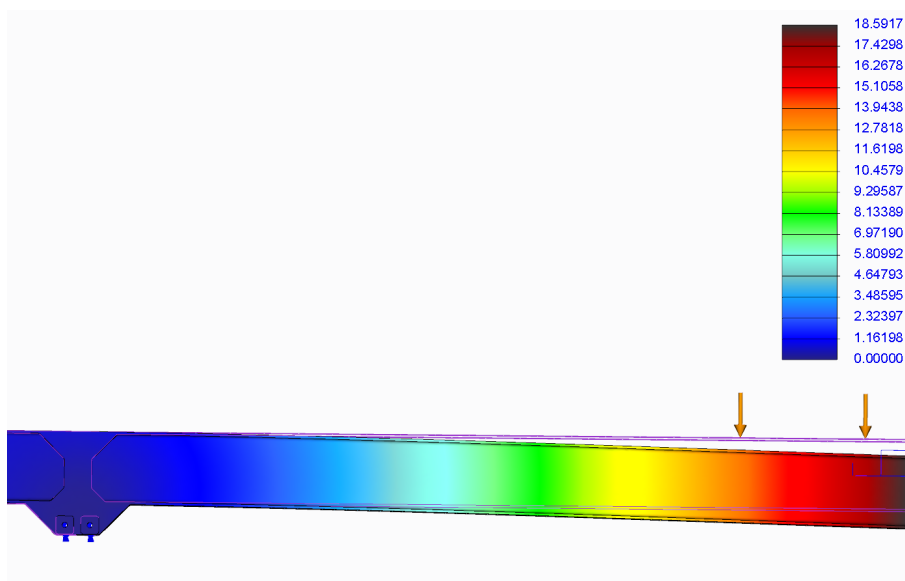


Figure 4.27: Maximum deflection δ_{\max} close up.

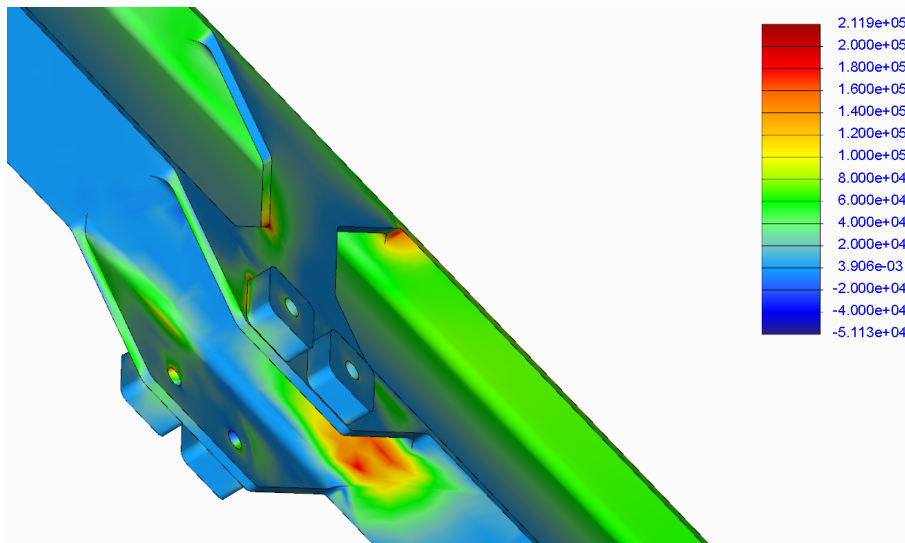


Figure 4.28: Max Von Mises stress $\sigma_{\text{Von Mises}}$ occurring in the the support area connecting to the rollers.

4.6.2.2 Structural Simulation of Lower Beam Frame

Identical to the section above. The same simulations were performed for the lower beam frame, which solely supports the upper beam frame. However, as the upper beam frame has the ability to translate from one end to the other, two load cases had to be analyzed in order to verify the structural integrity. The first load case represents the scenario where the upper beam is extended as far out as possible. This is where the system will experience the highest load, as this is where the actual swap will be performed. The second load case is the scenario where the upper frame is in its non-extended state, i.e. completely inside the swap station.

In the figures below, the results of the simulations are presented for first load case, including maximum displacement δ_{max} and the Von Mises stress $\sigma_{\text{Von Mises}}$. The maximum displacement is approximately 0.5 mm, which occurs at the outermost end of the I-beam under full load conditions. The maximum Von Mises stress is calculated to be 1.477×10^5 kPa, equivalent to 147.7 MPa.

Analogous to before, for this load case the design has a SF of approximately 1.69 to 2.40.

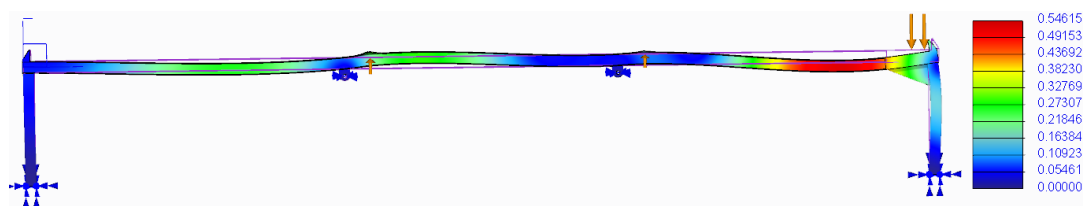


Figure 4.29: Maximum deflection δ_{max} of lower beam frame, first load case.

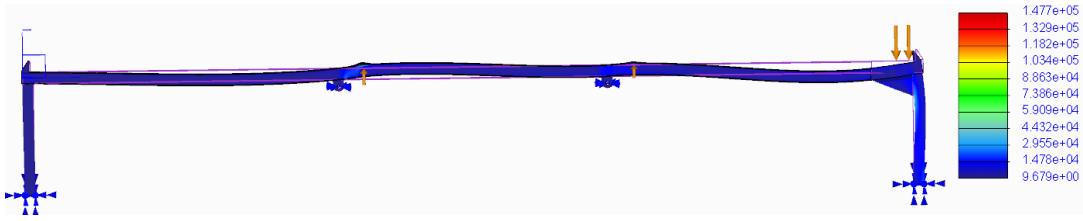


Figure 4.30: Max Von Mises stress $\sigma_{\text{Von Mises}}$ of lower beam frame, first load case.

The boundary conditions applied during the simulations are depicted in all the figures above. The blue arrows in the middle of the structure represent the supports connected to the frame, which are modeled as simply-roller supports under a concentrated in-plane load. These were the same for both the first and second load case, although only shown in the figures above.

The yellow arrows denote the point loads applied to the I-beam in both the positive and negative Y-direction, representing the upper beam frame. As described earlier, the actual load occurs when the upper beam frame is fully extended, hence this simulation has been modeled according to the respective reaction forces which will differ due to the distance to the load.

The reaction forces for the given beam structure were calculated using the principles of static equilibrium according to Figure 4.31.

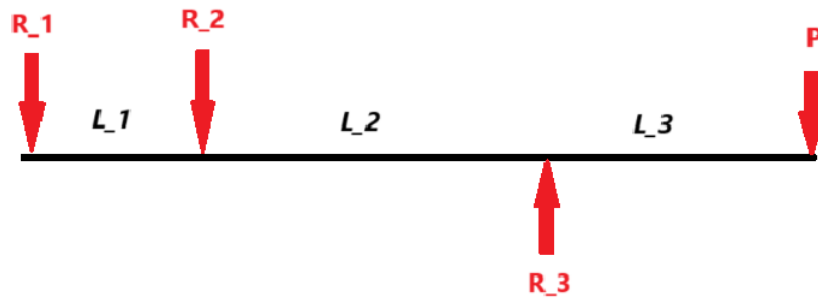


Figure 4.31: Simplified model for calculating the force distribution for the lower beam frame.

The reaction forces for the given beam structure were calculated using the principles of static equilibrium. The equilibrium conditions were defined as follows:

- Sum of vertical forces:

$$R_1 + R_2 - R_3 + P = 0$$

- Sum of moments about point R_1 :

$$(P \cdot (L_1 + L_2 + L_3)) - (R_2 \cdot L_1) - (R_3 \cdot (L_1 + L_2)) = 0$$

- Sum of moments about point R_2 :

$$(P \cdot L_3) - (R_1 \cdot L_1) - (R_3 \cdot L_2) = 0$$

The given parameters for the problem were:

- Applied load: $P = 35 \text{ kN}$
- Distances: $L_1 = 3.635 \text{ m}$, $L_2 = 3.57 \text{ m}$, $L_3 = 4.5 \text{ m}$

By solving the system of equations, the reaction forces were determined to be:

$$R_1 = -17.19 \text{ kN}, \quad R_2 = -9.43 \text{ kN}, \quad R_3 = 61.62 \text{ kN}$$

The negative values for R_1 and R_2 indicate that these reaction forces act downward, and R_3 acts upward. These results align with the physical constraints of the problem and ensure static equilibrium is maintained and were therefore used as input for the first load case simulation.

For the second load case illustrated in Figure 4.32, and Figure 4.33, again including maximum displacement δ_{\max} and the Von Mises stress $\sigma_{\text{Von Mises}}$. The maximum displacement is approximately 1.65 mm, which occurs at the outermost end of the I-beam under full load conditions. The maximum Von Mises stress is calculated to be $1.697 \times 10^5 \text{ kPa}$, equivalent to 169.7 MPa.

Analogous to before, for this load case the design has a SF of approximately 1.47 to 2.09.

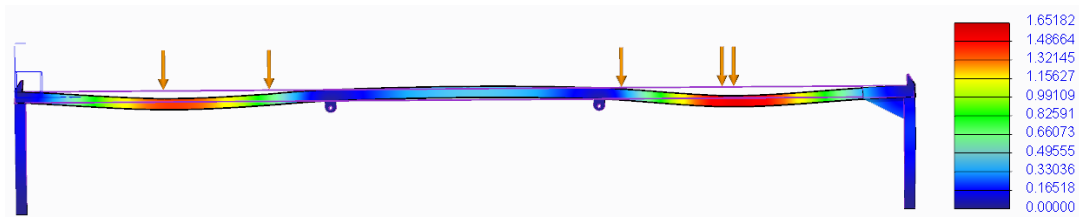


Figure 4.32: Maximum deflection δ_{\max} of lower beam frame, second load case.

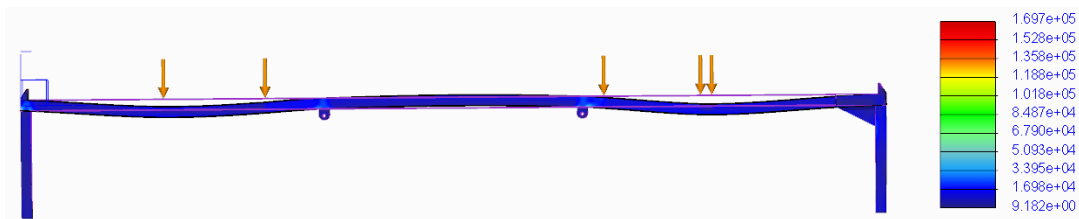


Figure 4.33: Max Von Mises stress $\sigma_{\text{Von Mises}}$ of lower beam frame, second load case.

4.6.3 Final Design Electrical System

The battery swap station will be able to hold a total of 7 batteries. In order for the system to be efficient during a full workday the chargers inside needs to be powerful enough to fully charge all batteries during the runtime of each machine. In order to gain further understanding of how the electrical system would have to be dimensioned, analyzing Volvo CE's current electric portfolio was performed.

The Volvo L90 Electric wheel loader with its 180 kWh battery has an indicative runtime of 4-5 hours. Depending on the use case this number might vary and in order to utilize the battery the most efficiently the state of charge should go between 20-80%. In this context a 'fully charged' battery has 80% SOC. This would result in an approximate runtime of 2.5-3 hours. For an electric articulated hauler, this number should be expected to be on the lower side since these types of machines will transport more mass which consumes more energy, and travel further distances or keep continuous motion more often than wheel loaders.

If the battery swap management system should be able to handle different types of machines as well as different runtimes, dimensioning the chargers after the machines with the biggest batteries or the shortest runtime was deemed a reasonable approach. Assuming the batteries used in the machines are 180kWh and might potentially run for 2.5 hours before needing a swap, this resulted in a requirement of two chargers with charging power of around 180kW each.

Using this level of charging power would result in one battery being charged from 20% to 80% in approximately 0.6 hours and since there will be two chargers it means 2 batteries takes 0.6 hours to be charged. If all seven batteries are fully depleted it would take 2.6 hours to fully charge the whole BSMS. As a result of this the recommended amount of machines the BSMS can support if 6 machines if the runtime is assumed to be 2.5 hours in each machine.

As mentioned previously, different machines have different runtime and energy consumption. This means the battery swaps might happen during different times during a workday, not just every 2.5 hours. To give an example of how it would look like the following charging schedule shows how three wheel loaders and three articulated haulers using the same BSMS could look like.

The workday is assumed to be 8 AM to 5 PM with a break between 12-1 AM. In this schedule the assumption is made that the articulated haulers have a runtime of 2.5 hours and the wheel loaders 3 hours. In the morning all machines are fully charged or all machines gets a battery swap in order to start the day with full capacity. At 10:30 AM all articulated haulers get their batteries swapped. Then at 11 AM all the wheel loaders gets their batteries swapped. A break is assumed to be 12 AM - 1 PM which means at 2 PM the articulated haulers needs their second swap. Then at 3 PM the wheel loaders get their second swap. Before the end of the workday at 4:30 PM the articulated haulers gets their third swap and final swap of the day. At 5 PM the wheel loaders could get a preventative swap in order to be fully charged

for the next working day.

4.7 Selection of Miscellaneous Components

The choice between hydraulic and electric systems for various movements in the battery swap management system was based on technical feasibility, performance requirements, and practical constraints.

For lifting the lower frame, hydraulic systems were chosen over electric actuators due to the significant weight involved. As hydraulics provide superior load-bearing capabilities and generate the required force effectively, making them the optimal solution for this heavy-duty application.

Similarly, supporting hydraulic pistons were selected for stabilizing the station during operation as well as lifting the station itself of the trailer. These pistons handle substantial loads, and as previously explained, the high force output of hydraulic systems ensures reliable and stable performance. Hydraulics were also chosen for translational and rotational movements required to position the underlying assembly of the trolley to the machine.

For the translational movement of the upper beam frame and the trolley itself, electric motors with gearboxes were selected. This decision was based on equations Equation 2.1 to Equation 2.10 presented in the theory section, and their alignment with the requirements specified in the requirement specifications. These components need to cover greater distances, and electric motors offer high torque, efficiency, and control over extended ranges. Additionally, electric motors with integrated gearboxes consisting of spur gears were the most space efficient solution and in combination with low complexity, these were selected.

Hoists powered by hydraulics were chosen for their superior speed and torque capabilities as the time for lifting the attachment plate is assumed to be critical for reducing the swap time.

For the attachment plate connecting to the batteries, electric actuators were selected. This choice was influenced by the technical challenges of routing hydraulic hoses to this part of the system. Electric actuators simplify the design while meeting the requirements for reliability and functionality. The selection of actuators and hydraulic systems was primarily based on mass calculations performed in Creo, combined with the requirements outlined in the specification.

4.7.1 Bill of Materials

The purpose of the Bill of Materials (BOM) is to provide a comprehensive list of all components used within the BSMS. It serves as a structured inventory, divided into two categories: off-the-shelf components that can be purchased and custom components that need to be designed and manufactured by VCE.

To ensure clarity and organization, the BOM has been structured according to the sub assemblies in the CAD model which was structured according to DFA and DFM as outlined in subsection 4.6.1. Again these sub assemblies include:

- Frame
- Trolley
- Attachment Plate
- Battery Charging Infrastructure
- Trailer and Base plate

The purpose of the BOM is partly to estimate the cost of components giving the possibility to calculate the total cost of the BSMS. The sum of each sub-assembly was calculated in order to get an understanding of the most costly sub-assemblies in the BSMS. As can be seen by Figure 4.34 the charging infrastructure makes up for 47% of the total cost. Another category with a considerable cost is the labor costs for building the BSMS.

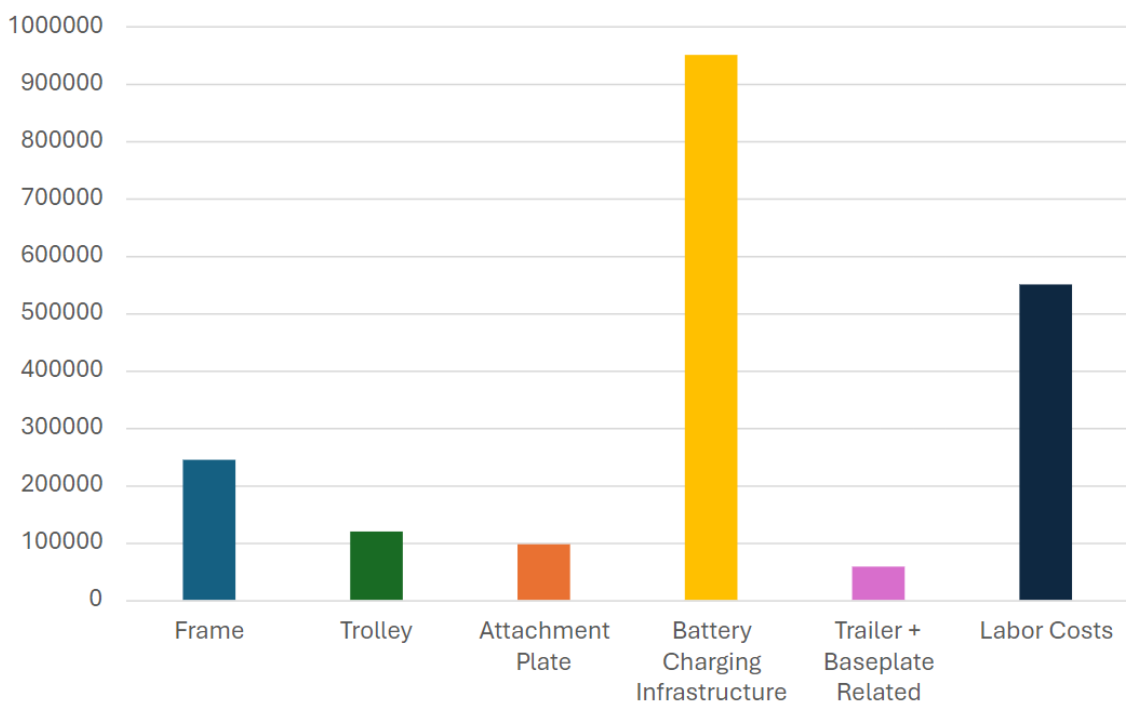


Figure 4.34: Cost diagram of each sub assembly in the BOM.

The complete BOM can be found in Appendix G. For each component listed, all relevant details are included. This encompasses quantities or amounts (or lengths

where applicable), pricing, and suppliers for off-the-shelf parts. For in-house components, the BOM provides an estimated cost based on manufacturing and material requirements.

The BOM not only supports the technical aspects of this development project, but also serves as the underlying data for the commercial assessment presented further in section 4.8. This linkage highlights the importance of the BOM in connecting the technical design with the financial and commercial feasibility.

4.8 Commercial Assessment

To determine the economic aspect of the BSMS a commercial assessment was made. Several factors such as market, pricing, customers and competing technology will be examined further in order to get a detailed overview of how the BSMS can be positioned in the market of current and future construction machinery.

4.8.1 Market Overview

The clean energy sector has been increasing quickly over the last four years and during 2024 reached approximately 2000 Billion USD worldwide [42]. In order for the transportation industry to meet coming emission regulations the need for electric vehicles is large, which in turn means batteries will play a significant role. As for the potential market size Volvo group sold roughly 16,000 construction machines in Europe year 2023 [43]. Looking at Volvo Group's vision for 2030, at least 35% of the vehicles sold should be fully electric[44] in the year 2030. Assuming an annual compound annual growth rate of 4.73% [45], this would indicate Volvo would sell a total of approximately 22,500 vehicles year 2030.

If 35% of these are fully electric that would mean approximately 7900 machines. The majority of these machines will not be made for battery swap. An assumption made is around 10% of these machines are made for battery swap. The amount of BSMS needed to support the machines is directly related to how many vehicles one BSMS can handle. As mentioned previously, one BSMS will be able to support six vehicles. This means around 130 BSMS would be enough to support a fleet of approximately 790 electric vehicles per year.

4.8.2 Pricing and Suppliers

The price of the BSMS will partly determine its competitiveness in the market with electric machines. Even though the initial investment for electric machinery is higher together with a BSMS compared to having a ICE driven machines, in the long run it will be lower cost for the customer to operate the electric machines in combination with the BSMS without losing runtime compared to ICE machines.

Many of the components inside the BSMS are off-shelf sold by external suppliers. The reasoning behind this is to keep the cost of manufacturing down since the development is in a very early phase and developing components that can be bought would not be very cost effective at this stage. Another reason to use existing components is the possibility of changing or upgrading. This could be due to different needs such as battery size used in the BSMS or simply because a function inside the BSMS needs to be modified. Further detailed overview of the components inside the BSMS can be found in the BOM.

One of the larger costs in the BSMS will be assembly costs. This is due to the many parts that need welding, routing cabling and hydraulics but also aligning and

adjusting the moving parts of the system. Some of the components inside the BSMS are also inherently more costly such as the battery chargers and control systems. Another aspect that needs to be taken into consideration is when the BSMS will be industrialized, upfront cost of components can be expected to be lower due do established supplier contracts, higher volume and optimization in the production. Using the supplier network of Volvo Group can be assumed to lower many of the costs that exist in the BOM.

Since the BSMS will act as a supporting function to electric machines, there are other factors which might affect the end price. When selling the electric machines in combination with the BSMS, pricing might be adjusted in order to create attractive offers. Other aspects is the ownership of such system, leasing or renting a BSMS with the necessary batteries might be another way to finance it to customers.

4.8.3 Total Cost of Ownership ICE vs. Electric Fleet

In order to derive a selling price for the BSMS, and ultimately investigate the business case for VCE, an analysis regarding the Total Cost of Ownership (TCO) was conducted. This includes comparing metrics related to the initial investment cost, operating costs, maintenance costs, and finally the residual value.

In order for the BSMS to be commercially viable, the TCO for investing in an electric fleet of machines should preferably be equal, or lower compared to the TCO of investing in a fleet consisting of ICE machines. Therefore, a scenario was created comparing the two systems with the following input data shown in Table 4.1. An important note regarding this analysis is that it does not consider local governmental policies such as excise duties, back tax, fluctuation in fuel and electricity prices, as well as tariffs.

Table 4.1: Parameters with corresponding data for each fleet.

Parameters	Unit	Diesel Fleet	Electric Fleet
Price / machine	SEK	7 000 000	10 500 000
Number of machines	N/A	6	6
BSMS cost	SEK	N/A	0
Residual Value factor Machine	0-1	0,50	0,40
Residual Value factor Swap Station	0-1	N/A	0,50
Residual Value / Machine	SEK	3 500 000,00	4 200 000,00
Residual Value Swap Station	SEK	N/A	0,00
Maintenance cost	SEK/machine/year	96 830	67 781
Electricity cost	SEK/kWh	N/A	1,00
Diesel cost	SEK/l	12,00	N/A
Electricity consumption	kWh/h	N/A	84,00
Diesel consumption	l/h	30,30	N/A
Annual usage	h/year	2 080	2 080

The scenario was based on a construction site consisting of six machines over a period of five years. A fleet of six machines was chosen, as this results in the highest use capacity for the BSMS, which is in accordance to the results presented in

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subsection 4.6.3. The initial investment costs for the electric machines compared to ICE powered equivalent is assumed to be 1.5 times [7]. The investment cost of the BSMS is initially assumed to be zero, as it will be reflected as a cost difference in the cumulative TCO comparison year five.

Looking at the residual value factors, it's assumed to be slightly lower for the electric machine as batteries and electric driveline technology is expected to have advanced to a greater extent potentially making older technology more obsolete [7]. Due to the nature of electric machinery, the maintenance costs are 30% lower compared to the equivalent ICE machines [46]. Regarding fuel consumption, it's assumed to be 30.3 l/h for the ICE machine [47]. The energy consumption for the electric machine assumed to be 84kW according to internal information from CPAC together with the cost of diesel and electricity[7]. Finally, the annual usage is based on 40 hours of work per week times 52 weeks, resulting in an annual usage of 2080h.

Figure 4.35 below illustrates the annual costs for the scenario with the assumption that the initial investment is evenly spread over the period of five years in the form of a write-off. The figure shows that the initial cost for an electric fleet is 1.5 more expensive compared to an ICE based fleet as explained above. However, for the ICE based fleet, the annual operating and maintenance costs are around 4.3 and 1.4 more expensive respectively compared to the electric fleet.

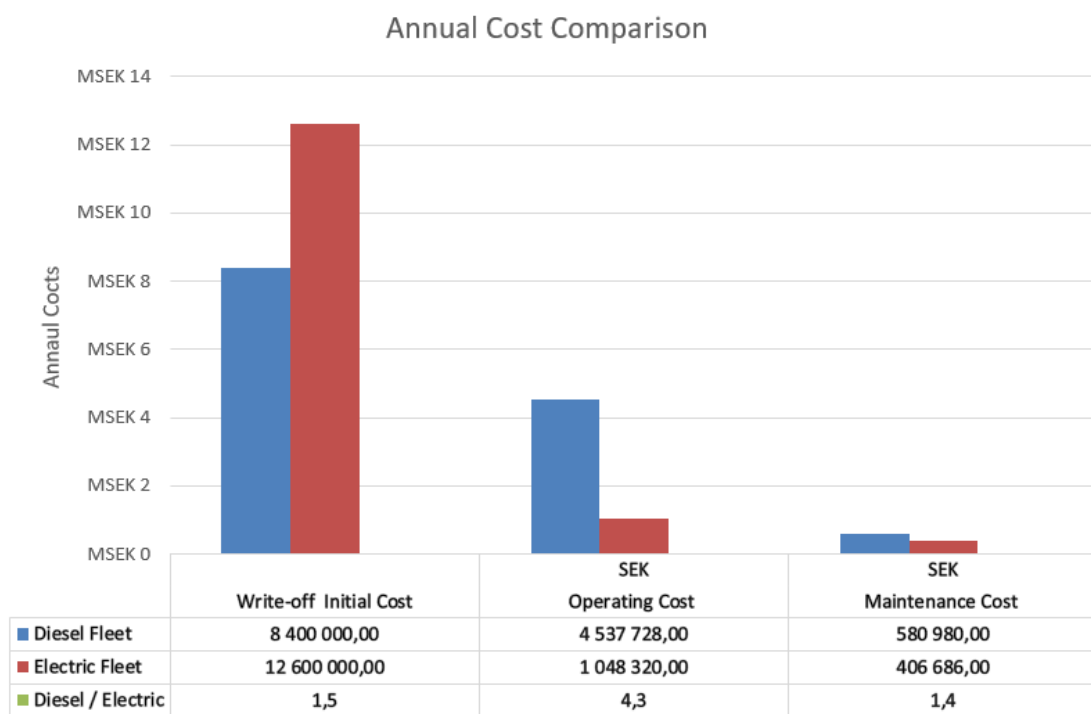


Figure 4.35: Cost comparison Year 0 for each system.

Finally, the total cumulative annual costs for year five are shown in Figure 4.36 below resulting in the final TCO. At this point in time, both fleets benefit from a revenue due to the residual value from the machines, i.e. both fleets are sold.

This is based on the assumption that the machines are no longer useful or that the lease term has expired. The difference in costs represents the residual value of the BSMS. As the residual value factor as shown in Table 4.1 is assumed to be 50%. The maximum sale price of the BSMS is therefore calculated to be 3,037,020 SEK to achieve an equal TCO based on the input parameters.

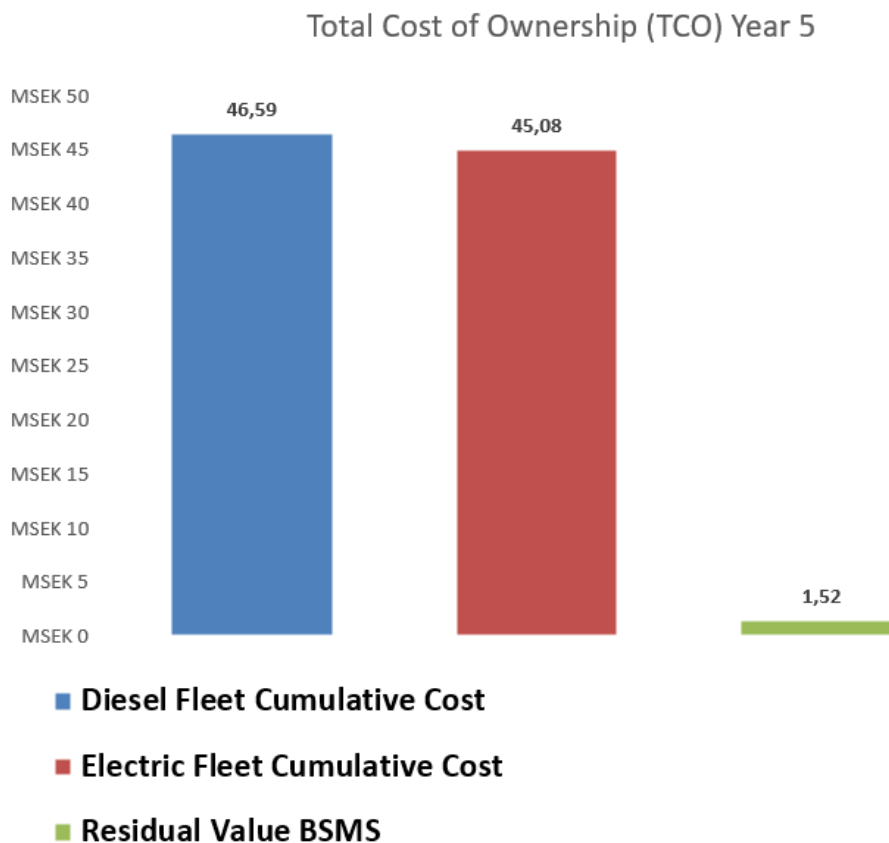


Figure 4.36: TCO Year 5 with the residual value of the BSMS.

4.8.4 Net Present Value

To determine the value of the investment needed into the BSMS the difference between the present value of cash inflows and outflows over time is calculated. Based on the selling price calculated in the previous section and parameters such as development, manufacturing, production and service costs this gives an overview of the Net Present Value (NPV) after a set period of time.

4.8.4.1 NPV Calculation

The calculation of the NPV was based on several different values stemmed from both internal and external information. Using calculated costs such as manufacturing cost from the BOM, sale price from the fleet TCO analysis, internal information from CPAC Systems regarding development costs and production cost, an detailed

approximation of the NPV could be performed.

Sales volume was assumed to be in relation to the market overview section of approximately 130 BSMS sold per year. Another assumption made was a decrease in the retail price since lowering the costs after a certain period was deemed likely in order to have competitive pricing in the future. The product development period is spread over a four-year period. During the last year production will start with the potential for necessary changes or improvements on early BSMS produced. The table below shows a summary of the values used as inputs for the NPV.

Table 4.2: Financial model inputs NPV Calculation.

Model Inputs	Model Values			
Quarterly Sales Profile, BSMS	20%	25%	25%	30%
Sales Volume Growth, BSMS	5% per year			
Initial Sales Volume, BSMS	25 units/quarter			
Initial Retail Price, BSMS	3,000,000 kr per unit/ quarter			
Retail Price Growth, BSMS	-5% per year			
Product Development	54.0 MSEK over 4 year period			
Equipment and Tooling	10.0 MSEK over 2 year period			
Production Ramp-up	10.0 MSEK over 1.5 year period			
Market Launch	5.0 MSEK			
Marketing and Support	5.0 MSEK			
Production Cost	2,000,000 kr per unit			
Production Overhead	1.0 M/year			

The total time frame for the NPV extends over several years, based on the four years of development with the last year being in combination with production. Then seven years of only production which gives a total time period of 11 years.

As can be seen in Appendix F the net present value for the BSMS is calculated to be 1174.59 Million SEK.

4.8.4.2 Cash Flow Analysis

Using the NPV as the base case it was possible to calculate the cash flow during the same time period. This indicates the break-even point as well as payback time over the time frame. As can be seen in Figure 4.37 the payback time occurs in Q4 year 4, with a corresponding break even point of 70 BSMS sold, which reinforces the NPV as a very strong case with short payback on investments.

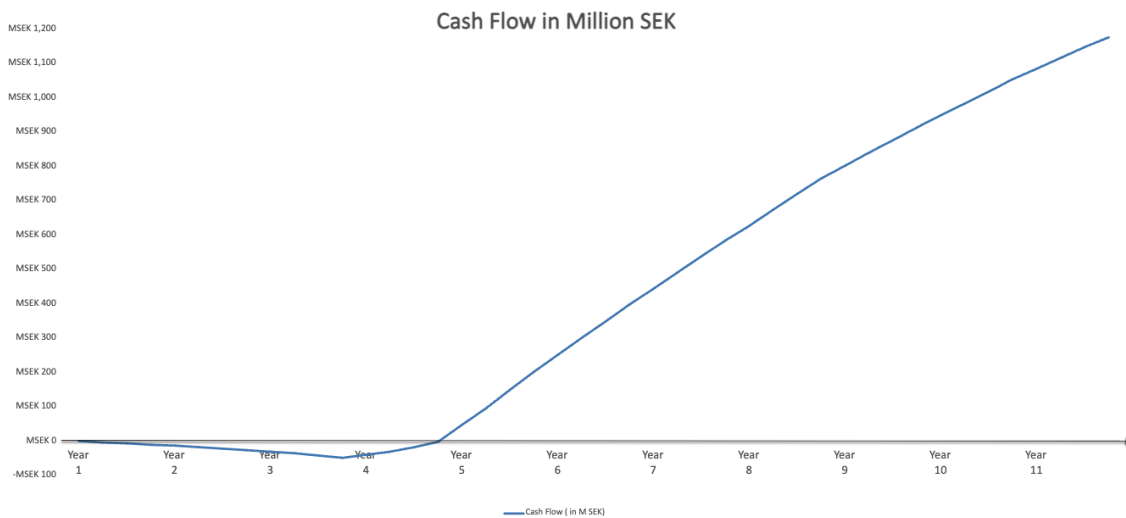


Figure 4.37: NPV Cash Flow in million SEK.

4.8.4.3 Sensitivity Analysis

To get an understanding of which aspects of the NPV will affect its value the most a sensitivity analysis was created. The analysis is based on an uncertainty model that considers the worst-case and best-case scenario of the NPV. The base case assumptions was -5% for worst-case and +15% for best-case. This provides the potential minimum and maximum values for each parameter. For instance, if production costs were to increase, the model indicates how much the NPV would be impacted. The purpose of the sensitivity analysis is to show if certain inputs of the NPV would drastically change the outcome thus highlighting those specific parameters. The input for the sensitivity analysis can be seen in table below.

Table 4.3: Input Values Sensitivity Analysis.

Sensitivity Analysis Data		Base NPV	Million SEK					
		1174.59	Worst-Case Analysis		Best-Case Analysis			
Model Parameter	Value	Base-Case	Value	NPV, M SEK	% Δ NPV	Value	NPV, M SEK	% Δ NPV
Product development	54M SEK 4 years		62.1M	1169.6	-0.4%	51.3M	1177.3	0.2%
Equipment and tooling	10M SEK 2 year		\$5M	1173.1	-0.1%	\$3M	1175.1	0.0%
Production ramp-up	10M SEK		\$2.5M	1173.1	-0.1%	\$1.5M	1175.1	0.0%
Market launch	5M SEK		\$15M	1174.4	0.0%	\$8M	1175.4	0.1%
Marketing and support	5M SEK		\$6M	1173.8	-0.1%	\$4M	1174.8	0.0%
Production direct cost, machines	2000000 SEK/unit		2,300,000.00 kr	932.6	-20.6%	1,900,000.00 kr	1255.2	6.9%
Initial sales volume, machines	100 units/year		95	1112.0	-5.3%	115	1351.0	15.0%
Sales volume growth, machines	5%/year		1115.9	1115.9	-5.0%	1350.8	1350.8	15.0%
Initial retail sale price, machines	3000000 SEK/unit		2,850,000.00 kr	1030.9	-12.2%	3,750,000 kr	1893.0	61.2%
Retail price growth, machines	5% - /year		-7	1022.0	-13.0%	0	1603.0	36.5%

For the sensitivity analysis to become more visually comprehensible a tornado diagram was created. This is stacked showing the parameters affecting the NPV the most. As can be seen in Figure 4.38 below, the 'initial retail price' is the parameter affecting the value of the NPV. This is because of the potential price range of the

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BSMS, since it is based on making the TCO between electric and ICE powered machines as close as possible in order for VCE to have as high as possible margin in the BSMS. This results in the BSMS acting somewhat as a buffer depending on the profits set out to be made.

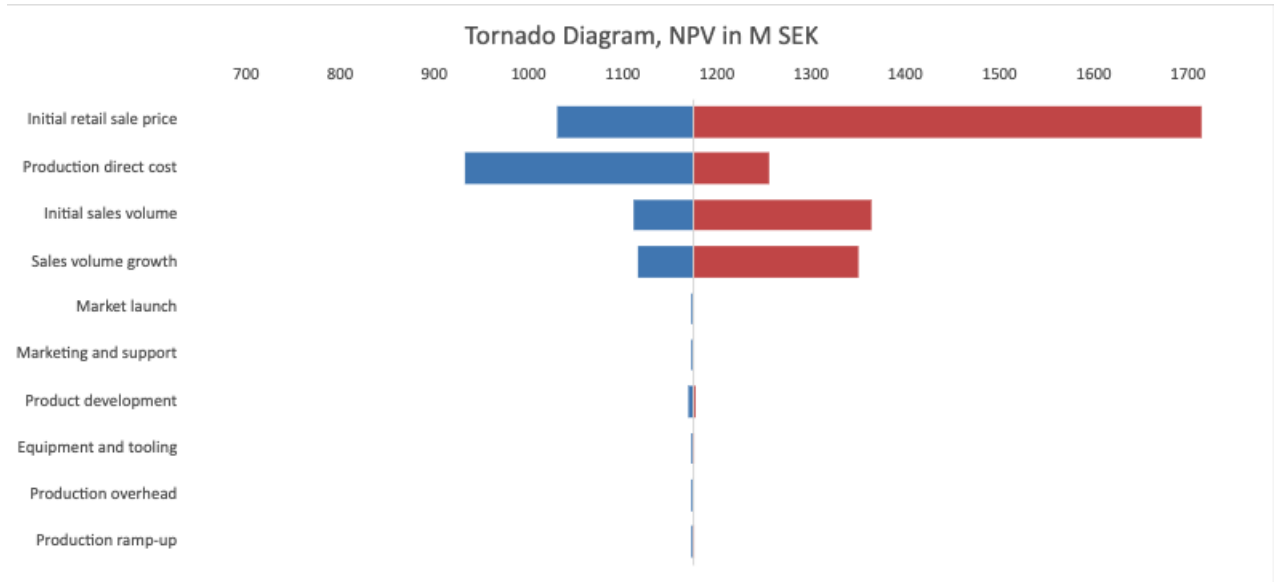


Figure 4.38: Tornado Diagram of the sensitivity analysis.

4.8.5 Financial Conclusion

The financial evaluation of the BSMS demonstrates a compelling case for its development and market introduction, with strong potential for both economic and environmental benefits. Despite the higher initial investment associated with electric machinery combined with the BSMS, the TCO analysis reveals that operational cost advantages make this system more competitive in the long term compared to ICE machines.

Lower maintenance and energy costs play a significant role in achieving these savings. Moreover, the global transition toward sustainability and reduced emissions further strengthens the case for electric machinery as mentioned in subsection 4.8.1.

From a cost management perspective, the BSMS leverages off-the-shelf components and Volvo Group's extensive supplier network, which helps to minimize manufacturing and assembly costs. This approach reduces financial risk during the early development stages and provides flexibility for future upgrades or component replacements.

Financial metrics further underscore the strength of the BSMS business case. The NPV analysis, which calculates a return of 1,174.59 million SEK over an 11-year time frame, demonstrates the financial viability of the project. With a break-even point reached in the Q3 of year three and full payback achieved by the Q4 of year

four, the BSMS demonstrates a strong return on investment within a short time-frame.

5

Discussion

This chapter will go further into the findings and analyze the results in relation to the research questions. Further evaluations and potential limitations will also be discussed in order to deepen certain decisions taken. Further development steps as well as concluding action is also discussed towards the end of the chapter.

5.1 Research questions

RQ1: How can the key customer requirements, including metrics such as performance, speed, cost, and size, be systematically identified, prioritized, and benchmarked to facilitate the development of the battery swap system for VCE?

Several of the requirements on the BSMS are governed by external factors. This not only includes the external dimensions but also what type of components could fit inside. Since the BSMS should be able to be transported to different construction sites, road legality became a crucial requirement. This meant meeting the Swedish Transport Administration Agency requirements for trailers in terms of height, weight, width and length.

These dimensions did in turn affect other parts of the BSMS such as battery capacity since there was a limit of how many would fit but also factors such as speed of the system, since moving parts would be constrained to certain spaces thus minimizing the different types of components used for solving the function.

All of these aspects would in turn affect the key customer requirements such as battery swap time. From a customer perspective, the most important aspect is to have as much runtime as possible, which means the battery swap needs to be performed as quickly as possible.

Benchmarking the metrics was made in relation to market analysis. Currently, there is no direct competition to this type of system. Since this project focused on construction machinery most of the patents found were for a completely different vehicle category. It is however possible to compare performance-related numbers such as battery swap time, battery capacity, or transportability where the developed BSMS is superior in almost all metrics.

The BSMS has also been developed in such way future requirements will be able to be implemented without massive changes to the BSMS. Battery size, battery interfaces or extra functions have been taken into consideration in order to keep the BSMS as flexible as possible for future-proofing and competitiveness.

RQ2: What are the components needed in order for the battery swap system to work and what are their relative importance for the POC?

The main component is the bottom frame. This is based on the same type of bottom plate as a container chassis, which allows the BSMS to be transported using any type of standardized truck trailer. The upper part of the BSMS has the very important feature of raising and lowering, which means the BSMS will be able to be transported on a public road as well as perform battery swaps as quickly as possible. This function became very important for the overall functionality and legality of the BSMS.

The most important and unique part of the BSMS is the 'trolley and attachment plate'. This subassembly is dependent on nearly all other components of the BSMS, but to reduce the swap time the capability it offers is critical to the system. This is due to the ability to lift and control two batteries simultaneously as well as individually.

This solution enables the swap time to be drastically reduced compared to existing solutions on the market today as the machine doesn't have to wait for the system move batteries in and out of the BSMS. From a functionality perspective, this trolley is as necessary as some of the other components, the upper frame moving in and out is very much needed as well since the batteries will not be able to reach a machine standing next to the BSMS otherwise.

In terms of the overall performance-increasing component, the 'trolley and attachment plate' is the utmost important component in the whole BSMS. It is also packed with many advanced components allowing it to have the possibility of rotating, moving longitudinally and transversely as well as lifting batteries up and down.

More components inside the BSMS help support many of the functions. These components include power converter, chargers, control unit, and hydraulic pumps. These all fulfill important functions in making sure other systems will work as expected. Individually these are not as important as the bigger function-solving components as mentioned previously, but combined the supporting components also play a pivotal role in the BSMS.

In terms of subsystems, hydraulics have a very important role since many of the systems are driven by hydraulics. Not only to drive pumps for the winches, rotator plate, or sideways adjustment of the attachment plate but especially to raise and lower the top part of the BSMS which is a crucial part of its function.

RQ3: How can the system be deployed on construction sites with various sizes and energy requirements?

The BSMS has been developed to support a maximum of six machines. However, this can vary depending on the battery capacity and the physical size of each battery. The most flexible way of adjusting to a construction site with less machines is simply by not putting as many batteries inside the BSMS, if only four machines are operating then only four batteries would be placed inside the BSMS.

This will however affect TCO, since the cost of the BSMS itself would be the same regardless of how many batteries are placed inside it and it means it would not be utilized as efficiently as possible. On the other hand, if the four machines have a shorter runtime than the Volvo L90 used for dimensioning the BSMS, the need for more battery swaps is solved by simply using all batteries possible in the BSMS. The charging times for each battery are always the same regardless of how many batteries are placed inside, it is only the total charging time that changes depending on how many batteries are placed inside the BSMS.

If there are more than six machines on the same construction site, using a second BSMS is the easiest way to handle the extra need. This does however yet again depend on the runtime for each machine. One BSMS could support more than six machines if the runtimes are longer for some of the machines. If half of the machines has double the runtime as the other half then two battery swaps would be made for half of the machines in the same time frame as one battery swap for the other half. In conclusion, in order to give specific answers each site would be different. Depending on how many machines, which type of machines and work conditions (energy usage) for each machine the answer would be different. The most important takeaway is that the BSMS has the possibility of adapting in relation to the number of, and type of machines used on a construction site.

RQ4: How does the financial viability of the new product, considering profitability, required capital investment, market conditions, and projected customer demand, influence business decisions?

Looking at the NPV the value is positive after five years. The parameter affecting the NPV the most is the retail price because of the relatively large margin. Depending on how the BSMS will be distributed and sold in order to support the electric machines at VCE, this price could potentially vary to some extent. The calculation of the price is based on the earlier findings in the subsection 4.8.3, where the difference in total running costs between the ICE and electric machinery was deemed as base for the BSMS price. This would give Volvo the largest possible margin on the BSMS while the customer would still have the same running costs even though two different propulsion systems are compared.

The capital investment for the project is relatively low since the payback time is within five years, barely one year after production has begun. This will continue with large profits each year thereafter resulting in a NPV of 1174.59 Million SEK year 11.

In terms of market conditions and customer demand, the BSMS has the possibility of functioning with different types of machines within VCE. With some modifications, it could also work with other manufacturers. The distribution inside the BSMS can be changed depending on the battery size and shape if other types of batteries need to be used. This all means the BSMS is ready to be adapted to market changes which could mean changed battery capacity in terms of physical size, but also if needed to serve a larger variety of machines more than just Volvo, the BSMS could be rebuilt for non-Volvo machines.

5.2 Detailed Design

Parts of the detailed design missing in this project for the BSMS to be fully functional include many smaller components such as control units and cabling. This is both for the electronic and hydraulic components throughout the BSMS. Since many parts moving have cabling it means the cabling needs to be able to move as well. For hydraulics, the idea was to place a winding mechanism above the battery chargers which would feed cabling to the upper frame when it extends outside the BSMS.

For electrical cabling using cable carriers would be a solution taking up small space but still being able to extend over longer distances. In the frontmost part of the BSMS, space was made for electronics to be placed as well as a hydraulic reservoir for the hydraulic system. Mounting and placement of necessary boxes have not yet been done. Another part that was not fully finished was the covering of the BSMS. There needs to be protection against outside elements with the possibility of extending or contracting when the BSMS is raised or lowered.

The analysis of the FEM also shows room for improvement, more specifically with respect to the safety factor. The highest stress in both simulations appears as stress concentrations, in this case where there are other components interacting with the beams. By refining these areas, the highest stress that occurs would most likely decrease, resulting in a higher safety factor.

Additionally, more load bearing components could have been analyzed, but due to the time frame this was not achievable. However, as most components have been sourced as off the shelf components, data sheets regarding each component have been analyzed and used as a baseline for dimensioning for the load cases.

5.2.1 Further Development Aspects

A potential development aspect is the possibility of not having to raise and lower the upper part of the BSMS. Since this function is directly related to the total height not exceeding 4.5m to be able to drive on the public road network, an alternative solution is to use a lower trailer. This would give the BSMS a permanent height of 4.5m and no need for the hydraulic system and appurtenant beams used for raising

and lowering. However, the main downside using a lower trailer is the need to build custom trailers just for this application, thus losing parts of the flexibility with a standard trailer. If the trailer is permanently integrated into the BSMS it would also mean the trailer would only be in use when the BSMS is being moved, as compared to a standard trailer which could be used for other task when not transporting a BSMS.

The cost of building such trailer and not using it would mean having assets not generating any money most of the time. Using a standard truck trailer as efficiently as possible means moving it around and doing different tasks during the time the BSMS is operating. As mentioned in previous section several smaller components needs to be designed and placed inside the BSMS such as control units and cabling. Covering also needs to be attached on the outside of the BSMS which can collapse and extend if it is in the raised or lowered position.

6

Conclusion

This chapter provides a summary of the thesis findings, answers to the research questions, and reflects on the implications of a utilizing a BSMS for the electrification of construction machinery. It also discusses the limitations of the study, suggests directions for future work, and concludes with the broader impact of the proposed system on the industry.

6.1 Summary of Key Findings

This thesis aimed to develop a conceptual semi-automatic BSMS for electric construction machinery, solely articulated haulers and wheel loaders, addressing operational challenges associated with electrification. By systematically identifying customer needs and leveraging the framework from Ulrich & Eppinger's product development process, a comprehensive virtual POC was developed. The final design incorporates the necessary components to enable fast, safe, and efficient battery swaps. The concept is projected to significantly increase operational time compared to traditional charging methods, thus enhancing the operational feasibility of electric vehicles in construction settings.

6.2 Research Questions Answered

RQ1: How can the key customer requirements, including metrics such as performance, speed, cost, and size, be systematically identified, prioritized, and benchmarked to facilitate the development of the battery swap system for VCE?

Customer requirements, including metrics such as performance, speed, cost, and size, were identified through literature studies, stakeholder analysis, and benchmarking competitive products. Many of these requirements had already been established by previous research conducted at VCE and CPAC Systems, however their relative importance for the POC were thoroughly discussed and compared thorough meetings with both the involved stakeholders as well within the development team. The requirements were later on consolidated and continuously refined into a requirement specification which heavily influenced the system's design and final specifications.

RQ2: What are the components needed in order for the battery swap system to work, and what are their relative importance for the POC?

The development of the BSMS began with identifying the key functionalities required for the system. This was achieved through the creation of a functional model, which allowed the system to be broken down into smaller sub-functions and their corresponding solutions. Key components, such as mechanical structures, electrical systems, positioning systems, and connectors, were developed or sourced, and subsequently integrated into the virtual POC.

To ensure the technical and economical feasibility of the system, various solutions were proposed for each sub-function and analyzed through methodologies like morphological matrices, Pugh matrices, and Kesselring matrices. This method facilitated a structured evaluation and selection of the most suitable concepts. By following this iterative process, the relative importance and interaction of the components were thoroughly assessed, enabling final design of the POC to meet the various demands and wishes in the requirement specification.

RQ3: How can the system be deployed on construction sites with various sizes and energy requirements?

The BSMS demonstrates significant adaptability to varying operational demands across diverse construction site conditions. Although designed to support a maximum of six machines, the system's flexibility allows for reduced utilization when fewer machines are in operation, achieved by adjusting the number of batteries housed within the BSMS.

For construction sites with more than six machines, the deployment of a second BSMS or optimization of machine runtime schedules can address increased energy demands. Furthermore, the BSMS is designed to be placed on any standard trailer capable of transporting regular containers which enhances its portability and facilitates transportation between sites. This feature ensures that the system is well-suited for dynamic and geographically dispersed construction projects.

Additionally, the BSMS can function independently of grid power, making it a viable solution for remote locations where access to the electrical grid is unavailable by utilizing one of its own batteries to power the swap operations. In this case however, the BSMS would need to be transported to a location with grid access after all batteries have been swapped.

RQ4: How does the financial viability of the new product, considering profitability, required capital investment, market conditions, and projected customer demand, influence business decisions?

The financial viability of the BSMS was evaluated by first determining the maximum acceptable sales price through a TCO analysis. This analysis compared a

traditional ICE-based fleet to an electric fleet of machinery, with the BSMS as a necessary component to minimize downtime and make the two scenarios operationally comparable. The TCO analysis considered key parameters such as initial investment costs, operational efficiency, and long-term maintenance requirements, providing a comprehensive view of the cost dynamics involved in both fleet types.

The results of the TCO analysis were then utilized as input for the NPV calculation, which assessed the profitability and financial feasibility of the BSMS over its development, market launch and projected sales. The NPV analysis accounted for variables such as capital investment, projected cash flows, market conditions, and customer demand to provide an accurate measure of the system's long-term economic performance.

This approach ensured that the financial assessment had a high level of detail and aligned with industry expectations. The analysis demonstrated that the BSMS offers a cost-effective and sustainable solution compared to traditional ICE fleets. Moreover, it highlighted the BSMS's potential to enhance the economic viability of electrified machinery, thereby supporting the broader industry shift toward sustainability and regulatory compliance.

6.3 Implications for Industry

The BSMS represents a solution for minimizing operational downtime due to charging in electric construction machinery, addressing one of the key barriers to the widespread adoption of electrified fleets. Its design ensures that electric machinery can achieve operational efficiency comparable to ICE-powered counterparts. By minimizing downtime through quick battery swaps, the BSMS enhances the usability and productivity of electric machines, making them a viable alternative.

Moreover, the BSMS supports the strategic goals of reducing CO₂ emissions and meeting regulatory targets, such as the EU's Green Deal. By offering a solution that combines mobility, modularity, and adaptability, the BSMS addresses not only current challenges but also positions Volvo Group and its affiliates to lead the transition to sustainable construction.

6.4 Closing Remarks

This thesis underscores the critical role of a BSMS in supporting the electrification of construction machinery fleets. By addressing downtime due to charging, which is a key operational challenge, the system ensures that electric machinery can deliver performance levels comparable to ICE-powered fleets. The virtual POC provides a robust foundation for further development and innovation, supporting the industry's transition to sustainable and efficient construction operations while meeting regulatory and customer expectations.

Bibliography

1. Volvo Group. *The road to net-zero 2024*. <https://www.volvogroup.com/en/sustainable-transportation/responsible-business/climate.html#:~:text=Our%20ambition%20is%20to%20reach%20net%2Dzero%20value%20chain%20emissions,should%20have%20net%2Dzero%20emissions..>
2. *European climate law: Council and Parliament reach provisional agreement* May 2021. <https://www.consilium.europa.eu/en/press/press-releases/2021/05/05/european-climate-law-council-and-parliament-reach-provisional-agreement/>.
3. Fjeldal, P. & Borgli, E. B. *Handlingsplan for direkte klimagassutslipp fra utbyggingsprosjekter: 55 % reduksjon 2020–2030* Report No. 949. 2023. <https://www.vegvesen.no>.
4. Hayes, M. Volvo CE unveils mobile charging unit for heavy equipment. <https://www.constructionbriefing.com/news/volvo-ce-unveils-mobile-charging-unit-for-heavy-equipment/8031628.article> (Sept. 2023).
5. *Eldrivna entreprenadmaskiner och utrustning I Volvo CE* <https://www.volvoce.com/sverige/sv-se/products/electric-machines/>.
6. Equipment, V. C. Innovative mobile charging solution from Volvo CE set to transform off-grid work. <https://www.volvoce.com/europe/en/about-us/news/2024/innovative-mobile-charging-solution-from-volvo-ce-set-to-transform-off-grid-work/> (May 2024).
7. Anders Ek. CPAC Internal Project Meeting. 2024.
8. US Department of Energy. *How lithium-ion Batteries Work* 2024. <https://www.energy.gov/science/doe-explainsbatteries#:~:text=To%20accept%20and%20release%20energy,through%20the%20circuit%20and%20electrolyte..>
9. *Introduction to DC/DC Converters* https://www.monolithicpower.com/en/learning/mpscholar/power-electronics/dc-dc-converters/introduction-to-dc-dc-converters?srsId=AfmB0opXp9_NdwdW9WMFKjfd0YFExwnBv218U1QkixqJv0CRPUt
10. *CCS type1 Combo 1 Connector EV Charger DC Fast Charging 150Amp Sae J1772 Plug* <https://www.midacharger.com/ccs-type1-combo-1-connector-ev-charger-dc-fast-charging-150amp-sae-j1772-plug-product/>.
11. Bose, B. K. *Power Electronics and Motor Drives: Advances and Trends* Feb. 2006. https://books.google.se/books?id=ywiBVSny6IC&redir_esc=y.
12. Renesas Electronics Corporation. *What are Brushless DC Motors* 2025. <https://www.renesas.com/en/support/engineer-school/brushless-dc-motor-01-overview>.

13. Orientalmotor. *Basics of Stepper Motors* 2024. <https://www.orientalmotor.com/stepper-motors/technology/stepper-motor-basics.html#:~:text=Stepper%20motors%20convert%20electricity%20into%20turns%20the%20motor%20one%20step..>
14. Velling, A. *Mechanical power transmission* Jan. 2024. <https://fractory.com/mechanical-power-transmission/>.
15. Mägi, M., Melkersson, K. & Evertsson, M. *Maskinelement* (Jan. 2017).
16. Motion, E. *Spur Gear - Eltrex Motion* Jan. 2020. <https://www.eltrex-motion.com/en/spur-gear/>.
17. Oberg, E. & Green, R. E. *Machinery's Handbook* (American Society of Mechanical Engineers, Jan. 1996).
18. Escudier, M. A. & Atkins, T. *A Dictionary of Mechanical Engineering* (July 2019).
19. IQS Directory. *Electric Actuators: Types, Applications and Benefits* 2025. <https://www.iqsdirectory.com/articles/linear-actuator/electric-actuators.html>.
20. Joyce, J. *How a Hydraulic System Works* Jan. 2023. <https://blog.brennaninc.com/how-a-hydraulic-system-works#:~:text=The%20principle%20of%20a%20hydraulic%20system%20is%20based%20on%20Pascal's,a%20piston%20within%20a%20cylinder..>
21. Jack Green, Robson Forensic. *Failures Fundamentals: Hydraulic Systems* 2018. <https://www.robsonforensic.com/articles/hydraulics-expert-witness>.
22. StructX. *Overhanging Beam - Point Load on Beam End* 2025. https://structx.com/Beam_Formulas_026.html.
23. Lemonis, M. *Moment of Inertia of I/H Section* Feb. 2024. <https://calresource.com/moment-of-inertia-doubletee.html>.
24. AZoM. *Structural Steel - S235, S275, S355 Chemical Composition, Mechanical Properties and Common Applications* Apr. 2023. <https://www.azom.com/article.aspx?ArticleID=6022>.
25. Official Journal of the European Union. *Regulation (EU) 2023/1230 of the European Parliament and of the Council of 14 June 2023 on machinery and repealing Directive 2006/42/EC of the European Parliament and of the Council and Council Directive 73/361/EEC (Text with EEA relevance)* June 2023. <https://eur-lex.europa.eu/eli/reg/2023/1230/oj>.
26. Karl T. Ulrich, Steven D. Eppinger and Maria C. Yang. *Product Design and Development* ISBN: 978-1-260-04365-5 (McGraw-Hill Education, 2020).
27. Julian M. Bonde, Adam Mallalieu, Massimo Panarotto, Ola Isaksson, Lars Almefelt, Johan Malmqvist. *Morpheus: The Development and Evaluation of a Software Tool for Morphological Matrices*. <https://www.designsociety.org/publication/45130/Morpheus%3A+The+Development+and+Evaluation+of+a+Software+Tool+for+Morphological+Matrices> (2022).
28. *Choosing the best alternative using the PUGH Matrix Method – Continuous Improvement Toolkit* <https://citoolkit.com/articles/pugh-matrix/>.
29. Sany. *Sany Products* 2024. https://www.sanyglobal.com/product/truck/semi-trailer_tractor/138/.

30. *SANY's first intelligent battery swapping station debuts* <https://trends.nauticexpo.com/sany-group/project-199500-334327.html>.
31. *XCMG's relocatable battery swapping station* <https://etrucks.co.nz/xcmgs-relocatable-battery-swapping-station/>.
32. *First cooperative NEHDT battery swapping station between Foton Motor, Sinochem New Energy commissioned* <https://www.marklines.com/en/news/308531>.
33. *Nio Power Swap Station: does it work?* <https://www.carmagazine.co.uk/car-news/tech/nio-power-swap-station-does-it-work-/>.
34. *Ample's Disruptive EV Charging Solution* <https://www.batterytechonline.com/battery-news/ample-s-disruptive-ev-charging-solution>.
35. *Mobile battery replacement equipment and battery replacement method thereof* <https://worldwide.espacenet.com/patent/search/family/089679520/publication/CN117486105A?q=XCMG%20battery%20swap&queryLang=en%3Ade%3Afr>.
36. *CN113895300A - Mobile truck battery replacing device* <https://worldwide.espacenet.com/patent/search/family/079189676/publication/CN113895300A?q=XCMG%20battery%20swap&queryLang=en%3Ade%3Afr>.
37. *CN116061749A - Mobile battery replacing station* <https://worldwide.espacenet.com/patent/search/family/086178438/publication/CN116061749A?q=battery%20swap%20trailer>.
38. *WO2023173794A1 - INTEGRATED VEHICLE BATTERY SWAP SYSTEM, METHOD AND DEVICE, AND STORAGE MEDIUM* <https://worldwide.espacenet.com/patent/search/family/081774671/publication/WO2023173794A1?q=battery%20swap%20trailer>.
39. *CN216636218U Mobile battery replacing station* <https://worldwide.espacenet.com/patent/search/family/081743992/publication/CN216636218U?q=battery%20swap%20trailer>.
40. *Remorque Porte-Conteneurs (Container) | 3D CAD Model Library | GrabCAD* May 2023. <https://grabcad.com/library/remorque-porte-conteneurs-container-1>.
41. Trafikverket. *Villkor för transportdispenser* Dec. 2024. <https://bransch.trafikverket.se/for-dig-i-branschen/vag/Transportdispens/infor-ansokan/Villkor/>.
42. Agency, I. E. *World Energy Investment 2024* Dec. 2024. <https://www.iea.org/reports/world-energy-investment-2024/overview-and-key-findings>.
43. Volvo, A. *Volvo Annual Report 2023* 2023. <https://www.volvogroup.com/en/news-and-media/events/2024/feb/annual-report-2023.html#:~:text=In%202023%2C%20the%20Group's%20currency,all%5C%20regions%5C%20except%5C%20South%5C%20America..>
44. Volvo, A. *Volvo Annual Report 2022* 2022. <https://www.volvogroup.com/content/dam/volvo-group/markets/master/investors/reports-and-presentations/annual-reports/AB-Volvo-Annual-Report-2022.pdf>.
45. astuteanalytica. *Europe Construction Equipment Market 2024*. <https://www.astuteanalytica.com/industry-report/europe-construction-equipment-market>.

46. *L90 Electric | Electric Machines | Overview* <https://www.volvoce.com/europe/en/products/electric-machines/l90-electric/>.
47. *Fuel efficiency guarantee* <https://www.volvoce.com/united-states/en-us/volvo-services/fuel-efficiency-services/fuel-efficiency-guarantee/>.

A

Requirement Specification

Table A.1: Requirement Specification for the Battery Swap System

Requirement specification					
Authors: Eric Fabricius, Carl Ingemarsson	Created: 12/09/2024				
	Modified: 23/09/2024				
Criteria	Target value	D/W (Demand /Wish)	Weight	Verification method	Reference
Performance					
1.1 Battery swap time (Swap per battery pack)	< 120 s	D		Simulation	CPAC Systems
1.2 Battery pack capacity (Amount of battery packs stored in the system)	6 pcs	D		Power calculation	Product planning
1.3 Setup time (time to get swap station ready for use)	< 1h	W		Simulation	Product Planning
1.4 Operating time (Dependent on grid availability, charging the battery packs)	8h	D	3	Testing	VCE CE
1.5 Island mode (Power the swapping station without connection to the grid)	1 full working day	W		Simulation	Product Planning
1.6 Expandability (possibility of combining swap stations)	30 battery packs	W	4	Simulation	Product Planning

A. Requirement Specification

1.7 Bi-directional flow (batteries will be removed and installed within very short time span)		D		Simulation	Product Planning
Lifespan					
2.1 Endurance (battery swaps)	> 23500 cycles (10 years, 10 swaps/working day)	D		Fatigue Test	VCE
Size					
3.1 Total Volume	<140 m ³	D		Calculating CAD-model	Product planning
3.2 Maximum Length	<16.2 m	D	5	Calculating CAD-model	Product planning
3.3 Maximum Width	<2.5 m	D	5	Calculating CAD-model	Product planning
Mass					
4.1 Maximum weight	30 tons	W		Calculating CAD-model	Product planning
Safety					
5.1 Fire Suppression System		W	4	None / CAD Model	NFPA (2023). NFPA 866 Standard for the Installation of Stationary Energy Storage Systems
5.2 Emergency shutdown buttons	Electrical circuit disconnect	D		CAD Model	Standard for shutdown procedure
5.3 Electrical Protection for machines		D		Rules and legislation	VCE
5.4 Electrical Protection for workers		D		Rules and legislation	ISO standards

5.5 Machine visibility should fulfil ISO 5006		D		Simulation	VCE
Distribution					
6.1 Ease of transportation		D		Testing	VCE
6.2 Attachment points for transportation	Standardized attachment point	D		CAD design	Product Planning
Operations					
6.1 Automated charging of battery packs		D	4	Testing	VCE & customers
6.2 Machine helps with the swap		W	3		

B

Functional Model



Elimination Matrix

Battery Swap Station Elimination Matrix																
Created by: Eric Fabricius and Carl Ingemarsson								Date: 03.10.2024								
								Modified: 29.10.2024								
								+ Yes		+ Keep solution						
								- No		- Eliminate solution						
Name	Combination of sub-solutions						Elimination Criteria				Comments	DECISION				
	Un/Load Batteries	Minimize Swap Time	Transport Batteries to Charging Location	Store Batteries in Swap Station	Enable interoperability across diverse battery interfaces	Provide Mobility	Battery swap time	Battery Pack Capacity	Bi-directional flow	Minimize risk of collision with			Take up as little space as possible	Weight less than 30 tons	Max Width < 2.5m	Feasible technically and fits into all construction sites
Solution 2797	Conveyor Belt	Vertical Ferris Wheel	Gantry	Guide Rails	Manual Cable Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2798	Conveyor Belt	Vertical Ferris Wheel	Gantry	Guide Rails	Modular Location of Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2799	Conveyor Belt	Vertical Ferris Wheel	Gantry	Clamping Holders	Manual Cable Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2800	Conveyor Belt	Vertical Ferris Wheel	Gantry	Clamping Holders	Modular Location of Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2801	Conveyor Belt	Vertical Ferris Wheel	Gantry	Stackable Trays	Manual Cable Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2802	Conveyor Belt	Vertical Ferris Wheel	Gantry	Stackable Trays	Modular Location of Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2803	Conveyor Belt	Horizontal Rotating Bin	Gantry	Guide Rails	Manual Cable Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2804	Conveyor Belt	Horizontal Rotating Bin	Gantry	Guide Rails	Modular Location of Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2805	Conveyor Belt	Horizontal Rotating Bin	Gantry	Clamping Holders	Manual Cable Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2806	Conveyor Belt	Horizontal Rotating Bin	Gantry	Clamping Holders	Modular Location of Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2807	Conveyor Belt	Horizontal Rotating Bin	Gantry	Stackable Trays	Manual Cable Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2808	Conveyor Belt	Horizontal Rotating Bin	Gantry	Stackable Trays	Modular Location of Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2809	XY Table	Vertical Ferris Wheel	Gantry	Guide Rails	Manual Cable Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2810	XY Table	Vertical Ferris Wheel	Gantry	Guide Rails	Modular Location of Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2811	XY Table	Vertical Ferris Wheel	Gantry	Clamping Holders	Manual Cable Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2812	XY Table	Vertical Ferris Wheel	Gantry	Clamping Holders	Modular Location of Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2813	XY Table	Vertical Ferris Wheel	Gantry	Stackable Trays	Manual Cable Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2814	XY Table	Vertical Ferris Wheel	Gantry	Stackable Trays	Modular Location of Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2815	XY Table	Horizontal Rotating Bin	Gantry	Guide Rails	Manual Cable Connector	Trailer	+	+	+	+	+	+	+	-	Two different solutions for load	+
Solution 2816	XY Table	Horizontal Rotating Bin	Gantry	Guide Rails	Modular Location of Connector	Trailer	+	+	+	+	+	+	+	-	Financial feasibility	-
Solution 2817	XY Table	Horizontal Rotating Bin	Gantry	Clamping Holders	Manual Cable Connector	Trailer	+	+	+	+	+	+	+	-	Two different solutions for load	+
Solution 2818	XY Table	Horizontal Rotating Bin	Gantry	Clamping Holders	Modular Location of Connector	Trailer	+	+	+	+	+	+	-	+	Financial feasibility	-
Solution 2819	XY Table	Horizontal Rotating Bin	Gantry	Stackable Trays	Manual Cable Connector	Trailer	+	+	+	+	+	+	-	+	Technical feasibility	-
Solution 2820	XY Table	Horizontal Rotating Bin	Gantry	Stackable Trays	Modular Location of Connector	Trailer	+	+	+	+	+	+	-	+	Technical feasibility	-
Solution 2821	Rollers	Vertical Ferris Wheel	Gantry	Guide Rails	Manual Cable Connector	Trailer	+	+	-	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2822	Rollers	Vertical Ferris Wheel	Gantry	Guide Rails	Modular Location of Connector	Trailer	+	+	-	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2823	Rollers	Vertical Ferris Wheel	Gantry	Clamping Holders	Manual Cable Connector	Trailer	+	+	-	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2824	Rollers	Vertical Ferris Wheel	Gantry	Clamping Holders	Modular Location of Connector	Trailer	+	+	-	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2825	Rollers	Vertical Ferris Wheel	Gantry	Stackable Trays	Manual Cable Connector	Trailer	+	+	-	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2826	Rollers	Vertical Ferris Wheel	Gantry	Stackable Trays	Modular Location of Connector	Trailer	+	+	-	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2827	Rollers	Horizontal Rotating Bin	Gantry	Guide Rails	Manual Cable Connector	Trailer	+	+	-	+	+	+	-	+	Not bi-directional	-
Solution 2828	Rollers	Horizontal Rotating Bin	Gantry	Guide Rails	Modular Location of Connector	Trailer	+	+	-	+	+	+	-	+	Not bi-directional	-
Solution 2829	Rollers	Horizontal Rotating Bin	Gantry	Clamping Holders	Manual Cable Connector	Trailer	+	+	-	+	+	+	-	+	Not bi-directional	-
Solution 2830	Rollers	Horizontal Rotating Bin	Gantry	Clamping Holders	Modular Location of Connector	Trailer	+	+	-	+	+	+	-	+	Not bi-directional	-
Solution 2831	Rollers	Horizontal Rotating Bin	Gantry	Stackable Trays	Manual Cable Connector	Trailer	+	+	-	+	+	+	-	+	Not bi-directional	-
Solution 2832	Rollers	Horizontal Rotating Bin	Gantry	Stackable Trays	Modular Location of Connector	Trailer	+	+	-	+	+	+	-	+	Not bi-directional	-
Solution 2833	Conveyor Belt	Vertical Ferris Wheel	Overhead Crane	Guide Rails	Fixed Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2834	Conveyor Belt	Vertical Ferris Wheel	Overhead Crane	Guide Rails	Manual Cable Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2835	Conveyor Belt	Vertical Ferris Wheel	Overhead Crane	Guide Rails	Modular Location of Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2836	Conveyor Belt	Vertical Ferris Wheel	Overhead Crane	Clamping Holders	Fixed Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-
Solution 2837	Conveyor Belt	Vertical Ferris Wheel	Overhead Crane	Clamping Holders	Manual Cable Connector	Trailer	+	+	+	+	+	+	-	+	Ferris wheel is not feasible	-

C. Elimination Matrix

Solution 2914	Rollers	Vertical Ferris Wheel	Gantry	Guide Rails	Fixed Connector	Trailer	+	+	+	+	+	+	-	-	Ferris wheel is not feasible	-
Solution 2917	Rollers	Vertical Ferris Wheel	Gantry	Clamping Holders	Fixed Connector	Trailer	+	+	+	+	+	+	-	-	Ferris wheel is not feasible	-
Solution 2920	Rollers	Vertical Ferris Wheel	Gantry	Stackable Trays	Fixed Connector	Trailer	+	+	+	+	+	+	-	-	Ferris wheel is not feasible	-
Solution 2923	Rollers	Horizontal Rotating Bin	Overhead Crane	Guide Rails	Fixed Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2924	Rollers	Horizontal Rotating Bin	Overhead Crane	Guide Rails	Manual Cable Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2925	Rollers	Horizontal Rotating Bin	Overhead Crane	Guide Rails	Modular Location of Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2926	Rollers	Horizontal Rotating Bin	Overhead Crane	Clamping Holders	Fixed Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2927	Rollers	Horizontal Rotating Bin	Overhead Crane	Clamping Holders	Manual Cable Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2928	Rollers	Horizontal Rotating Bin	Overhead Crane	Clamping Holders	Modular Location of Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2929	Rollers	Horizontal Rotating Bin	Overhead Crane	Stackable Trays	Fixed Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2930	Rollers	Horizontal Rotating Bin	Overhead Crane	Stackable Trays	Manual Cable Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2931	Rollers	Horizontal Rotating Bin	Overhead Crane	Stackable Trays	Modular Location of Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2932	Rollers	Horizontal Rotating Bin	Gantry	Guide Rails	Fixed Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2935	Rollers	Horizontal Rotating Bin	Gantry	Clamping Holders	Fixed Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2938	Rollers	Horizontal Rotating Bin	Gantry	Stackable Trays	Fixed Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2941	Overhead Crane	Horizontal Rotating Bin	Overhead Crane	Guide Rails	Fixed Connector	Trailer	+	+	+	+	+	+	+	+	Fulfills all criteria	+
Solution 2942	Overhead Crane	Horizontal Rotating Bin	Overhead Crane	Guide Rails	Manual Cable Connector	Trailer	+	+	+	+	+	+	+	+	Fulfills all criteria	+
Solution 2943	Overhead Crane	Horizontal Rotating Bin	Overhead Crane	Guide Rails	Modular Location of Connector	Trailer	+	+	+	+	+	+	+	+	Fulfills all criteria	+
Solution 2944	Overhead Crane	Horizontal Rotating Bin	Overhead Crane	Clamping Holders	Fixed Connector	Trailer	+	+	+	+	+	+	+	+	Fulfills all criteria	+
Solution 2945	Overhead Crane	Horizontal Rotating Bin	Overhead Crane	Clamping Holders	Manual Cable Connector	Trailer	+	+	+	+	+	+	+	+	Fulfills all criteria	+
Solution 2946	Overhead Crane	Horizontal Rotating Bin	Overhead Crane	Clamping Holders	Modular Location of Connector	Trailer	+	+	+	+	+	+	+	+	Fulfills all criteria	-
Solution 2947	Overhead Crane	Horizontal Rotating Bin	Overhead Crane	Stackable Trays	Fixed Connector	Trailer	+	+	+	+	+	+	-	+	Technical feasibility	-
Solution 2948	Overhead Crane	Horizontal Rotating Bin	Overhead Crane	Stackable Trays	Manual Cable Connector	Trailer	+	+	+	+	+	+	-	+	Technical feasibility	-
Solution 2949	Overhead Crane	Horizontal Rotating Bin	Overhead Crane	Stackable Trays	Modular Location of Connector	Trailer	+	+	+	+	+	+	-	+	Technical feasibility	-
Solution 2950	Overhead Crane	Horizontal Rotating Bin	Gantry	Guide Rails	Fixed Connector	Trailer	+	+	+	+	+	+	+	-	Two different solutions for load	-
Solution 2951	Overhead Crane	Horizontal Rotating Bin	Gantry	Guide Rails	Manual Cable Connector	Trailer	+	+	+	+	+	+	+	-	Two different solutions for load	-
Solution 2952	Overhead Crane	Horizontal Rotating Bin	Gantry	Guide Rails	Modular Location of Connector	Trailer	+	+	+	+	+	+	+	-	Two different solutions for load	-
Solution 2953	Overhead Crane	Horizontal Rotating Bin	Gantry	Clamping Holders	Fixed Connector	Trailer	+	+	+	+	+	+	+	-	Two different solutions for load	-
Solution 2954	Overhead Crane	Horizontal Rotating Bin	Gantry	Clamping Holders	Manual Cable Connector	Trailer	+	+	+	+	+	+	+	-	Two different solutions for load	-
Solution 2955	Overhead Crane	Horizontal Rotating Bin	Gantry	Clamping Holders	Modular Location of Connector	Trailer	+	+	+	+	+	+	+	-	Two different solutions for load	-
Solution 2956	Overhead Crane	Horizontal Rotating Bin	Gantry	Stackable Trays	Fixed Connector	Trailer	+	+	+	+	+	+	+	-	Two different solutions for load	-
Solution 2957	Overhead Crane	Horizontal Rotating Bin	Gantry	Stackable Trays	Manual Cable Connector	Trailer	+	+	+	+	+	+	+	-	Two different solutions for load	-
Solution 2958	Overhead Crane	Horizontal Rotating Bin	Gantry	Stackable Trays	Modular Location of Connector	Trailer	+	+	+	+	+	+	+	-	Two different solutions for load	-
Solution 2959	Robotic Arm	Horizontal Rotating Bin	Overhead Crane	Guide Rails	Fixed Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2960	Robotic Arm	Horizontal Rotating Bin	Overhead Crane	Guide Rails	Manual Cable Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2961	Robotic Arm	Horizontal Rotating Bin	Overhead Crane	Guide Rails	Modular Location of Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2962	Robotic Arm	Horizontal Rotating Bin	Overhead Crane	Clamping Holders	Fixed Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2963	Robotic Arm	Horizontal Rotating Bin	Overhead Crane	Clamping Holders	Manual Cable Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2964	Robotic Arm	Horizontal Rotating Bin	Overhead Crane	Clamping Holders	Modular Location of Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2965	Robotic Arm	Horizontal Rotating Bin	Overhead Crane	Stackable Trays	Fixed Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2966	Robotic Arm	Horizontal Rotating Bin	Overhead Crane	Stackable Trays	Manual Cable Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Solution 2967	Robotic Arm	Horizontal Rotating Bin	Overhead Crane	Stackable Trays	Modular Location of Connector	Trailer	+	+	-	+	+	+	+	-	Not bi-directional	-
Total amount of concepts before elimination matrix																135
Concepts eliminated																123
Concepts left																12

D

Pugh Matrix

Battery Swap System Concept Evaluation	Pugh Matrix 1			
Authors: Eric Fabricius and Carl Ingemarsson				Created: 21/10/2024
				Modified: 28/10/2024
Criteria	Solution 2941	Solution 2942	Solution 2944	Solution 2945
Battery swap time	+		0	-
Battery Pack Capacity	0	R	0	0
	0		0	0
Minimize risk of collision with machines	0	E	0	0
Take up as little space as possible when parked	0		0	0
Weight less than 30 tons	0	F	0	0
Max Width < 2.5m	0		0	0
Feasible (technically and financially)	0	E	-	-
Fits into all construction site categories	0		0	0
Unloading/loading and transportation with same function	0		0	0
$\Sigma+$	1	R	0	0
$\Sigma 0$	9		9	8
$\Sigma -$	0	E	1	2
Net value	1		-1	-2
Ranking	1	C	2	3
Further Development	+		-	-
Decision	Yes	E	No	No

D. Pugh Matrix

Battery Swap System Concept Evaluation	Pugh Matrix 2			
Authors: Eric Fabricius and Carl Ingemarsson				Created: 21/10/2024
				Modified: 28/10/2024
Criteria	Solution 2941	Solution 2942	Solution 2944	Solution 2945
Battery swap time		-	0	-
Battery Pack Capacity	R	0	0	0
		0	0	0
Minimize risk of collision with machines	E	0	0	0
Take up as little space as possible when parked		0	0	0
Weight less than 30 tons	F	0	0	0
Max Width < 2.5m		0	0	0
Feasible (technically and financially)	E	0	-	-
Fits into all construction site categories		0	0	0
Unloading/loading and transportation with same function		0	0	0
Σ+	R	0	0	0
Σ 0		9	9	8
Σ -	E	1	1	2
Net value		-1	-1	-2
Ranking	C	1	1	2
Further Development		-	-	-
Decision	E	No	No	No

Battery Swap System Concept Evaluation	Pugh Matrix 3			
Authors: Eric Fabricius and Carl Ingemarsson				Created: 21/10/2024 Modified: 28/10/2024
Criteria	Solution 2941	Solution 2942	Solution 2944	Solution 2945
Battery swap time	+	0	+	R E F E R E C E
Battery Pack Capacity	0	0	0	
	0	0	0	
Minimize risk of collision with machines	0	0	0	
Take up as little space as possible when parked	0	0	0	
Weight less than 30 tons	0	0	0	
Max Width < 2.5m	0	0	0	
Feasible (technically and financially)	+	+	0	
Fits into all construction site categories	0	0	0	
Unloading/loading and transportation with same function	0	0	0	
Σ+	2	1	1	
Σ 0	8	4	4	
Σ -	0	4	4	
Net value	2	1	1	
Ranking	1	2	2	
Further Development	+	+	+	
Decision	Yes	Yes	Yes	

E

Kesselring Matrix

		Kesselringmatrix:															
Issuer: Battery Swap Station Thesis - Eric Fabricius and Carl Ingemarsson																	
Criteria		Alternatives:															
		Ideal Concept		Concept 2815		Concept 2887		Concept 2890		Concept 2896		Concept 2941		Concept 2942			
Name	w	v	t	v	t	v	t	v	t	v	t	v	t	v	t		
Battery swap time	0.10	5	0.50	2	0.20	3	0.30	3	0.30	3	0.30	5	0.50	3	0.3		
Battery Pack Capacity	0.15	5	0.75	4	0.60	4	0.60	4	0.60	4	0.60	5	0.75	5	0.75		
	0.05	5	0.25	2	0.10	2	0.10	2	0.10	2	0.10	4	0.20	4	0.2		
Minimize risk of collision with machines	0.15	5	0.75	2	0.30	2	0.30	2	0.30	2	0.30	4	0.60	4	0.6		
Take up as little space as possible when parked	0.05	5	0.25	3	0.15	3	0.15	3	0.15	3	0.15	4	0.20	4	0.2		
Weight less than 30 tons	0.05	5	0.25	4	0.20	4	0.20	4	0.20	4	0.20	4	0.20	4	0.2		
Max Width < 2.5m (under transportation)	0.15	5	0.75	5	0.75	5	0.75	5	0.75	5	0.75	5	0.75	5	0.75		
Feasible (technically and financially)	0.10	5	0.50	4	0.40	4	0.40	3	0.30	4	0.40	4	0.40	4	0.4		
Fits into all construction site categories	0.10	5	0.50	3	0.30	3	0.30	3	0.30	3	0.30	5	0.50	5	0.5		
Unloading/loading and transportation with same function	0.10	5	0.50	1	0.10	1	0.10	1	0.10	1	0.10	5	0.50	5	0.5		
<i>T (Total weighted value)</i>	1	50	5	3.10	3.20	3.10	3.20	3.10	3.20	3.10	3.20	4.60	4.40	4.60	4.40		
<i>T / Tideal</i>		1	1	0.62	0.64	0.62	0.64	0.62	0.64	0.62	0.64	0.92	0.88	0.92	0.88		
Average		5	0.50														
Std-deviation		0	0.15														
Median		5	0.50														
Ranking					5		3		3		3		1		2		
Result		Chosen concept is : 2941															

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