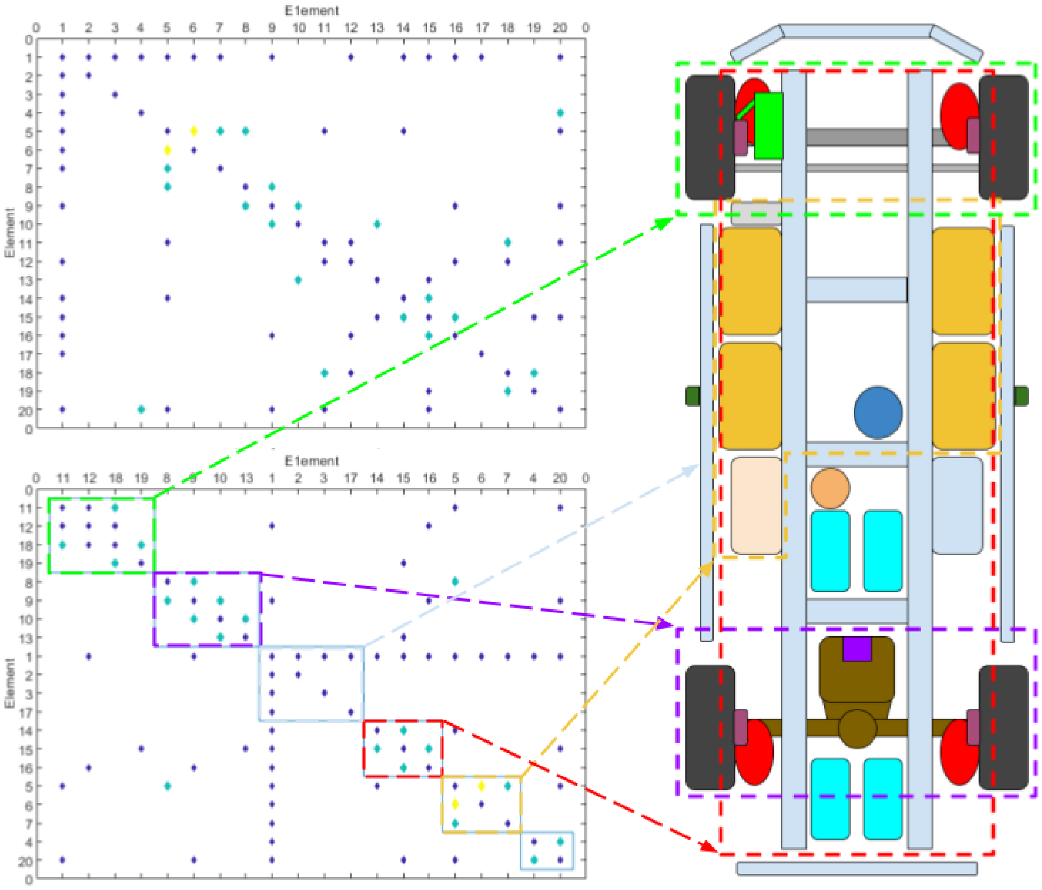
CHALMERS
UNIVERSITY OF TECHNOLOGY



Modularity in Chassis Design

An investigation of modular product architecture for a chassis of an autonomous electric truck

Master's thesis in Product Development

JOHAN ARVIDSSON & JESPER PENNDAL

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se

Master's thesis 2023

Modularity in Chassis Design

An investigation of modular product architecture for a chassis of an autonomous electric truck

JOHAN ARVIDSSON
JESPER PENNDAL

Department of Industrial and Materials Science
Division of Product Development
Chalmers University of Technology
Gothenburg, Sweden 2023

Modularity in Chassis Design
An investigation of modular product architecture for a chassis of an autonomous electric truck
JOHAN ARVIDSSON & JESPER PENNDAL

Supervisor and Examiner: Associate Professor Massimo Panarotto,
Department of Industrial and Materials Science

Master's Thesis 2023
Department of Industrial and Materials Science
Division of Product Development
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Cover: Original & clustered design structure matrices, with a visual representation of the product architecture for a chassis of an autonomous electric truck.

Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2023

Modularity in Chassis Design
JOHAN ARVIDSSON & JESPER PENNDAL
Department of Industrial and Materials Science
Chalmers University of Technology

Abstract

This master's thesis explores the strategy of modularity in chassis design for autonomous electric trucks (AET). The study aims to investigate the benefits and challenges of incorporating modular design principles in the development of chassis systems. The research methodology includes a comprehensive literature review, investigating stakeholder needs impact on a modular chassis design, and using design structure matrices to evaluate the performance and the product architecture of modular chassis concepts. The results demonstrate that technology changes are one of the most important factors to consider when developing a modular chassis for an AET. In addition, the research emphasizes the importance of information and energy connections in product architecture as the shift toward electrical and autonomous technology increases. In contrast to traditional manually operated trucks with internal combustion engines, the focus has traditionally been on spatial (physical) connections.

A design proposal for the product architecture is also presented based on the evaluated concepts generated by defining modules with a Design structure matrix. After that, visualized with an overview image with the components divided into modules and interfaces highlighted. Furthermore, the study examines the potential trade-offs between modularity and value dimensions identified through a value creation strategy. The findings contribute to the body of knowledge in the field of AET by highlighting the implications of modularity and how it should be applied to the design of a chassis. Estimating future legal and technology requirements and adapting to future changes is essential. This research provides valuable insights for AET manufacturers and designers seeking to leverage modular approaches in their chassis development strategies.

Keywords: Modularity, Chassis, Product architecture, Autonomous electric truck, Value creation strategy, Design structure matrix.

Acknowledgements

This master's thesis was conducted in the spring of 2023 at Chalmers University of Technology's Department of Industrial and Materials Science in association with a manufacturer of autonomous electric trucks.

First and foremost, we would like to sincerely thank Massimo Panarotto, our university examiner and supervisor, for your support, guidance, and enthusiasm during the thesis. As well as for continuously giving us feedback and taking the time to contribute with your expertise within the field of product development.

Secondly, we would like to thank the company with which we have had the opportunity to carry out this master's thesis. In particular, we would like to thank our supervisors internally from the company for taking the time and being flexible in helping and guiding us through the thesis. And we also want to take the opportunity to thank all departments and employees who participated in the interviews and also for your willingness to cooperate to contribute knowledge to our work.

Last but not least, we want to extend our gratitude to our friends, family, and anyone who has supported us in our work. For spending the time to discuss our work and for your support. Which enabled us to produce this thesis to the best of our ability.

Johan Arvidsson & Jesper Penndal
Gothenburg, June 2023

List of Acronyms

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

AET	Autonomous Electric Truck
DSM	Design structure matrix
EDS	Electric box
"E"	Energy connections
EF-M tree	Enhanced function-means tree
F-L	Front-Left
F-R	Front-Right
ICE	Internal combustion engine
"I"	Information connections
"M"	Material connections
R-L	Rear-Left
R-R	Rear-Right
"S"	Spatial connections
VCU	Vehicle control unit
VCS	Value creation strategy

Contents

List of Figures

List of Tables

1
Introduction

This master's thesis proposes how to asses modular product architecture chassis for an autonomous electric truck (AET). The introduction covers the thesis's background and introduces the investigated topic. In the background, the company with which the thesis is executed will be presented and is followed by the aim and research questions, objectives, scope, and delimitations. Finally, an outline of the thesis is presented.

1.1 Background

Trucks are today an essential part of freight transportation. Different businesses of various sizes depending on freight transportation to ensure high quality within deliveries, both in receiving and sending freight. In addition, other transport segments depend on the trucking industry, such as transport to and from airports, rail yards, and ports.(Mack, 2013). In the European Union, 77% of all freight transportation over land is carried by trucks (ACEA, 2022b). The total number of medium and heavy commercial trucks (over 3,5 tonnes) in 2021 was more than 6,4 million, see Figure 1.1. From 2017 to 2021, the total number of units increased by approximately 7,5 percentage points (ACEA, 2023). Consequently, how a truck is designed has a significant impact on society.

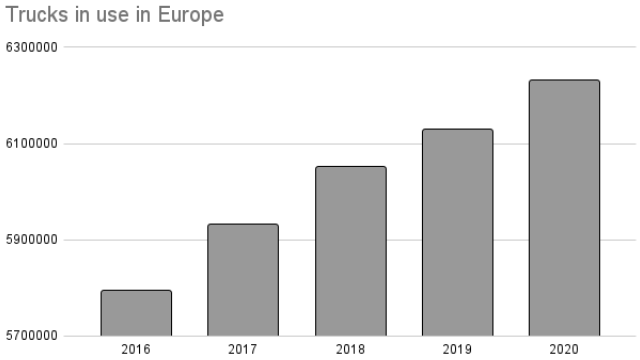


Figure 1.1: Units of medium and heavy commercial trucks (over 3,5 tonnes) in the European Union from 2016 to 2021 (ACEA, 2022c).

In December 2015, the Paris Agreement was signed by almost 190 different parties. The agreement includes a framework for keeping the global average temperature below 2°C and aiming for limiting it to 1,5°C (European-Union, 2023b). Due to this agreement, the European Union has established a long-term strategy to have net-zero greenhouse gas emissions by 2050 (European-Union, 2023a). Furthermore, according to the transport industry, truck manufacturers have stated that battery-electric trucks will play a vital role in the Paris Agreement by having zero-emission trucks on roads powered by electricity. Therefore, a transition in the electric truck sector is ongoing (ACEA, 2022a).

However, the number of electrical trucks is very few today compared to diesel-powered ones. Only 0,1% of the total number of medium and heavy commercial trucks is electrical, while 96,4% is diesel powered (ACEA, 2023). The European Union states that the technology is still under development and fast-changing due to emerging improvements in the field. Therefore this is important to consider when designing a product architecture for an AET. The automotive industry's rapidly changing technology has created an entirely new chassis architecture with integrated batteries. Where the robust structure of the batteries is used to support the chassis, instead of using additional beams for the frame, the overall weight of the chassis with batteries can be reduced. However, this radical change has not yet been possible for the truck segment due to the heavy cargo loads.

Nevertheless, the transition into electric and autonomous trucks demonstrates the possibilities of designing new architectures regarding technological changes, which will significantly impact the current chassis architecture. With the electrification of trucks, all the traditional components such as an engine, exhaust system, and transmission required by internal combustion engines (ICE) are no longer needed (Truett, 2022). Figure 1.2, shows the differences between a chassis architecture for a traditional ICE and a possible architecture for an AET. The engine and transmission cover the entire frame from front to rear in the manually operated ICE truck, compared to the AET, where the engine is directly integrated into the rear axle. Integrating the engine in the rear axle in the AET allows for placing batteries between the frame. As well as placing batteries on the sides of the frame since the fuel tanks are no longer needed in the AET. Furthermore, the control system differs between the two concepts as it is based on manual operation by a physical driver in the ICE concept. In comparison, the AET does not have space for a physical driver and is aimed to be self-driving, possibly controlled remotely.

Another ongoing transition within the truck industry is autonomous driving. Battery electric trucks and autonomous driving are vital for the future transport sector. The combination of these two factors has the potential to make the transport industry more cost-effective, sustainable, reliable, efficient, and safe. However, autonomous technology is emerging and will increase complexity within the trucking industry since mechanical and software components combined in different relationships and complex interactions are required.

Compared to a traditional steering system, an ICE concept is mainly based on a mechanical steering shaft that steers on one wheel and is connected with a link to the other, which can be seen in Figure 1.2. Applying a modular truck design is one possible solution to handle this complexity arising by having an autonomous and electric-powered chassis. Langlois (2002) defines modularity as a systematic approach to decreasing the complexity of a product by dividing it into modules (a group of components) with defined and standardized interfaces. This will lead to possibilities for further development and replacement of specific components within modules without affecting the entire product architecture (K. Ulrich, 1994). This can be applied to enable the possibility of adapting to new technology and reducing complexity by focusing on a specific module and not the entire product. Therefore, future needs and requirements must be predicted to create a chassis architecture that ensures the possibility of adapting to new technology and reduces complexity. Other aspects of development will also be a part of the transition to electric and autonomous. As truck manufacturers grow and increase volume in production, modular design is an established strategy used to develop and provide different products for various use cases from a common platform (Alvin P Lehnerd & Marc H Meyer, 1997).

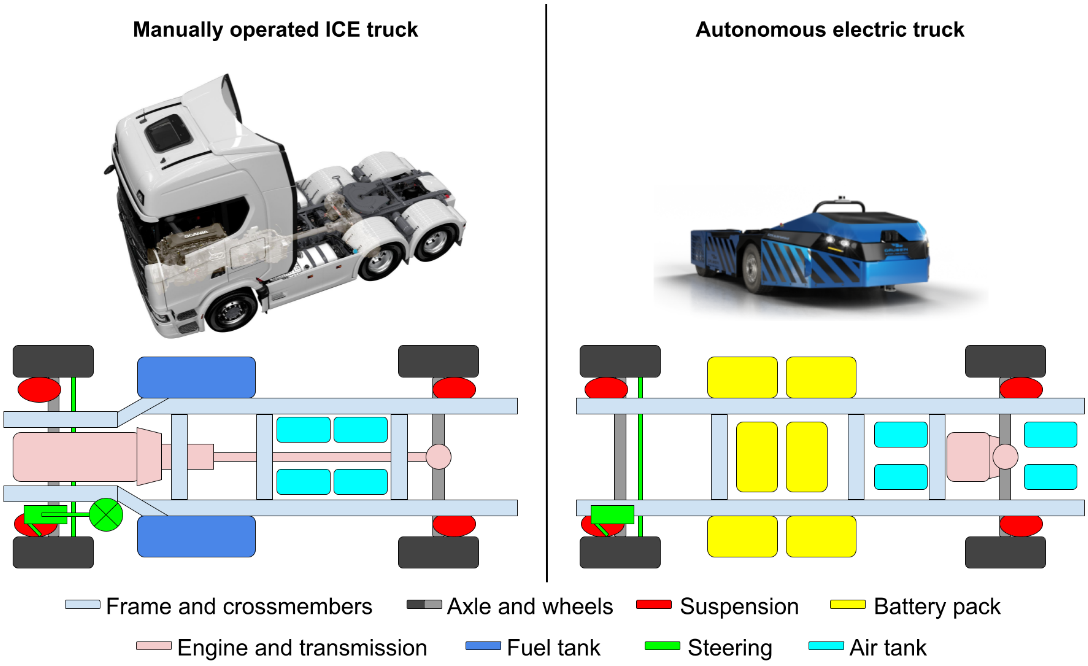


Figure 1.2: Visualized comparison of two different truck chassis. The chassis and truck to the left visualize an ICE setup with manually operated steering (Scania, 2021). To the right is an autonomous electric truck presented (Gaussin, 2021). The ICE concept (to the left) is based on the internal combustion engine, fuel tanks, and transmission while the AET has an integrated engine in the axle, enabling more space for the batteries.

1.1.1 The manufacturer

The thesis was conducted in collaboration with a company that was decided to be set anonymously through this report due to informational issues. The company is a Swedish manufacturer of autonomous electric trucks and will therefore be referred to “the manufacturer”, through the thesis. As they already manufacture AETs, they are interested in investigating how future needs will impact chassis design. Therefore, the manufacturer proposed the thesis to understand how a chassis for an AET can be designed with modularity. In-depth, the thesis will discover the possibilities of when and how modular product architecture can be implemented for an AET chassis. It is also essential to consider different trade-offs of the requirements when implementing modularity. Therefore, this thesis evaluates different concepts and requirements for a modular product architecture and how it would affect the manufacturer.

1.2 Aim and research questions

This thesis aims to analyze and define the critical factors and functions of developing a modular chassis architecture for an AET by investigating the impact of applying an electrical engine with battery packs and the system of autonomous driving within the chassis. Further, inspiration from the literature will be used to generate future visions of possible concepts and draw conclusions on how a modular architecture in a chassis design for an AET could be applied. Therefore, research, literature, and requirements from the manufacturer are used to conclude the impacts of applying modularity within the chassis architecture. Current and future needs must be defined and evaluated to facilitate the possibilities of modularity. As well as how different modular drivers should be selected and prioritized to match the manufacturer’s vision. Furthermore, define the value of modular architecture in chassis design for the manufacturer and what should be prioritized. This will be conducted with defined parameters in terms of needs and modular drivers, evaluated concerning field research, and adapted to theoretical methods to develop concepts for a modular chassis architecture. The final concepts are based on a product architecture of a chassis, presented in a schematic format by identifying the different modules and their components. Finally, the concepts will be critically evaluated and analyzed against each other according to different factors.

Several objectives are specified for the thesis, and the objectives are derived from the aim. The following objectives for the thesis are listed below.

1. Identify the components and the product architecture of a chassis for an AET, by exploring existing solutions and performing interviews with the manufacturer.

2. Define modularity on a chassis for an AET and identify critical modular components by implementing theoretical methods for product development projects within the design of modularity. This objective will be based on existing research on modularity as well as the internal needs of the manufacturer.
3. Create a schematic design proposition on how modularity should be implemented in a chassis for an AET.

To more clearly understand the purpose and the problems that the thesis is based on, two problem statements were specified as research questions. These research questions were evaluated throughout the work and guided the focus of the thesis. The two questions are based on one "what" and one "how" question. The research questions were answered at the end of the thesis, and conclusions were made on the stated research questions.

RQ1: What are the critical factors and functions to take into consideration when designing a modular architecture for a chassis of an AET?

RQ2: How can a modular architecture for a chassis of an AET be designed?

1.3 Scope and delimitations

Since this thesis was conducted for a limited time (20 weeks), the main focus of the result was to meet the project's aim and achieve the result; therefore, delimitations were established. The result is based on understanding the situation for the manufacturer and defining a modular chassis architecture for an AET. Therefore, the result contains a design proposal for an AET's modular chassis architecture. The components are divided into modules with specified interfaces and presented schematically. A Value creation strategy, an Enhanced function-means tree, and clustering of Design structure matrices were applied to achieve the intended result. However, the different concepts were not selected to be presented in detail due to the limited time of the thesis. Furthermore, the thesis was limited to mainly focusing on the mechanical systems of a chassis, according to the authors' previous knowledge and academic background.

Modularity is a broad subject and exists in many different fields. The existing research and literature contain different definitions depending on the field and researchers. In the early phases of the research, the broad subject of modularity was discovered and utilized to collect general information that can be adapted to electrification and autonomy. The field of AET is still under development; therefore, different sources of information can be adaptable for the specific subject, not only the traditional automotive industry. However, the collected information was analyzed and evaluated concerning the subject of AET to decide whether it would be valuable. The main focus of the result of the future presented chassis architecture design was not restricted to any specific or existing design from today.

Within the selection of methods for designing modularity in the product development field were only existing methods from the research selected. Due to the limited time, developing new methods was impossible. Therefore, existing methods were selected that are previously proven and can be reinforced by the literature as appropriate and adapted.

As mentioned earlier, there is extensive research in modularity, but the specific area of AET was much more limited. Therefore, this research focuses on modularity within the field of AETs. Since the manufacturer where this thesis has been carried out has general expertise in the field of AET, the primary source of information has been based internally. Therefore, all interviews took place internally. All conducted interviews were anonymized and generalized so that no contributors could be identified. In addition, only authorized material will be published to avoid the risk of disclosure of sensitive and confidential information about the manufacturer and individuals.

1.4 Outline of the thesis

The final report of this thesis consists of six chapters as follows:

Chapter 2 - Literature review
The Literature review for the thesis is presented in this chapter, which explains the topic discussed in the report and a theoretical explanation of methods.

Chapter 3 - Methodology
The methodology chapter presents all the selected methods for the thesis, which includes a description of each method and the motivation for the selected methods.

Chapter 4 - Results
All the results from the thesis are presented in the fourth chapter.

Chapter 5 - Discussion
From the result and output of the thesis, a discussion is presented in this chapter. The discussion includes explanations and evaluation of the findings and a critical analysis of the performed work.

Chapter 6 - Conclusion
The main findings and results of the thesis are presented in this chapter. Furthermore, a summary of the recommendations for future work is included.

2

Literature review

In this chapter, the theory connected to the thesis will be explained. The Literature review mainly consists of the theory behind the term modularity, the definition, and the value of modularity. The following terms, modularity, platform, and product architecture, will be discovered and distinguished to define which term is preferred to use in which case. Modularity in software is also presented to explore modularity in a different field, followed by a SWOT analysis created to generate insights into the implications of having a modular product architecture for an AET chassis. Finally, different methods for applying a modular design are presented.

2.1 Introduction and definition of modularity

Modularization is an approach that has been embraced by companies that are facing complexity within technology and fast-changing trends. While customers require a more comprehensive range of products, at the same time, low prices and instant delivery (Kotabe, Parente, & Murray, 2007). Several definitions have been stated for modularity, for example, Langlois (2002) defines it as a principle for managing complexity in general. Another definition by Sako (2003), is defined within the automotive industry where modules are seen as a “chunk” of physically related components assembled as a unit in the vehicle. The building blocks of the modules are defined as the components which do not require specific standardization and interfaces. Modules are named sub-assemblies and lead to reduced complexity and assembly time.

Within modularity, Sanchez and Mahoney (1996) define it as products created by different modules with standardized interfaces between each module. This enables product variety and combining modules according to different needs. This is also related to Langlois and Savage (2001), who address that developers can focus on their modules. Where they can work on *“perfecting their skills”*, and there is no need to understand the entire product. However, the fundamentals of focusing on one specific module and not the entire product can cause issues. According to Ethiraj and Levinthal (2004), important knowledge sharing among modules and product innovation overall can be limited.

Modularity can be described as how a product is physically divided into independent components. However, modularity has different meanings in different applications and different business fields. For example, modularity is often used to describe independent units when designing complex engineered systems. In order to construct a building, the term is also used to describe the use of numerous instances of standardized components. However, modularization is often used in manufacturing to describe how interchangeable parts create different product variants (K. Ulrich, 1994).

In product design, the requirements from the market have increased over the years. It is necessary to consider production costs, production and time-to-market, transportation methods, assembly forms, and user experience in product design. Modular design is used to create diversified products that can meet the market's and user groups' needs (Gao & Zhang, 2020). Therefore, modularization is a design method that can aid in managing the increased market requirements. New strategies have followed the introduction of modularity for companies in knowledge management (Grant, 1996) and has enabled them to develop products more effectively by having organization structures that are flexible and modular (Sanchez & Mahoney, 1996).

2.2 Value of Modularity

Concerning the definitions of modularity, there are also different benefits of applying modularity. Modularity has several potential benefits, which can create value for a product or company. Ten different benefits of modularity are identified, which are the following:

Component economies of scale
As modularity allows identical components to be used across different product variants and platforms, the components are developed and produced as standardized components. Compared to using specific components for specific products, the production volume of a standardized component rises when it is used in a variety of products. Therefore, standardization allows development resources and expenses to be amortized over a large number of units and products. In return, it allows companies to utilize higher-volume and more-efficient production technology in their manufacturing processes. These economies of scale can lower the product cost, and standardization also increases reliability and performance due to the production of high-volume standard components (K. Ulrich, 1994).

Product change
Modularity makes it easier to change a product. Different components in a product change at different rates over time, and the demand for product change arises from customer preference or technological changes. Another benefit of modularity in product change is reusing elements from an existing design. For example, if a product is designed with well-defined interfaces, the next generation can borrow components from the previous product (Rothwell & Whinston, 1990).

Product upgrade and extensions is another form of product change affecting customers directly. It is much easier to achieve these benefits with a modular design (K. Ulrich, 1994).

Product variety
Another benefit of modularity is the possibility of creating a large variety of products from a smaller set of different components. Modular products allow developers to combine additional components to create different products with various functions and applications. This is possible because of the well-defined interfaces between the components (K. Ulrich, 1994). Without modularity, designing a specific product for each desired application would be necessary. Product variety reduces the complexity and resources required to develop and manufacture new products (Nevins & Whitney, 1989).

Flexibility in use
Modular products are also beneficial when it comes to the variety in use. Furthermore, it is easy to modify modular products to be used for other purposes. It is, therefore, possible to modify a product or a specific module to be used in a different area, compared to the intended use (K. Ulrich, 1994).

Order lead-time
When customers demand a customized product, modularity decreases the order lead-time compared to producing a product with no standardized components. As customers order a customized product, the required standardized components can be combined to meet the customers' demand (Mather, 1987).

Decoupling of tasks
The well-defined interfaces in modular products enable decoupling design and production tasks. Decoupling of tasks allows developers to complete tasks concurrently, and the complexity of the tasks decreases as well. Therefore, it is an essential aspect of modularity, and the decoupling of tasks reduces the lead times in product development. Furthermore, the decoupling of tasks also affects production, as components can be produced and verified separately (Clark & Fujimoto, 1991).

Production focus
When modular products are divided into independent components, it allows design and production operations to be specialized and focused. Different focuses can be identified as special production facilities. For example, clean-room environments can be confined to a specific facility or production area. Therefore, it is unnecessary to extend the clean-room environment over the complete production area (Shirley, 1990).

Component verification and testing
As each component in a modular system corresponds to a specific function, functional tests can be performed on individual modules. Furthermore, the interaction between modules in a modular system is limited to the modules critical to the product's functioning. Therefore, it is possible to simulate the interface between the module and the rest of the product (K. Ulrich, 1994).

Differential consumption
The benefit of product change is similar to the benefit of differential consumption. These types of benefits occur in products where a component or element of a product is consumed faster than the rest. Examples of these benefits can be found in the products and components of vacuum cleaner bags, razor blades, and camera films. These components must be replaced earlier than the remaining components (K. Ulrich, 1994).

Ease of product diagnosis, maintenance, and repair
After modular products have been put into service, the benefits, ease of product diagnosis, maintenance, and repair can be acquired. In addition, modularity enables more accessible and faster repairs as faulty modules can easily be replaced (K. Ulrich, 1994).

2.3 Understanding Product Platform, Architecture, and Interface design

To understand the context and value of modularity, terms such as product platform, architecture, and interfaces appear frequently. Therefore, the following section will define and explain these three different subjects. The product platform is highlighted as a possible solution for creating a common basis for components that can be used for several use cases of the chassis. In contrast, product architecture is associated with defining the various components and their interconnected configurations to create a chassis. Finally, interfaces are stated as specific connections between modules within the chassis.

2.3.1 Product platform

Focusing on the product platform, various definitions exist based on different sources. A broad definition in the literature is based on the focus of the product or object itself and considering it as a platform (McGrath, 1995; Meyer & Utterback, 1993). This also relates to the definition from Wilhelm, Ericsson, and Erixon (1997; 1999). Where a physical product has common shared *"elements"* with other products, by bringing combinations of subsystems and interfaces together, a standard structure will occur with the ability to create derivative products, which is the definition of a platform by Meyer and Lehnerd (1997).

Companies and manufacturers in different industries constantly need to change their product offerings as customer preferences change over time. Several factors can cause a change in customer preference, affecting products in terms of visual design and preferred functional attributes, which results in market changes. There are two alternatives for manufacturers to adapt to current or future market changes. First, the company can either design a completely new product or develop one by modifying an existing one to meet the new customer preferences. If several modifications are executed systematically, where several components are shared across multiple products, it is defined as a platform strategy (Suh, De Weck, & Chang, 2007).

As a new product is developed according to the platform strategy, the new product is composed of three different types of components **New-Unique**, **Carryover-Common**, and **Carryover-Modified**. **New-Unique** components are identified as entirely new components which are not shared or derived from any other product within the platform. **Carryover-Common** components are identical components used by one or several products within the platform. Finally, **Carryover-Modified** are similar to existing components in the platform and are generated by redesigning the existing components (Suh et al., 2007).

Jiao, Simpson, and Siddique (2007) presents a holistic view of product family design and development where a product family refers to a group of products derived from a specific platform. The holistic view addresses fundamental issues related to the product family design decision. Which, as a result, are affected by conceptual design implications of a product family, product platform, product architecture, product variety, modularity, and commonality.

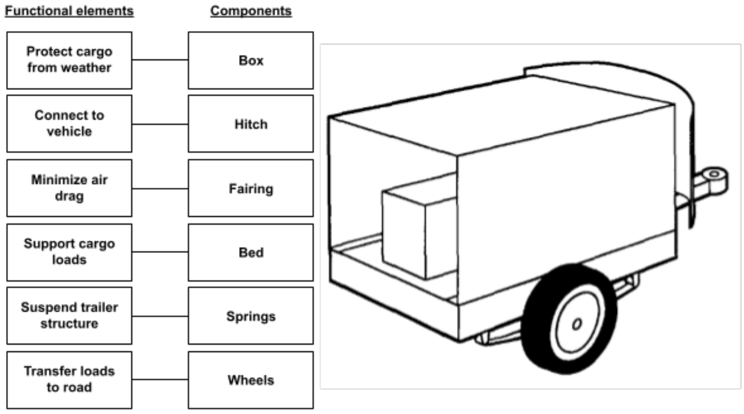
Jiao, Simpson, and Siddique (2007) mention three different types of product platforms: modular platform, scalable platform, and generational platform. The modular platform is based on variants created using a modular framework, configuring existing modules (Alvin P Lehnerd & Marc H Meyer, 1997). A scalable platform makes it easier to differentiate variants with the same function but different capacities (Simpson, Maier, & Mistree, 2001). Finally, while generational platform enhances the product life cycle for the rapid development of upcoming next-generation products (Martin & Ishii, 2002).

2.3.2 Product architecture

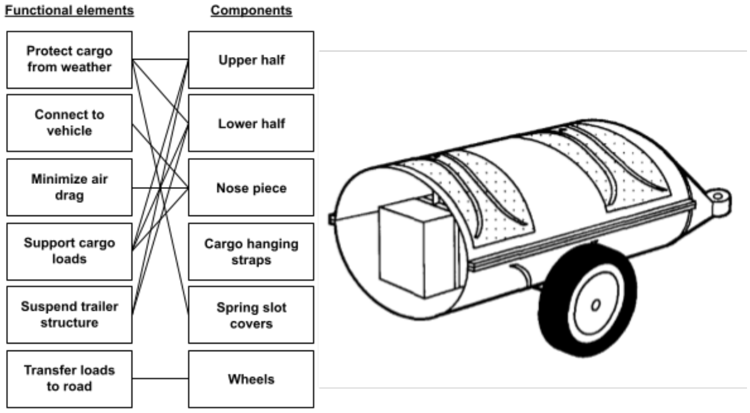
It is necessary to specify the product variation within the strategy of establishing a product platform. The product variation can be derived from the product architecture. Ulrich (1995) has stated a definition of the product architecture (PA) based on three building blocks:

1. The arrangement of functional elements
2. The mapping from functional elements to physical components
3. The specification of the interfaces among interacting physical components

The PA can be aligned to entire product families and specific products. Erens and Verhulst (1997) argue that a PA is common to product families, while Ulrich (1995) applies it to specific products. Another level of PA is to divide it into sub-categories as modular and integrated, which is visualized in Figure 2.1, with two examples of trailers. The modular PA has similarities with the different definitions of modularity, where specific product components can be swapped independently without affecting other components and displayed in Figure 2.1, where the modular PA (a) is constructed by having one component connected to each functional element. This makes it possible to offer different products with common components, which can lead to an economic advantage for companies. Integrated PA is seen as the opposite of modular PA. Where several components depend on each other, a specific change or update of a component will influence the PA. This is displayed in Figure 2.1, where the functional elements are connected to several components. However, performances of the entire product, such as dimension, mass, and material properties, are feasible to improve with an integrated PA (K. Ulrich, 1995).



(a) Modular product architecture



(b) Integrated product architecture

Figure 2.1: Modular PA (a) and Integrated PA (b) visualized with the example of trailers (K. Ulrich, 1995).

2.3.3 Type of modular interface design

Designing one or more interfaces for a modular product architecture is necessary. The interface is the connection that attaches the different modules. To connect the modules, the interfaces must be capable of carrying out different functions. This results in design requirements for the interfaces that may vary depending on the functionality of the modules. Some examples of different design requirements for interfaces are transfer of mechanical loads, transfer of electrical power, transfer of thermal loads, and providing connection for data communication. A critical requirement for interfaces can be that they are identically designed and manufactured for all connections between modules. This enables the possibility of connecting all modules independently of each other. Identical interfaces result in design constraints for all modules. Since the interfaces of all modules are required to fulfill all interface requirements, regardless of the functional requirements of the modules (Rodgers, Hoff, Jordan, Heiman, & Miller, 2005).

In the book, The role of product architecture in the manufacturing firm, Ulrich (1995) presents three modular architectures based on a specified interface type between different modules. The different types of modular architectures are Slot, Bus, and Sectional. Slot modularity makes the interchangeability of the different modules more difficult, as each interface between the modules has a different design compared to the others. Bus modularity, on the other hand, is when all modules have the same interface connection with a common bus component. This makes it possible to reorder and switch the placement of the different modules. Finally, all interfaces are the same type in the sectional modular architecture. Therefore the modules can be connected to each other and do not have to be linked to a common bus component (Doe, 2020). Below, a visual representation of the different modular architectures is presented in Figure 2.2.

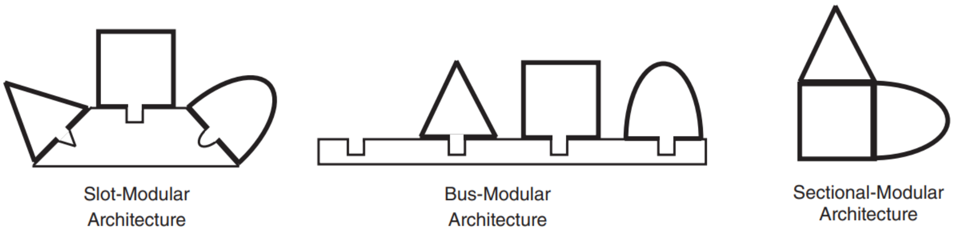


Figure 2.2: A visual representation of different types of modular architectures (Slot, Bus, and Sectional). Figure from Ulrich (1995)

2.4 Modularity in software

In the first part of the Literature review, modularity has been focused on product design. Modularity often refers to a physical product with interchangeable components that create product variants. However, this is not the only field where modularity is applied. Modularity is also used in software development where different functions can be loaded and unloaded depending on the use case (Hare & Kaplan, 2016).

Modularity in software design is defined as how well the software is decomposed into smaller segments with standardized interfaces. This allows developers to create products by combining different segments of reusable code. A software module can have different definitions, similar to a physical component. The software module is independent of other modules, which means that the module can be developed and changed without affecting other segments. However, when running the program, the developed or changed module can still depend on other modules. An independent software module increases productivity in development as engineering teams become independent when creating, maintaining, and testing code. A software module is also defined as a module that can be reused in different systems or products. Reusable software modules are advantageous as they can assist in shortening the time to market (Bråtegren, 2023).

The benefits of reuse in software modularity were proven in a case study by Hongyi Sun, Waileung Ha, Pei-Lee Teh, and Jianglin Huang (2017). By implementing a reuse program, the organization managed to increase the reuse of software modules from 31% to 71%. This, in return, leads to an increase in productivity by 258%, a cost reduction of 70%, and a quality increase of 72% (Sun et al., 2017).

2.5 SWOT analysis of a modular product architecture

Because there are no existing AET chassis available on the market within a large production scale (the manufacturer, internal communication, 2023), it was decided to perform a SWOT analysis on a modular product architecture of a chassis to understand the effects on the business strategy for an AET. The technology of electric and autonomous driving is fast-changing. This section presents the SWOT analysis for a modular product architecture of a chassis for an AET. The SWOT analysis's strengths, weaknesses, opportunities, and threats are presented in Table 2.1, below.

Table 2.1: SWOT analysis

Strengths	**Weaknesses**
• Cost savings due to having common components for various use cases • Decreased complexity in future upgrading/development • Reuse of elements from existing design • Simplifies assembly process • Concurrent engineering, developing multiple modules simultaneously • Easier system verification and testing	• An extended lead time when establishing the design for the first product • Risk of oversizing product • Predicting future changes • High initial investment
Opportunities	**Threats**
• Easy to meet changes in market demand • Flexibility in outsourcing • Flexibility of use for modules	• Never providing a product with the absolute best performance • Threat of low market demand due to immature market • Difficulty in collaboration with suppliers

Strengths

Designing a modular product can generate cost savings in many different fields. One of the many strengths of having a modular chassis for an AET is using common components for different use cases. One example would be to have a standardized interface between the axles and the chassis, enabling the possibility of adding or removing axles depending on the required load capacity for a use case. This would result in product variety which reduces the required resources in development and manufacturing (K. Ulrich, 1994). The first round of interviews mentioned that a modular chassis architecture would benefit manufacturing, as it simplifies the assembly process by having standardized tools. This strengthens the business strategy of having a modular chassis architecture, as the manufacturing reduces complexity and cost. Another strength of modular chassis architecture is the possibility of concurrent engineering. If the chassis components are divided into different modules, engineers and developers can focus on developing their specific module without understanding the entire product (R. N. Langlois & Savage, 2001). This results in a more efficient and cost-effective development process.

A modular chassis architecture can also decrease complexity regarding future upgrading and development. When the first modular product architecture is designed, modules and components can be modified or re-used in future products (Suh et al., 2007). For example, the battery packs and power train could be re-used in the chassis, and other components could be changed to create a new product. This also results in cost savings in new development, supply management, and manufacturing fields.

Weaknesses
There are some weaknesses in the business strategy of modular chassis architecture. First, it requires a higher time investment in the initial design phase (Hackl & Krause, 2016). This increases initial cost investment compared to developing an integral product. Furthermore, applying modular design to an existing integral product will require a redesign of the product architecture. Ensure that the intended product architecture benefits as much as possible from the modular design. The redesign will require time and additional costs (Pandremenos, Paralikas, Salonitis, & Chryssolouris, 2009). Hackl and Krause also state that the communal use of components is one of the main modular drivers, and this is often achieved by oversizing. Which ultimately leads to the product becoming potentially larger, heavier, and less energy efficient. This can affect several life phases of the product, such as reduced product performance and higher manufacturing costs (2016). Another weakness of developing a modular product architecture is adapting to future changes. Specifying a modular product architecture is essential to predict future technological changes affecting the product architecture. This is done by developing a future robust product architecture and estimating which parts are expected to change and to what extent. Failing to design a future robust product architecture can lead to increasing complexity (Krause, Gebhardt, & Oltmann, 2017).

Opportunities
A modular product architecture enables the possibility of adapting to new market demands (Gao & Zhang, 2020). This applies if the product architecture is designed for variety and is considered a future robust product architecture (Krause et al., 2017). Therefore, as market demand shifts, a chassis with a future robust product architecture can continue to be relevant for a longer time, which presents a business strategy opportunity. A modular chassis can also impact the business strategy by enabling flexibility in use, where modules can be modified for other purposes (K. Ulrich, 1994). For example, the batteries in an electric vehicle will lose capacity over time, and they could be modified for other purposes, extending the battery's overall lifetime. This is possible if the battery pack has standardized interfaces and is separable from the rest of the chassis. Another opportunity enabled by having a modular architecture chassis is the possibility of outsourcing. The flexibility for a product owner to remove, add, or switch suppliers increases (Garud & Kumaraswamy, 1995). This is therefore seen as an opportunity for the business strategy, as it makes it easier to switch suppliers if the company is unsatisfied with the supplier's deliverables.

Threats
A commonly discussed threat of having a modular product is the negative aspect of the reduced performance in a modular product compared to integral design approaches (Agrawal, Sao, Fernandes, Tiwari, & Kim, 2013), this can result in sales loss due to better-performing products on the market. In addition, having a modular product architecture for the chassis can lead to supplier complications. When the interfaces and the modules are defined, the suppliers requested to manufacture the modules might not agree to the design of the modules. Therefore, it might be necessary to either change the modules' design or the suppliers (Pandremenos et al., 2009). It is also mentioned in the first round of interviews that it can be challenging to influence suppliers to change designs after specific interfaces. This is considered to be a business threat as it has a negative impact on the development process. Another threat with a modular chassis architecture for an AET is the risk of focusing on and providing product variety to an immature market. For example, in the second round of interviews, it is mentioned that some potential customers have doubts about autonomous transportation. Therefore, it may not be enough market demand for certain variations if a modular product architecture for the chassis is developed with the ability to build many variants.

2.6 Value creation strategy (VCS)

To cover different stakeholder needs in an early development phase, a Value Creation Strategy (VCS) can be applied. By prioritizing different sets of weighted stakeholder needs, the VCS is based on expectations to initiate the development as early as possible (Panarotto, Isaksson, Habbassi, & Cornu, 2020; Isaksson et al., 2013). This method enables the possibility to cover a broader range of stakeholder expectations, compared to traditional cases where the development is often divided into two parts, the engineering- and the business side. The engineering side focuses on specific requirements while the business side focuses on the financial value (Almefelt, Berglund, Nilsson, & Malmqvist, 2006; Dickinson, Thornton, & Graves, 2001). Additionally, in the process of developing a product that is of high complexity, VCS is suitable since the process requires methodological support for making all the complex information transparent, compared to conventional "waterfall" processes (Bajpai, Eppinger, & Joglekar, 2019).

To execute a VCS, it is required to identify stakeholder needs by collecting expectations from different stakeholders (Panarotto et al., 2020). Then the stakeholder needs are analyzed and validated, where a suitable value dimension is selected for each stakeholder's need. The value dimension is a selected attribute to classify each stakeholder's need (Isaksson et al., 2013). Finally, value drivers are identified for each need, these will be a factor in whether the corresponding stakeholder needs are achieved. Value drivers must not be linked to a specific target value or function. However, they may lead to measurable targets and requirements in a later stage (Isaksson et al., 2013).

By defining different business scenarios, the established value dimensions and value drivers are prioritized accordingly to each scenario. As a result, the business and engineering teams can communicate how real business scenarios affect different priorities. This also allows the ability to work concurrently with different concepts and base them on the different priorities from the business scenarios (Panarotto et al., 2020). One possible way of targeting different business scenarios is to identify driving forces for the intended objective. For example, in the literature by Wheelwright and Clark (1992), three main driving forces for new product development are highlighted, which can be used to identify different business scenarios:

- Intense international competition
- Diverse and rapidly changing technologies
- Fragmented, demanding markets

After completing the VCS and prioritization of the value dimensions, the different references of the contextual information can be translated into validated requirements (Isaksson et al., 2013).

2.7 Methods for applying product modularization

Several methods and tools exist when designing a modular product architecture. Three methods have been discovered, Design structure matrix, Modular Function Deployment, and Design for Variety. These three methods provide guidelines and tools for applying a modular design approach.

2.7.1 Design structure matrix

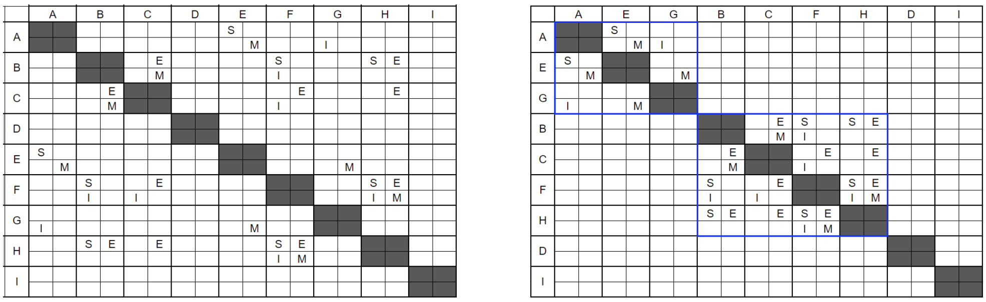
Design structure matrix (DSM) is a method that can be used to identify whether a product or a system has an integral or modular product architecture (Jiao et al., 2007). The DSM is a network modeling tool that visualizes and specifies a system's components and how they interact with each other. Based on the DSM analysis, it can be used to identify modules in the system or product (Habib, 2014).

A matrix of the product architecture for the intended product or system needs to be established to perform a DSM analysis. The matrix is defined in two steps. First, the product or system needs to be divided into components or subsystems. Next, the different components or subsystems must be labeled along the rows and columns in a square matrix. The second step of defining the matrix is identifying the connections between components or subsystems and specifying the type of connection using marks or values in the square matrix (Eppinger & Browning, 2012). The different connections in the product or system are mapped out from predefined interfaces, the most common connections mapped out when performing a DSM analysis are presented below (Habib, 2014).

- Spatial - Physical connections between components.
- Material - Flow of material between components (e.g., fuel, water, compressed air).
- Energy - Flow of energy between components (e.g., mechanical power, thermal).
- Information - Shared information between components (e.g., signals, data, commands).

According to Eppinger and Browning (2012), a product architecture DSM can generate valuable insights, and the most common method used for analyzing the DSM is called clustering. The clustering is used to reorder the rows and columns in the DSM to group them according to the number or strength of the connections. The purpose of clustering is to form groups that can increase the effectiveness of the architecture, as the clustered components shares a common membership in each cluster. The clustering can also be used to choose or identify modules, as they are independent. This aims to minimize the connection between modules and results in a modular product architecture (K. Ulrich, 1994). Clustering is an assignment problem that aims to assign the N number of components to the M number of clusters in the best possible way.

In Figure 2.3, Figure 2.4, and Figure 2.5, a visual representation of the clustering is presented with different results. The rows and the columns in the matrices represent the components of a product, if two components share a connection, it is marked as an "S" (spatial), "M" (material), "E" (energy), or "I" (information) (Habib, 2014). The original DSM matrix is displayed in the matrix shown in Figure 2.3(a). Figure 2.3(b) represents the clustered DSM matrix and visualizes how the components have been reordered depending on the clustered connections (Kulkarni et al., 2018). By performing a DSM clustering, different conclusions can be made by visually analyzing the clustered matrix. The clustering presented in Figure 2.4, shows how an overlapping cluster can be identified from the connections in the original matrix. In Figure 2.5, it is visualized how a common bus component can be identified in the clustering.



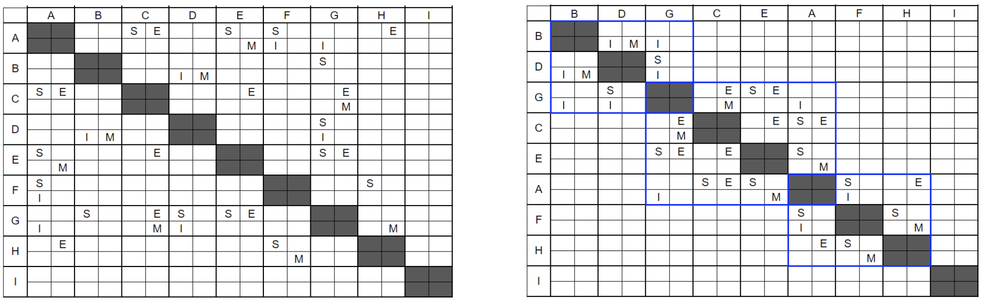
	A	B	C	D	E	F	G	H	I
A	■				S M		I		
B		■	E M			S I		S E	
C		E M	■			E I		E	
D				■					
E	S M				■		M		
F		S I	E I			■		S E I M	
G	I				M		■		
H		S E	E			S E I M		■	
I									■

(a) Original matrix

	A	E	G	B	C	F	H	D	I
A	■	S M	I						
E	S M	■	M						
G	I	M	■						
B				■	E M	S I	S E		
C				E M	■	E I	E		
F				S I	E I	■	S E I M		
H				S E	E	S E I M	■		
D								■	
I									■

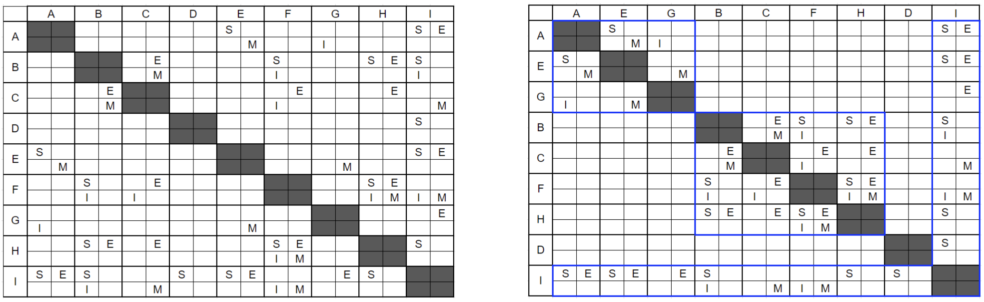
(b) Clustered matrix

Figure 2.3: DSM cluster structures (Kulkarni et al., 2018; Habib, 2014).



(a) Original matrix **(b)** Clustered matrix

Figure 2.4: DSM cluster structures with overlapping clusters (Kulkarni et al., 2018; Habib, 2014).



(a) Original matrix **(b)** Clustered matrix

Figure 2.5: DSM cluster structures with a common bus component (I) (Kulkarni et al., 2018; Habib, 2014).

The DSM clustering introduces several challenges as a trade-off occurs between two conflicting goals in the analysis. The first goal of clustering is to minimize the number of connections outside the cluster. The second goal of clustering is to minimize the size of the clusters. However, Eppinger and Browning state that (2012), obtaining several clusters from different objectives and comparing the clusters can often lead to valuable insights about the product architecture.

Therefore, using DSM clustering has many benefits. DSM can generate insights and visualization into the product architecture and the components' interaction. It can also be used to increase product modularity and identify critical interfaces, which is necessary when designing for modularity (Sanchez & Mahoney, 1996). Eppinger and Browning (2012) also address two main benefits of using DSM clustering, as follows:

1. "Concisely represent a relatively large number of components and their relationships."
2. "Highlight important groups of components and patterns of connections, such as those influencing modularity."

2.7.2 Modular Function Deployment

Modular Function Deployment (MFD) is a method that can systematically be used to develop modular products by having different module drivers as guidelines, such as quality, variance, purchasing, manufacturing, and after-sales. The method is feasible from the beginning of development all the way to concept-level design (Erixon, 1998). One or a few module drivers shall be selected according to the company's needs when applying this method. MFD could be described as more management than engineering-oriented method (Ericsson & Erixon, 1999). The method has five steps, as seen in Figure 2.6.

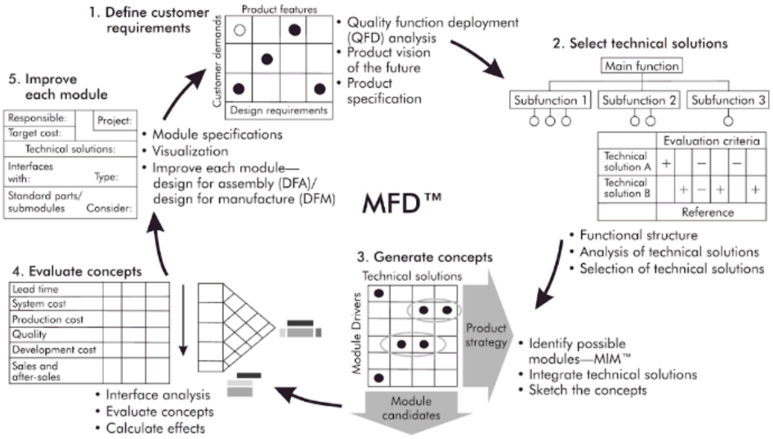


Figure 2.6: An overview of the five steps within Modular Function Deployment (Ericsson & Erixon, 1999).

1. **Define customer requirements**
   The first step is based on finding and defining customer requirements. Requirements in the sense of properties that are required from the product to fulfill present and future demands. These requirements can be derived from existing customers' and competitors' requirements.
2. **Select technical solutions**
   The identified requirements from step one are translated into functions in the second step. All functions are deemed to solve the requirements, and related technical solutions are selected. To solve specific requirements, several functions might be required. Only the most feasible technical solutions relevant to company criteria are selected.
3. **Generate concepts**
   The next step, generating concepts, is seen as the core of the MFD method. The selected technical solutions are evaluated to identify possible modules, supported by the result from the two first steps and the specified module drivers. Furthermore, concepts of modules are generated, and interfaces are derived.

4. **Evaluate concepts**
   Generated concepts and interfaces are evaluated in step four. The evaluation is based on economic forecasts and expected results of modularization, e.g., if the concept is more reasonable than existing products on the market or feasible for development and production.
5. **Improve each module**
   In the last step, technical information regarding data about the modules, cost targets, planned development, and description of variants are summarized. Each module can, at this stage, be further developed.

2.7.3 Design for Variety

With different product variations and demands to change product design continuously, Design for Variety (DFV) is a method that could be used to measure external factors (Daniilidis, Enßlin, Eben, & Lindemann, 2011; Martin & Ishii, 2002). When designing a product, a vital factor is defining customer needs. The most simple and common way is to base the product on present needs. Another part of this factor is the future needs, which are less simple to define than the present. Future needs are relatively based on changing technology, new customers, and competitors' offers. Whit these aspects, some uncertainties make it impossible to determine the outcome fully. Therefore, estimations are required to conclude how future needs should be defined. The focus should be applied to external drivers and parts that may require future changes to decrease possible future design work and related costs. DFV is based on creating two indexes, the Generational variety index (GVI) and the Coupling index (CI). The two indexes help resolve the uncertainty about which parts may need future changes and the different relationships between different product parts (Martin & Ishii, 2002).

Generational Variety Index
By creating a GVI, external drivers that could require future product changes must first be defined. External drivers can, for example, be regulations, environmental factors, or requirements of reduced price. As a part of this phase, the lifetime of the intended product needs to be estimated. In the next phase, all customer requirements should be listed. An optional tool for this is a modified version of the Quality Function Deployment (QFD) matrix. In addition, an extra column is added to the QFD matrix to estimate future changes to the requirements. The next phase is to add estimated values to metrics of how the requirements can change over time by analyzing customers or benchmark competitors. An optional phase is to add existing market values to the metrics in the previous phase, enabling the possibility of plotting future changes. The last and final phase is to generate the GVI matrix and determine the costs for the future development of components. All estimated costs are given a rating of 0, 1, 3, 6, or 9, representing a percentage of each component's original development cost. Furthermore, all ratings are summarized for all components, indicating which components will probably require future development (Martin & Ishii, 2002).

Coupling Index
If a specific component is changed and further developed, the possibility of affecting other components is not unusual. Components that are affecting each other can be seen as coupled. The coupling rate among components is essential to determine and understand the possible influence, which can be located by creating a Coupling index (CI). Firstly, the entire product layout is mapped with all the components. In the mapped layout, control volumes are created for the different components. Within the different control volumes, lists of specifications are formed with information about how each control volume is related to other control volumes. With this information, it is possible to determine which components are strongly coupled and essential to be aware of in future development. Each specification is rated according to its sensitivity level with 0, 1, 3, 6, or 9 ratings. Low sensitivity means a specification can be changed much without affecting coupled components. Compared to high sensitivity, minor changes in a specification will significantly impact the coupled components. The specifications are divided into supplying and receiving, depending on the impact of other specifications. With all the specifications rated both in supplying and receiving, they are summarized in a matrix. This will determine the rate of a coupling index seen to supply and receive (Martin & Ishii, 2002).

Summarizing GVI, CI, and developing a product architecture
When both the GVI and the CI have been formulated, the next step is to analyze the result and determine the rate of modularity for the intended product. Martin and Ishii (2002) argue that components should be standardized and modularized. A general example is if a component is standardized, it should have a low GVI and CI-Reciving, as close to zero as possible. Standardizing a component would mean the design is frozen, and no further development will occur. Furthermore, the product architecture will be designed based on the result from the matrices with standardized parts or modular parts that enable future changes. When designing the product architecture, the aim is to evaluate the different components to ensure that future developments or changes within the product will not cause issues. Several actions can be taken into consideration, for example, by reducing the coupling of components, the sensitivity will decrease and allow further development. As well as, by standardizing components, it is essential to remember that the standardization will lock the ability for future development (Martin & Ishii, 2002).

3

Methodology

The thesis was conducted in a four-step defined process: Exploratory phase, Establishing specifications, Generating product architecture, and Product architecture evaluation. Within each phase of the process, different methods were applied to ensure that the desired aims would be reached, which are presented in Figure 3.1. The process is based on the Concept development process by Ulrich, Eppinger, and Yang (2020).

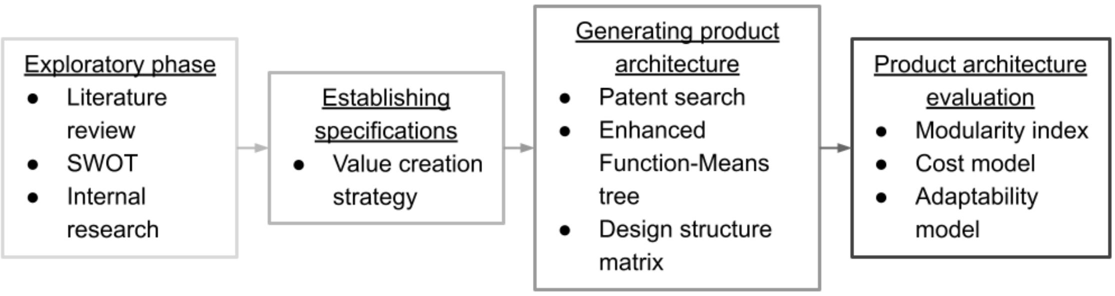


Figure 3.1: The following process for the thesis, visualizing the four main phases: Exploratory phase, Establishing specifications, Generating product architecture, and Product architecture evaluation. Based on the Concept development process (K. Ulrich et al., 2020).

3.1 Exploratory phase

In the first phase of the thesis, the main goal was to better understand modularity at the manufacturer and for AET. Because the combination of modularity in chassis design for an AET is something new that needs to be discovered, it was decided to conduct an exploratory study. The exploratory study was feasible when a hypothesis did not exist and data needed to be collected to create an understanding of the problems in an early stage (Babbie, 2007). To be able to address the exploratory phase, three different methods were selected to follow, literature review, Swot analysis, and internal research. These three methods of the exploratory phase are described in detail in the following sub-sections.

3.1.1 Literature review

Firstly, as a part of the exploratory phase, a Literature review was conducted to collect data about modularity. Secondary research was selected as a method for the Literature review, which is a method to use when collecting data and information that is already published (Church, 2002). This improved the understanding of the subject and enabled future analysis and decisions. Within the subjects of modularity, platform, product architecture, and interface design, general information was collected in different fields and not only the automotive industry to ensure that a wide perspective was discovered. Followed by research about methods for developing modular and architectural systems. As well as including information about different methods used to measure and evaluate modularity in product architecture.

The main source of information was collected from published literature and research from databases Chalmers Library, Google Scholar, Scopus, and ScienceDirect. The following initial keywords, both individually and collectively, were used in the search for relevant literature: Modularity, Platform, Product, Architecture, Value of modularity, Hardware, Software, Automotive, Truck, Chassis, Production, Methods, Design structure matrix, Modular function deployment, Design for variety, and Value creation strategy. The search from the databases resulted in approximately 600 000 different publications of relevance according to the selected keywords. All the collected literature was documented continuously in a sheet to keep track of the information and sources. The sheet contained the information in the form of title, author(s), year, journal, paper type, and URL.

It is also important to understand how a modular product architecture affects the business strategy, in terms of positive and negative aspects. Therefore, a SWOT analysis was conducted. SWOT stands for strengths, weaknesses, opportunities, and threats. These features are analyzed to identify internal and external factors that affect the company and the business performance (Namugenyi, Nimmagadda, & Reiners, 2019). The strengths specified in a SWOT analysis are the internal capabilities that positively impact the business. Weakness is internal constraints that can obstruct the performance of a company or organization's business strategy. The opportunities in a SWOT analysis are the factors that improve the business establishment with connections outside a company or organization. They are specified as external opportunities that companies can take advantage of. Threats are defined as negative factors external to a company or organization that may prevent achieving pre-defined goals (Culp, Eastwood, Turner, Goodman, & Ricketts, 2016). The SWOT analysis is therefore divided into four segments where strengths and weaknesses are specified as internal factors, while the opportunities and threats are specified as external factors.

3.1.2 Internal research

Concurrently, information about the manufacturer and the AET was collected in the exploratory phase. General information about the manufacturer gave a better understanding of the status of today's technology, as well as future possibilities and challenges. Therefore, internal research was conducted, more specifically by both data collection as well as informal- and formal qualitative research. The reason for using qualitative research was concluded as the need to gather and analyze employees' experiences related to the manufacturer and the AET. Qualitative research is described as a method used to collect and analyze non-numerical data to comprehend people's knowledge according to each interviewee's past experiences (DiCicco-Bloom & Crabtree, 2006). Two rounds of interviews were conducted with employees in different areas and competencies. The interviews were as far as possible held physically, which gave a better way of interpreting the interviewees, both verbally and through body language (Knott, Hamid Rao, Summers, & Teeger, 2022).

During the interviews, the collected information was documented by taking notes continuously. Furthermore, was the interviews recorded, which enabled the possibility of transcribing retrospectively. This way of collecting the information ensured that valuable information was not lost. To ensure that all the interviews were ethically conducted, all the interviewees were contacted beforehand and informed about the purpose of the interview. The purpose and the subject to discuss during the interview were presented. When contacting each interviewee, it was checked that the proposed topic of the interview would be relevant. Before the interview started the interviewee needed to approve the recording and that notes were taken continuously. The interviewees were also informed that each interview would be presented anonymously. To maintain an ethical standard in the interviews, the framework published by Denscombe in the book "The Good Research Guide - For small-scale social research projects" was followed (2010).

Internal data collection

Since the manufacturer develops its own AETs, it was significantly important to understand the whole picture of the AET. This means not only the chassis since components on the AET are in correlation with each other. The information about the AET was collected internally by searching internal documentation. Internal documents consisted of CAD models, BOMs, product documentation, and documents provided by suppliers. At the same time, the data collection was supported by informal qualitative research by discussing with supervisors, managers, and employees at the manufacturer. The discussions gave a better understanding of the collected data and provided important knowledge in specific areas.

First round of interviews

For the first round of interviews, the formal qualitative research was conducted through semi-structured interviews with employees at the manufacturer. The main goal of the interviews was to discover different departments of the manufacturer and understand the organization.

As well as presenting the topic of the thesis and allowing the different people to share views from their own experience and field of work (Knott et al., 2022). By having semi-structured interviews a framework of themes to discuss during the interviews was created, which can be seen in Appendix section A.1. The framework for the first round of interviews began with general questions about the interviewee and their responsibilities. This was followed by a request to define AET components and the differences between an AET and a traditional truck with an internal combustion engine (ICE). Finally, the term modularity was discussed in general, specifically how the interviewee thought it could affect the company. The first round of interviews was conducted in February of 2023. The list below shows the different areas of employees who were interviewed presented.

- Mechanical design
- Systems engineering
- Power supply
- Manufacturing
- Product architecture
- Operational
- Product engineering

Second round of interviews

In the second round of interviews, the focus shifted from general questions to more in-depth questions. Therefore the characteristics of the interviews were structured. Depending on the interviewees' interests and knowledge, specific questions were asked during the interview. This allows each interview to be tailored to specific interviewees and gain as much information as possible (Knott et al., 2022). Before the interviews, a framework of questions was created to cover the different specific areas, which can be seen in Appendix section A.2. In total, ten different sections based on different areas were listed for the framework:

- General questions on chassis and the AET
- The Frame
- The axles
- Brakes
- Steering
- Powertrain
- Battery package
- Use cases
- Manufacturing
- Business

Initially, all interviewees had to answer the questions from the first general section. This section contained mainly technical questions about the chassis and how it works today and general development potential. The general section was followed by a specific section based on the interviewee's competencies, which contains specific questions on how the technology works for the different areas presented. All interviews executed in the second round were conducted in March of 2023. The different areas of interviewees from the second round are presented in Table 3.1, below.

Table 3.1: Interviews conducted in second round

Interviewee	Section(s) from the framework
Power supply engineer	Battery packs
System engineer	Brakes and Steering
System engineer	Brakes
System engineer	Powertrain and Axles
Operational manager	Business case and User experience
Product engineer	Business case
Manufacturing engineer	Manufacturing
Product architect	Business case
Mechanical engineer	Frame

3.2 Value creation strategy (VCS)

The thesis was motivated to use the VCS to support the information between the manufacturer's engineering and business perspectives in developing a modular product architecture for AET. Different stakeholder expectations were defined from the second round of interviews, with more in-depth information collected. By elaborating on the stakeholder expectations, the establishment of stakeholder needs, value dimensions, and value drivers was possible. The methodology of the VCS is visualized in Figure 3.2.

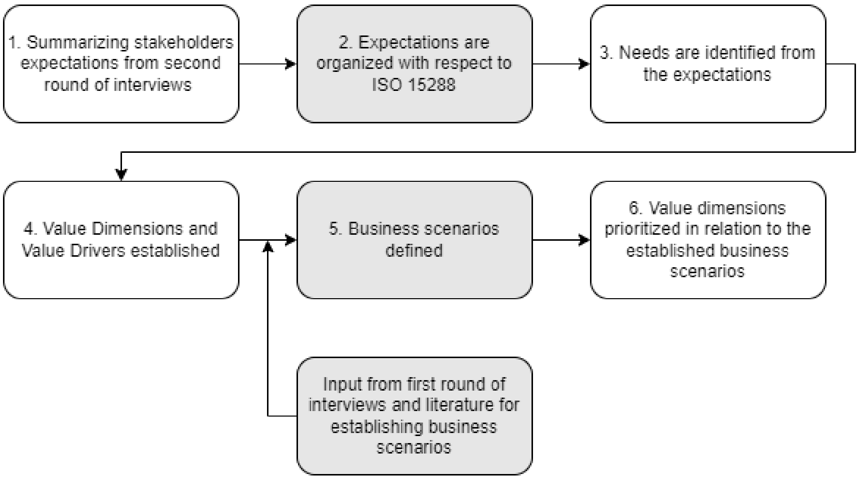


Figure 3.2: An overview of the applied method for executing the VCS

In the first step (1), all stakeholders' expectations from the second round of interviews were summarized. As well as validated to ensure that they were relevant to the chassis. All stakeholders' expectations were revised in the next step (2). As different stakeholders had similar expectations, these needed to be reviewed. Therefore, similar expectations were merged and presented as one common expectation. All expectations were organized after the technical standard ISO 15288 developed by International Organization for Standardization (ISO) to ensure that the entire chassis and relevant processes were covered.

The standard is a framework of processes for an entire life cycle of a system developed by humans. There are four different main categories of the standard, Agreement processes, Organizational project-enabling processes, Project processes, and Technical Processes (International Organization for Standardization, 2015). For the chassis, the technical processes were selected to follow. This category covers the entire cycle for the intended product, from defining stakeholder requirements- to disposal processes. The third step (3) included defining needs from the stakeholder expectations, by interpreting raw data in terms of customer needs. At this step, the collected data from the expectations were converted into statements of stakeholder needs. The following guideline from Ulrich et al. (2019) were considered when the expectations were converted into stakeholder needs.

- “Express the need in terms of what the product has to do, not in terms of how it might do it.”
- “Express the need as specifically as the raw data.”
- “Use positive, not negative, phrasing.”
- “Express the need as an attribute of the product.”
- “Avoid the words must and should.”

The next and fourth step (4) was to establish value dimensions and value drivers from the stakeholder needs. Each need was given a relevant value dimension as an attribute. Furthermore, value drivers were created for each value dimension. Sets of value drivers for each value dimension are based on engineering aspects, which indirectly create value for the affected stakeholder. With all value- dimensions, and drivers established, the next step (5) included defining different business scenarios. Various business scenarios were used to prioritize the different value dimensions according to the selected scenarios. As stated in the Literature review, different business scenarios enable the possibility to concurrently work with different concepts and base them on different priorities (Panarotto et al., 2020).

Lastly were all the value dimensions prioritized in relation to the established business scenarios in the final step (6). Creating a prioritization matrix for each scenario gave all value dimensions a priority index in a percentage distribution. The prioritization matrix took all value dimensions into account. Where each value dimension was weighed with respect to the other. A numerical value of “1” and “0” was used for the weighting. Where “1” corresponded to the specific value dimension being more important than the dimension it was weighted against and vice versa with “0”. Subsequently, the amount of “1’s” for each value dimension was summarized, and thus a percentage prioritization of the numbers of “1’s” for each value dimension could be calculated. Finally, all priorities of the different value dimensions were also compiled in a radar chart to visualize how they differed between the different business scenarios clearly. The radar chart was created to visualize how real business scenarios affect different priorities, as explained in the Literature review (section 2.6).

3.3 Generating product architectures

Different product architecture concepts were generated after establishing value dimensions and value drivers to develop a modular product architecture with the VCS. This was done by conducting a patent search and using the Enhanced Function-Means tree and Design structure matrix methods.

3.3.1 Patent search

The patent search was performed to provide inspiration for future concepts, presented as an overview of the changing technologies' impact on chassis architecture. Another aim of the patent search was to identify active patents that could possibly affect the development of a modular chassis architecture. To perform the patent search, two different databases were used: the European Patent Office's online service, Espacenet, and Google Patents. The collected information from the patent search was documented in a table with the following information, patent number, description, the status of the patent, IPC (international patent classification), and keywords used to find the patent.

3.3.2 Enhanced Function-Means tree

It was decided to use an enhanced function-means tree (EF-M tree) to generate different concepts and design solutions for a chassis. The EF-M tree is used to visually represent functional requirements and design solutions for a product. Assessing various design solutions for common functional requirements provided the possibility of creating several concepts simultaneously (Schachinger & Johannesson, 2000). Compared to the use of a function-means tree, the EF-M tree allows representation of the connections between solutions and links them according to different relations (Denman, Kaushik, & de Weck, 2011). The connections that were specified in the EF-M tre are spatial, energy, information, and material. These are seen to be the most common connections investigated when designing a modular product architecture (Habib, 2014).

The EF-M tree was created with the design exploration and business activity simulator (DEBAS). The DEBAS tool was provided by the SED-lab at Chalmers University of Technology. In the tool, different functional requirements for a chassis were mapped out together with different design solutions. Displaying the functions and different solutions in this way, made it possible to configure different concepts that can vary in terms of the chassis architecture. Specifying connections between the different concepts enabled the possibility of creating the DSM matrices.

3.3.3 Design structure matrix and clustering

The design structure matrix (DSM) was the method chosen for the thesis to design product architectures and evaluate modularity. As the DSM is an efficient method for visualizing and generating insights into the product architecture (Eppinger & Browning, 2012). The method was selected to visualize different chassis product architectures and understand how connections and modularity change over different concepts. The concepts evaluated with DSM clustering were generated from the EF-M tree. As the DSM method can also be used to design a modular product architecture (Eppinger & Browning, 2012), it was selected to cluster components and systems into modules and specify the different interfaces in the product architecture.

To analyze the DSM a clustering algorithm was selected, to be able to cluster the components into modules with minimum dependencies based on the connections between components (Eppinger & Browning, 2012). The clustering was performed with the numeric computing platform MATLAB and the algorithm for setting up the matrices and clustering was provided by Thebeau. Based on his investigation in knowledge management of system interfaces and interactions for product development processes (2001). In each DSM matrix, the cells were marked with an "S", "E", "I", and "M", identifying whether there was a spatial, energy, information, or material connection between two different components. From the results obtained in the EF-M tree, the components and the connections were mapped in original DSM matrices in a sheet. Thereafter, the matrices were converted to MATLAB code, in order to cluster the matrices.

With the MATLAB code, it was only possible to cluster DSM matrices based on a value, not the type of connections. Therefore, a connection between two components in the DSM matrix was assigned "1", in the MATLAB code. The DSM matrices were therefore separately clustered four times for each selected concept, in relation to each type of connection. They were then compared and analyzed to evaluate the changing modularity index between the different connections and concepts. Besides performing clustering individually on the different connections, a complete clustering was performed, with respect to all different types of connections between the components which was named total clustering. To perform the total clustering, the components with several types of connections were weighted higher than those with only one type of connection. This was inspired by Thebeau who used a similar approach of weighting the connections from strong to weak, by assigning high or low values for the connections (2001). The connections were weighted with different values to create the weighted connections in the MATLAB code. If there was one type of connection identified between two components it was assigned "1" (low-weighted), for two types of connections it was assigned "1,5" (medium-weighted), and for three or more connections it was assigned "2" (heavy-weighted).

The algorithm runs iterations of the clustering and selects the optimal clustered matrix, by applying a modularity cost function. The modularity cost function results in a value that changes depending on the penalties that are distributed in the algorithm. The penalties are assigned to the clustered matrix based on two different results: the clusters' size and the number of connections outside of a cluster. Equation 3.1 shows how penalties are assigned depending on the size of the cluster. In Equation 3.2, display how penalties are assigned depending on the number of connections that occur outside of a cluster. The total modularity cost function is affected by the penalties assigned in the algorithm, presented in Equation 3.3 (Thebeau, 2001). Then the total modularity cost function of the clustering algorithm was translated to a modularity index. As the modularity cost function decreased, the clusters became more modular. Therefore, a lower modularity index converts to a more modular product architecture.

$$IntraClusterCost = (DSM(j,k) + DSM(k,j)) * ClusterSize(y)^{powcc} \tag{3.1}$$

$$ExtraClusterCost = (TotalCost, k) + DSM(k,j)) * DSMSize^{powcc} \tag{3.2}$$

$$TotalCost = \sum IntraClusterCost + \sum ExtraClusterCost \tag{3.3}$$

where:

$TotalCost$ =Total cluster cost
$IntraClusterCost$ =Cost of connections occurring within a cluster
$ExtraClusterCost$ =Cost of connections occurring outside of clusters
$DSM(j,k), DSM(k,j)$=DSM connections between components j & k
$ClusterSize(y)$ =Number of components in the cluster y
$DSMSize$ =Number of components in the DSM
$powcc$ =Penalizes the size of clusters

Because the resulting modularity index of the clustering is highly affected by the sizes of clusters, an optional feature is available in the algorithm. The algorithm enables extracting a specific component and forcing it to be excluded from any clustering. This makes it possible to exclude specific components from large clusters which the algorithm initially generates. By excluding components with a high number of connections, the larger clusters can be minimized and lower the modularity index. It was decided not to use this feature, to create a consistent execution for clustering the concepts.

The MATLAB algorithm was used to create three different plots which highlighted key information about the product architecture. The different plots provided by the MATLAB code, are the following.

- The original DSM matrix
  - This plot creates the symmetrical matrix based on the initially marked connections between the components.
- The clustered DSM matrix
  - The algorithm plots the clustered connections between the components. Based on the lowest clustering cost the algorithm plots the optimal solution. The modularity index for the clustering was also presented in the clustered DSM matrix.
- The cluster member list
  - Based on the optimal solution for the clustered DSM matrix the algorithm plots a cluster member list. This plot visualizes which components are grouped together and into which clusters.

3.4 Product architecture evaluation

For the finalizing part of the conducted work, all the displayed results were used for further summarizing based on defining the critical factors and how a modular chassis for an AET should be designed. Transferring the result from the VCS and the DSM into two evaluation models enabled the possibility of defining the final results. The final result included a cost model, for evaluating the cost of each concept. Further, a model for defining the adaptability index to future changes. Finally, all concepts were evaluated in relation to each other in the three established factors, modularity index, cost, and adaptability index.

3.4.1 Cost model

By defining the costs for each concept and its modules, it was possible to compare the different concepts in terms of their total module costs. To enable this, it was decided to create a cost model. This model was based on developing a cost factor for the different components used in the concepts. The cost factor was based on internal discussions within the manufacturer and an estimation where made of the costs of the different components. As the cost factors were developed through internal data and analysis, it was chosen to translate their actual financial value to an anonymized scale. The anonymized scale starts from 0 and is infinitely large. This means that the value of the cost factor assigned to each component does not indicate the actual value of the component for the manufacturer. Instead, the cost factor reflects the relative difference in value between components and the concepts. Therefore, a list of the different components for the different concepts was compiled and each component was assigned a value according to the cost factor created. This gave a total value for each concept. Then the cluster lists from the DSM were used to calculate the value of each module for each concept.

This was done to understand the value of each module and if there were any differences between the cost and the different connections. The cost model resulted in two visualized results, one of which was a graph showing the total cost for each concept. Secondly, a table with all the modules and the costs, including the different connections from the DSM. Each module was assigned a color based on a color scale that shifted depending on the costs of the modules. Modules resulting in high costs were assigned a red color and as the cost decreased the color shifted into orange and yellow. The modules with the lowest costs were assigned a green color.

Using the internal data to determine the value of each concept was considered the most appropriate method as the manufacturer had overall knowledge about the required data. To realize what the current cost of constructing an AET would be, based on different concepts. The actual price for the components was based on the price of buying a component off-the-shelf from a supplier, in April 2023. The cost model could have been based on contacting different suppliers and requesting quotes for different components to summarize the data then. However, this was not considered feasible as the cost would mainly be based on the volume delivered by the supplier. This could lead to an uncertain distribution between different costs.

3.4.2 Adaptability model

An adaptability model was created to cover the second factor: adaptability to future changes. The model was based on creating two concepts that were considered futuristic and possible outcomes for the future. Where one concept focused on new technological solutions and the other on potential future legal requirements. The selected concepts were analyzed against the future concepts in order to determine their ability to adapt to future changes. As modularity increases the chances of changing a specific product by upgrading with new components (Rothwell & Whinston, 1990; K. Ulrich, 1994), the adaptability model was chosen to be based on how modular the specific concepts were. Therefore, the mean value of the modularity index between a specific concept and the two futuristic concepts (AET 4 and 5) was calculated. This was done for all concepts using the Equation 3.4, which displays an example of calculating the mean value for the concept “AET 1”. With the calculated mean value of all concepts, it was then decided to present the adaptability index by dividing 1000 with each mean value, as presented in Equation 3.5. This was done to allow the adaptability index to follow the same order as the other results, where the most favorable result is as low as possible.

$$\mathit{Mean\ value\ (AET\ 1)} = \frac{\mathit{AET\ 4} - \mathit{AET\ 1} + \mathit{AET\ 5} - \mathit{AET\ 1}}{2} \tag{3.4}$$

$$\mathit{Adaptability\ Index} = \frac{\mathit{1000}}{\mathit{Mean\ value\ (AET\ 1)}} \tag{3.5}$$

The Adaptability model provided an index for each concept based on the literature on modularity. Other factors such as similarities between modules and future concepts could also have been compared. However, this was discarded as future concepts were created to show what it could possibly look like. This means that these concepts cannot be fully relied upon in the future, only an estimate. Therefore, it was also not considered worthwhile to analyze individual modules.

3.4.3 Summarizing result

Finally, the results of the three factors were compiled, modularity index, cost, and adaptability index. Analyses could be finalized by lining up the different results for each concept in terms of the three different factors where each concept's performance in relation to the different factors was demonstrated. Since three different factors were to be presented simultaneously, a 3D chart was chosen for visualization. This gave a picture of how each concept related simultaneously to the different factors. As a lower value for the three different factors resulted in better performance, the concepts could be evaluated accordingly. This meant that the shortest distance between a concept and the origin of the chart gave a measurable value. The measurements made in the summary of results were used to determine the best concept in terms of modularity, cost, and adaptability.

4

Results

The following chapter presents the results of the First round of interviews, Value creation strategy, Concept generation, Design structure matrix and clustering, and Cost, adaptability, and modularity analysis. Chapter 4, provides data and information on a modular chassis architecture for an AET, which is later used to draw conclusions regarding the objective and aim of the thesis.

4.1 Critical insights for applying a modular chassis design

The first round of interviews conducted in the exploratory phase resulted in information about what employees at the manufacturer know about modularity and how it should be implemented in a chassis design for an AET. The questions that were asked can be seen in Appendix section A.1 and how it was performed is presented in subsection 3.1.2. The following sections present two critical insights from the first round of interviews.

4.1.1 Difference between chassis for an AET and ICE

The interviewees were asked to explain the major differences between a chassis for an AET and an ICE. This resulted in statements that explain the differences between the two chassis, some of the statements are presented in Table 4.1, below.

Table 4.1: Main differences between a chassis for an AET and ICE

AET	**ICE**
ICE	**AET**
"More components"	"Less components"
"Complex design"	"Easier design and geometrics"
"Bended chassis in the front"	"Easier placement of components"
"Propeller shaft"	"Electrical powertrain"
	"Stricter requirements on brakes"
	"Drive by wire"
	"No cabin"

The majority of interviewees mentioned that switching from a diesel-powered to electric-powered chassis will decrease the number of components required. Because there is no need for a propeller shaft and transmission, it will in return create more space for the placement of components in an electric-powered chassis. This leads to increased space for the placement of batteries, by removing the propeller shaft and transmission. As a result, this enables a chassis design that is slightly less complex than a chassis for an ICE. Some of the interviewees also mentioned that developing an autonomous-driven chassis will require a redundant braking and steering system. Since there is no physical driver in an AET, the system needs to be safe and reliable in operations. This can be solved by implementing a redundant steering and braking system.

4.1.2 Parts to be modular in future chassis

To generate an initial understanding of what the goal and objective of a modular architecture were for the manufacturer. The interviewees were asked to specify what components or systems they wished for to be modular in a future chassis architecture for an AET. The answers to this question are presented in a bar chart seen in Figure 4.1 below where the number of times that a component or system is mentioned (y-axis) and the different types of components or systems (x-axis) are displayed.

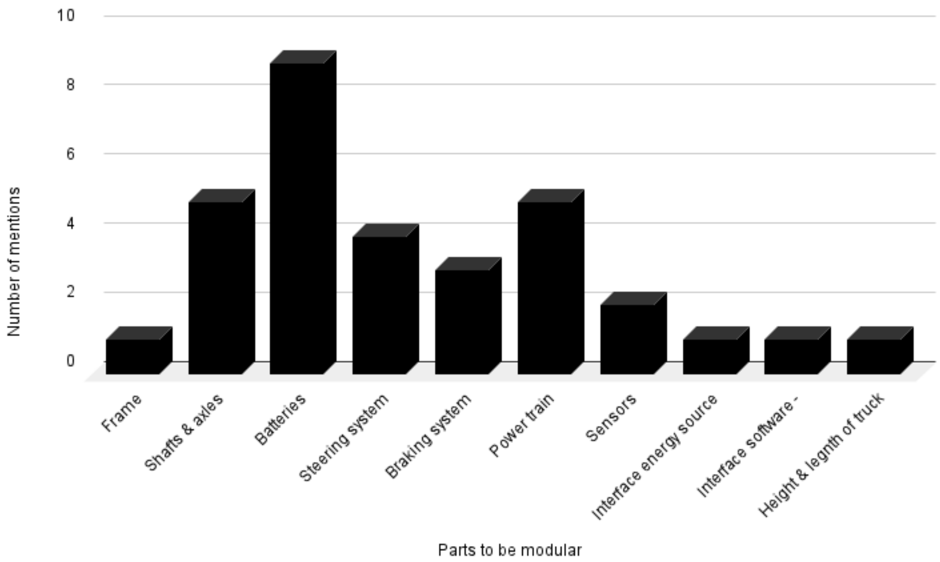


Figure 4.1: Number of mentions of different components to be modular in a chassis architecture for an AET

This showed that the component the interviewees wished for the most to be modular was the battery, and nine interviewees mentioned it. A reason for the interviewees mentioning the batteries was to enable the ability to provide a chassis with different sizes of battery packs. This would result in a chassis with a different range of options for a specific product. Five different interviewees mentioned the shafts/axles and the powertrain on the chassis. They were mentioned to be modular for enabling a variety of load capacities. A few interviewees also mentioned the braking and steering system to be modular, however, the reason for these systems to be modular differed compared to the other components. Having the steering and braking as modular systems were mentioned to enable the possibility of switching technologies and integrating new steering and braking components.

4.2 Needs and expectations for a new chassis design

From the second round of interviews, all the collected data were summarized and analyzed in the VCS, as presented in the Methodology (section 3.2). The collected data was used to define the stakeholder expectations and create value dimensions and value drivers for designing a new chassis. The finalized work of the VCS resulted in a table with 14 different value dimensions with the purpose of identifying value for designing a chassis for an AET. The entire table, including process, stakeholder, stakeholder expectations, stakeholder needs, value dimensions, priority (not specified in the table), and value drivers, can be seen in Appendix section C.1. The first round of summarizing data from the nine interviews resulted in 89 different expectations of a chassis for an AET. Organizing the different expectations with respect to those that included similarities and ISO 15288, resulted in 14 different expectations from the stakeholders.

4.2.1 Defining Value dimensions and Value Drivers

Accordingly, to the different processes and stakeholders, related expectations were summarized, translated into needs, and lastly specified into value dimensions and value drivers. The 14 different value dimensions and value drivers are presented in the following section.

- **Development process efficiency**
  The first value dimension is based on the expectation of having a high pace development process and simultaneously working with breakthrough technology. Therefore, Reducing lead time in the development cycle was identified as a stakeholder need. The selected value drivers for the value dimension were, Time-to-market (month/years) and Required resources (number of employees). This results in measurable values for evaluating the value dimension.

- **Supplier relationship**
  An expressed expectation from the interviews was based on the need to collaborate with suppliers during development while not sharing intellectual properties. Therefore, Supplier relationships were established as a value dimension. The related value drivers are the number of suppliers, the role of suppliers, and confidential agreements.

- **Flexible in adapting to technology changes**
  The third value dimension is identified from the expectation of working with breakthrough technology and is related to the first value dimension. The chassis will need to be built with adaptability taken into account in order to implement new technological changes. This will be driven by minimizing the number of integrated components, to allow for flexibility in changing specific components. As well as estimating to what extent new technology and customers will impact the design of the chassis.

- **Customization ability**
  The chassis should be designed for different use cases, e.g. transport of a container or trailer transport. Another example is the expectation of height-adjustable chassis so that loading and unloading can be adapted to different environments. The expectation leads to the value of having a chassis with the ability to customize. The specific value drivers can be seen in Appendix section C.1. Depending on a specific use case for an intended chassis several different form factors will act as a value driver. The number of different use cases will play a crucial role, in the possibility of integrating a variety of performances and creating a modular design that can be measured with a modularity index. More specifically, the outcome will depend on varying parameters such as the battery capacity, powertrain, and load.

- **Future legal requirements**
  The interviews revealed an awareness of complying with future legal requirements. This indirectly means that the chassis must be compliant with future legislation. It can be achieved through different strategies by focusing on compliance with current legislation without aiming for future changes. Or making predictions about future legislation and taking this into account when developing a chassis. Published legislation will be required to follow and will be used to predict future outcomes. For example, legislation for systems such as powertrains and batteries could be changed in the nearest future.

- **System reliability**
  In the scope of a fully autonomous truck, there is a need to ensure safety measures and redundancy in the operations. Therefore value drivers such as the number of safety systems and safety requirements are established. Furthermore, a reliability system is not only connected to autonomous operations, e.g., the diagnostics system of the entire chassis will affect the reliability. As well as the additional implications of placing heavy battery packs on the chassis and having a powertrain that is provided with electricity. This leads to the importance of having reliable cooling/heating systems that ensure the vehicle can operate safely.

- **Reduced complexity**
  In the process of defining the architecture of a chassis, the expectation of reducing components to decrease complexity which would lead to more open space was stated. By allowing for more open space other opportunities would be enabled, such as more efficient assembly and future changes of components, according to the manufacturer. The value drivers of reducing complexity are established in relation to the total number of components, unit cost, reduced weight, placement of components, and available space.

- **Battery safety reliability**
  There are several factors to consider when mounting the battery packs on the chassis, mounting them safely and not exposing them to harmful vibrations. The cells in the battery pack can withstand a certain degree of vibration during operation. However, the actual degree to which the cells are exposed can be influenced by a number of different driving factors. These factors are indirectly affected by the architectural placement of the packs on the chassis, as well as managing to absorb vibrations. As a part of protecting the battery packs, it is also important to ensure the safety of the surrounding environment, e.g., how the battery pack placement would impact a collision with a vehicle.

- **Optimized functional placement**
  The performance of each function in the chassis is directly influenced by the placement of certain components. Different functions, such as steering, braking, and powertrain, are all affected by individual and collective components. By optimizing the functional placement of the components, the efficiency of e.g. the steering, braking, and powertrain can be improved.

- **Manufacturability**
  The outcome of the previously defined processes will result in a designed chassis for the AET where production also needs to be taken into consideration. Production in this case includes the components' manufacturing and the chassis' assembly process. Both manufacturing and assembly are included in production because the manufacturer wants to explore different strategies for the production process. The expectations for production are that it should be simple and efficient by being standardized. In addition, manufacturability is therefore driven by the number of standardized components, the unit cost of the components, and the production processes respectively. Another expressed value driver for manufacturability was the placement of cables on the chassis. This was considered to affect many parts of the chassis as the cables have to be routed through several locations on the chassis.

- **Standardized components**
  Enabling components to be used for multiple use cases leads to more efficient development of new products and lower costs. This would be solved by having standardized components. However, this is influenced by various value drivers, such as the requirement for standardized interfaces to ensure the assembly of components in different variants. The number of standardized components and interfaces also affects the performance of the vehicle. Furthermore, having standardized components decreases component costs. Components can be bought based on off-the-shelf prices, which are lower than customized components' costs.

- **Operational reliability**
  As part of the design and production of the chassis, it is also important to cover and take into account the operational processes. Within the operational processes, a sector of reliability was discovered as an expectation of the chassis. Factors affecting reliability were expressed for the chassis and are applicable at different stages of the product life cycle. Firstly, during the design phase, the placement of components that indirectly affect the placement of gravity is a factor to be aware of. Secondly, factors such as vibration and energy consumption affect the reliability of the vehicle during the operational phase. Thirdly, it is important to analyze the total lifetime of components and the vehicle as a whole to estimate service intervals.

- **Energy efficiency**
  For the development of a fully electric chassis, it was expected that the number of energy conversions could be reduced. Reducing the number of energy conversions would lead to reduced energy consumption as the energy losses from the conversions would be eliminated. In advance, trucks traditionally rely on both hydraulic and compressed air systems. The interviews highlighted the interest in discovering the possibility of replacing hydraulic brakes with electromechanical brakes. Value drivers for energy efficiency are affecting electricity consumption overall, the efficiency of different systems, and the number of energy conversions. Other relevant factors are the energy efficiency of different systems (e.g., steering, braking, and powertrain) affected by friction and air resistance.

- **System serviceability**
  During the operation process, the ability to attach and detach components and access cables is stated as an expectation to increase the chassis' serviceability. Value drivers for system serviceability are applied in different life cycle phases of the chassis, both in the design and in the operation processes. In terms of the design phase, the choice and placement of components is crucial. Having an integrated architecture reduces the possibility of attaching and detaching specific components as they are interconnected with each other. The placement of the components can also provide various opportunities to reduce service time, i.e., having a more accessible placement. It is also important to have standardized service processes to enable greater efficiency during maintenance and the number of steps each process requires.

4.2.2 Prioritization accordingly to three business scenarios

To generate insights into how real business scenarios affect the design of a modular chassis architecture. Three different business scenarios were listed as the value dimensions are prioritized according to the business scenarios. The business and engineering perspectives are merged, to identify trade-offs between different business scenarios, as stated in the Literature review (section 2.6). The different scenarios were established by input from the first round of interviews, together with supporting literature that was focused on the driving forces of new product development. Therefore, the three different business scenarios were selected and are listed and explained below.

Low costs
The scenario was motivated by the sense of operating within an intense international competing market. Where focus on keeping the costs down needs to be prioritized for being able to acquire market shares, which the manufacturer mentioned. This is related to the development of a chassis for an AET where the focus would limit the development of a solution for one specific use case since focusing on several use cases would increase costs.

Adapting to technology and legislation changes
The second business scenario was linked to the literature by highlighting diverse and rapidly changing technologies. As well as combined with internal discussions about future legislation and how that could affect the development of a chassis. In terms of a chassis for an AET, this would result in a modular architecture with a focus on the ability to replace components based on new changes. Ensuring the possibility of meeting new changes without having to rebuild the entire architecture.

Customization ability
The third scenario was inspired by the literature where fragmented, demanding markets were mentioned. This also relates to the internal discussions with the manufacturer, who stated a wish to offer different solutions for various use cases. Applying a modular architecture would enable the possibility of offering different variations for different use cases.

The results of the VCS with the value dimensions prioritized accordingly to the three different scenarios were summarized in a radar chart, which can be seen in Figure 4.2. From the result, trade-offs between the different scenarios were identified. Presenting that a given business scenario will affect the priority of the value dimensions. For the following presented result of the thesis, the four value dimensions Flexible in adapting to technology changes, Customization ability, Flexible in adapting to future legal requirements, and Component standardization were mostly focused on. Because these value dimensions turned out to have a large variation in priority between the different business cases. And the following result showed that these value dimensions had a significant influence on the different architectures.

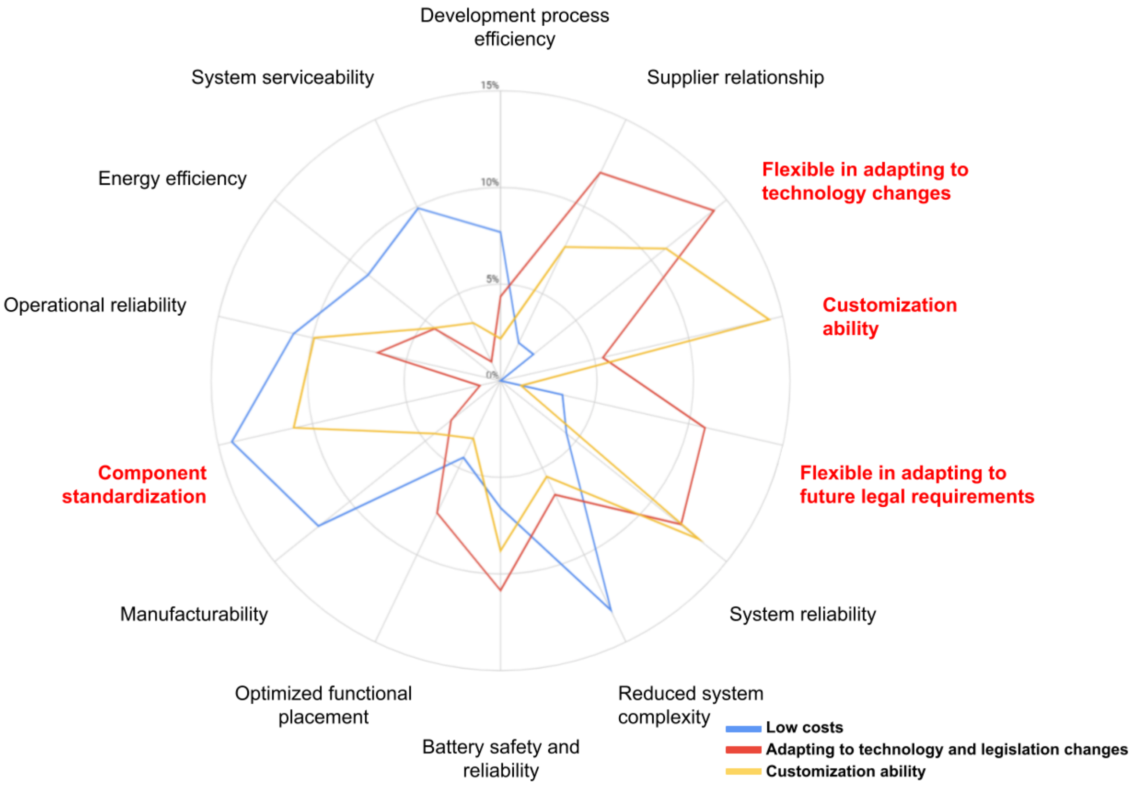


Figure 4.2: Presented result of the VCS with a radar chart where three different business scenarios were prioritized accordingly to 14 different value dimensions.

According to the value dimensions, Development process efficiency was the Low costs scenario highest prioritized (8 %), compared to the two other scenarios (4 % and 2 %). The value dimension was prioritized for all three different scenarios, however, the Low costs scenario requires more focus on efficiency within the development process.

The most prioritized scenario in the value dimension Supplier relationship was Adapting to technology and legislation changes (12 %) and followed by Customization ability (8 %). Compared to the Low cost scenario which received a significantly lower prioritizing (2 %). This was motivated by the possibility of delivering a product with different variations or adapting to future changes, which will require a well-functioning and developed relationship with suppliers. Compared to the Low cost scenario where developing relationships is less important, and the focus is on having the most cost-effective parts. In the two value dimensions Flexible in adapting to technology changes and Customization ability, was the Low cost scenario prioritized as the lowest. While the two other scenarios alternated being the highest and second highest prioritized. In the value dimension Future legal requirements, the customization ability scenario received a very low priority (1 %), which was lower than the Low cost scenario (3 %). This is due to the fact that future legal requirements are not prioritized in a solution that offers variations based on present needs.

The radar chart also included value dimensions where the Low cost scenario was prioritized highest compared to the other two scenarios. For example in Reduced complexity, Manufacturability, and Standardized components. For reduced complexity, the Low cost scenario succeeds in prioritizing this more compared to the other two scenarios where offering variety and technology changes is more prioritized compared to decreasing complexity.

In the value dimension Manufacturability, the Low cost scenario has a higher priority for manufacturing, due to the strong relationship between manufacturing and cost. Compared to the other two scenarios, where other value dimensions are more important. For the value dimension Standardized components, both Low cost (14 %) and Customization ability (11 %) resulted in high priorities. Compared to Adaptability for future changes, which received a significantly lower priority, only 1 %. Using standardized components increases cost efficiency as fewer new components must be designed and integrated. And in the case of a product architecture that can offer variants, the standardized components are important for building a foundation of the architecture. Therefore, having standardized components is more prioritized in the Low cost and Customization scenario than Adapting to future changes.

4.3 Concept generation

To generate different concepts it was chosen to display the functions and components of a chassis in an EF-M tree. The EF-M tree was selected because of the possibility of creating several concepts simultaneously based on common functional requirements. This is explained further in the Methodology (subsection 3.3.2). Several functions required for a chassis were added to the tree including possible design solutions. This resulted in several design alternatives for a common function. The different design solutions and functional requirements are identified from the results retrieved in the Literature review, patent search presented in the Appendix (section B.1), and first-round and second-round interviews.

The complete EF-M tree resulted in six different concepts for a truck's chassis. The different identified concepts were ICE, AET 1, AET 2, AET 3, AET 4, and AET 5. The different connections (spatial, energy, information, and material) between the design solutions were specified to create the original DSM matrices. Below, an excerpt of the EF-M tree is displayed in Figure 4.3. This figure shows the part of the EF-M tree which displays the main function of *providing acceleration*. In the following excerpt, it is displayed that solving the function of *providing acceleration* can be solved by the following three design solutions *internal combustion engine (ICE)*, *E-axle*, and *electric engine*. These different solutions in return have different functional requirements which need to be solved by other design solutions.

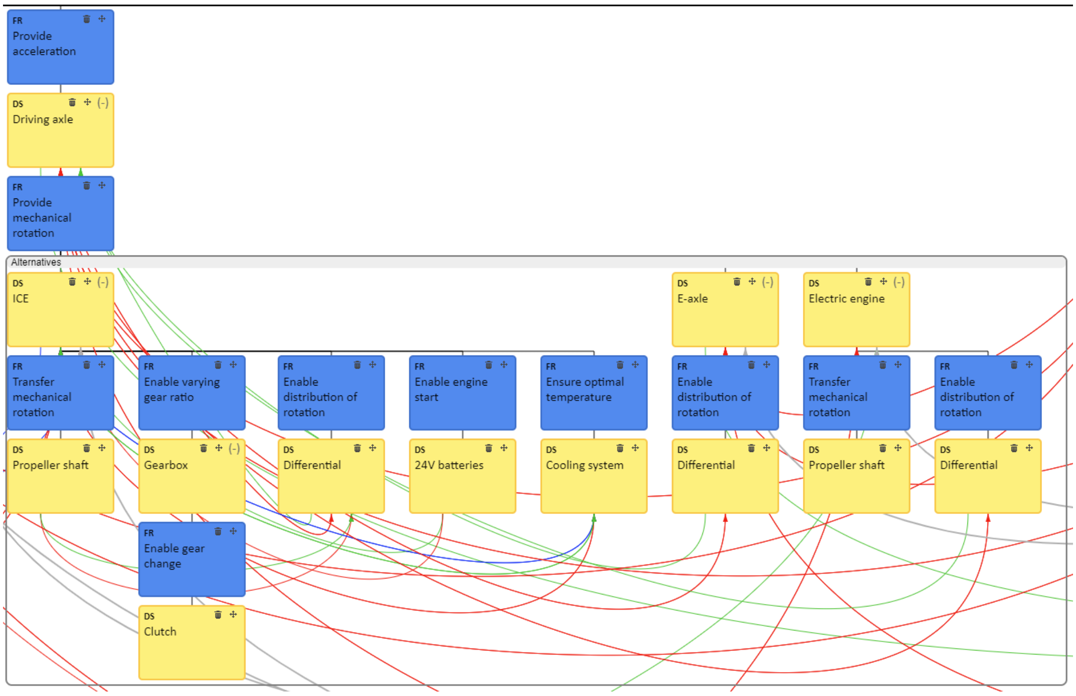


Figure 4.3: Excerpt of the EF-M tree showing the main function of *providing acceleration*, the different design solutions and connections between design solutions indicated with colored lines.

Chassis powered by an ICE and operated by a human driver: ICE

ICE is identified as a chassis for a truck operated by a human driver and powered by an internal combustion engine (ICE). The purpose of the ICE concept was to generate insights into how the components interact with each other. The ICE concept consists of 29 components that are presented in the list below.

1. Drive axle
2. Frame
3. Crossmembers
4. Air suspension
5. Rear wheels
6. Servo motor
7. Combustion Engine
8. Gearbox
9. Clutch
10. Propeller shaft
11. Transfer gearbox
12. Front wheels
13. Front brakes
14. Differential
15. AdBlue tank
16. Air tank
17. Fuel tank
18. Steering wheel
19. Air compressor
20. Cooling system engine
21. Batteries 24V
22. Fan
23. Steering joint
24. Exhaust pipe
25. Underrun protections
26. Brake pedal
27. Throttle (pedal)
28. Steering axle
29. Rear brakes

Chassis for an AET based on conventional components used in an ICE: AET 1

The second concept is a chassis for an AET based on conventional components from an ICE, and the concept was named AET 1. The components analyzed in this concept are similar to the components used for the ICE. However, some components are substituted so that the chassis has design solutions required for autonomous and electric chassis. This can be seen in Figure 4.3, where the electric engine was selected to provide mechanical rotation. The AET 1 consists of 27 components that are listed below. The components visualized in blue are the ones that are changed and added compared to the previous concept of Chassis powered by an ICE and operated by a human driver: ICE.

1. Frame
2. Underrun protection
3. Crossmembers
4. Sensors
5. Battery pack
6. Battery cooling/heating system
7. Charging system
8. Power controlling system
9. DC/DC converter
10. Electric engine
11. Gearbox
12. Driving axle
13. Rear wheels
14. Steering control system
15. Steering motor
16. Steering axle
17. Breaking control system
18. Rear brakes
19. Air compressor
20. Air tanks
21. Air suspension
22. Electric box (EDS)
23. Cooling system electric engine
24. Propeller shaft
25. Differential
26. Front wheels
27. Front breaks

Chassis for an AET based on new technologies within the field of electric and autonomous driven trucks: AET 2

Concept AET 2, is a chassis for an AET that is based on other technologies compared to the conventional components selected for AET 1. The purpose of this concept was to evaluate how variating technology can impact the product architecture and the modularity of the chassis. Two of the new components for the AET 2 concept are the E-axle and the Vehicle control unit (VCU). The E-axle serves as the chassis powertrain where the electrical engine is integrated with the driving axle. The VCU is also a new component that controls the chassis acceleration, braking, and steering. The components included in the chassis of AET 2 were selected based on information collected from the second round of interviews. The 20 components included in the concept AET 2 are listed below. The components visualized in blue are the ones that are changed and added compared to the previous concept of Chassis for an AET based on conventional components used in an ICE: AET 1.

1. Frame
2. Underrun protection
3. Crossmembers
4. Sensors
5. Battery pack
6. Battery cooling/heating system
7. Charging system
8. DC/DC converter
9. E-axle
10. Rear wheels
11. Steering motor
12. Steering axle
13. Rear brakes
14. Air compressor
15. Air tanks
16. Air suspension
17. Electric box (EDS)
18. Front wheels
19. Front breaks
20. VCU

Chassis for an AET without the compressed air system: AET 3

Another concept based on further technologies, was created and named AET 3. This concept visualizes how the chassis architecture was affected by removing the air system. During the second round of interviews, removing the need for compressed air in the chassis design was mentioned as an expectation. It was necessary to change the braking and air suspension systems to disable the need for compressed air in a chassis for trucks. AET 3, therefore, has electro-mechanical brakes and leaf springs instead of air brakes and air suspensions, which are used in AET 2. There are 19 components included in concept AET 3, listed below. The components visualized in blue are the ones that are changed and added compared to the previous concept of Chassis for an AET based on new technologies within the field of electric and autonomous driven trucks: AET 2.

1. Frame
2. Underrun protection
3. Crossmembers
4. Sensors
5. Battery pack
6. Battery cooling/heating system
7. Charging system
8. DC/DC converter
9. E-axle
10. Rear wheels
11. Steering motor
12. Steering axle
13. Rear brakes (electro-mechanical)
14. Electric box (EDS)
15. Front wheels
16. Front brakes (electro-mechanical)
17. VCU
18. Rear leaf springs
19. Front leaf springs

Futuristic design based on technology advancement for a Chassis of an AET with in-wheel motors: AET 4

A fifth concept named AET 4 was created. This concept was created to analyze how the chassis product architecture can change due to future changes in technology. Several new components and systems have been added to AET 4. The selection of components is based on the result of the patent search and the second round of interviews. It was decided to add in-wheel motors and steering on each wheel. This aims to optimize the truck's maneuvering capabilities of the truck (William J. Bluethmann et al., 2013), as presented in the patent search. Because the concept has in-wheel drive and steering on each wheel, it was decided to separate the components wheels, motors, steering, and brakes. These components were specified with F-R (Front-Right), F-L (Front-Left), R-L (Rear-Left), and R-R (Rear-Right), based on their placement. AET 4 was also equipped with a robotic arm connected to the chassis. The purpose of enabling the automatic loading and unloading of goods was raised as an expectation from the second round of interviews. Another change that was implemented in AET 4, was the function of train transportation. Therefore, a front and rear train connection was added to the chassis, which enables several trucks to drive in a connected train formation. The AET 4 concept resulted in 32 components which are presented in the list below. The components visualized in blue are the ones that are changed and added compared to all previously presented concepts.

1. Frame
2. Underrun protection
3. Crossmembers
4. Sensors
5. Battery pack
6. Battery cooling/heating system
7. Charging system
8. DC/DC converter
9. In wheel motor (F-R)
10. In wheel motor (F-L)
11. In wheel motor (R-L)
12. In wheel motor (R-R)
13. Front brakes (F-R)
14. Front brakes (F-L)
15. Rear brakes (R-L)
16. Rear breaks (R-R)
17. VCU
18. Wheel (F-R)
19. Wheel (F-L)
20. Wheel (R-L)
21. Wheel (R-R)
22. Steering motor (F-R)
23. Steering motor (F-L)
24. Steering motor (R-L)
25. Steering motor (R-R)
26. Air suspension
27. Air tank
28. Air compressor
29. EDS
30. Robotic loader/unloader
31. Train connection front
32. Train connection rear

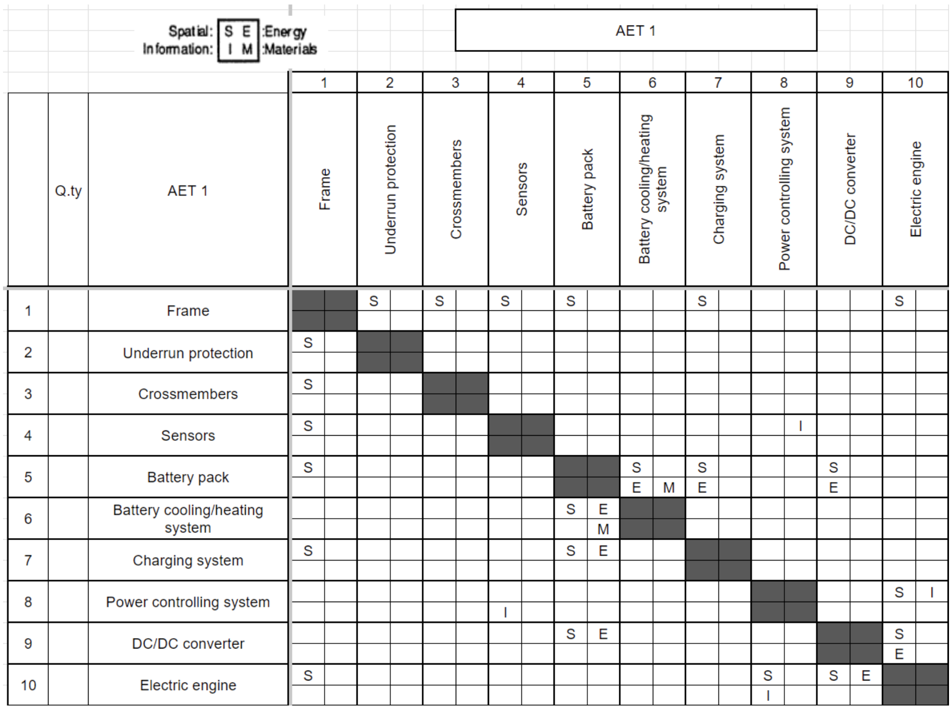
Futuristic design based on future legal requirements for a Chassis of an AET with multiple steering and braking systems: AET 5

It was decided to create a final concept that is related to future legal requirements, which was identified as a scenario in the VCS. This resulted in concept AET 5, including selected components with the purpose of following future legal requirements, that might occur in the field of autonomous and electric vehicles. The second round of interviews stated that an autonomous-driven chassis needs to be redundant for failure. One possible solution for redundancy is to have multiple steering and braking systems that are independent of each other. This means that if one system that controls the steering or braking fails, then the second system can still function and operate the vehicle safely. AET 5 is therefore equipped with multiple steering and braking systems, that can control the chassis if something were to fail. The concept is also equipped with a potential new type of battery pack called Lignode batteries. This is selected to meet new possible legal requirements that could prohibit the use of lithium batteries. Since the production of lithium batteries is harmful to the environment (Nature, 2021), legislators might force manufacturers to start producing more environmentally friendly batteries. Hence, Lignode batteries are a possible future solution to this. Due to the fact that they are made from a renewable material that can be found in trees called lignin (Storaenso, 2022). Another legal requirement that was predicted was the use of inductive charging. Countries are starting to explore the possibility of building electric roads with inductive charging (Power-Circle, 2021). If this is proven to be successful, countries might require electric vehicles to have inductive charging. Then it would be necessary to change the product architecture to enable flexible charging alternatives. AET 5 is therefore equipped with a component called, power electronics receiver, which makes it possible to use inductive charging. The concept AET 5, therefore, resulted in 26 components, which can be seen in the list below. The components visualized in blue are the ones that are changed and added compared to all previously presented concepts.

1. Frame
2. Underrun protection
3. Crossmembers
4. Sensors
5. Lignode batteries 1st
6. Battery cooling/heating system
7. Charging system
8. DC/DC converter
9. E-axle
10. Front brakes (air)
11. Rear brakes (air)
12. Reciver power electronics
13. Rear brakes (electro-mechanical)
14. Lignode batteris 2nd
15. Front brakes (electro-mechanical)
16. VCU 1st
17. VCU 2nd
18. Front wheels
19. Rear wheels
20. Steering motor 1st
21. Steering motor 2nd
22. Air suspension
23. Air tank
24. Air compressor
25. EDS
26. Steering axle

4.4 Generating and evaluating chassis product architectures

To identify the chassis architecture and analyze the modularity index, a design structure matrix supported by clustering was used, as described in the Methodology (subsection 3.3.3). By identifying the concepts and the connections between the components, the six original DSM matrices were created for each concept. An excerpt from the original DSM matrix of AET 1, showing the first ten components can be seen in Figure 4.4 below. By performing the analysis, the modularity index was identified for each product architecture of the concepts. This enabled the possibility of focusing on evaluating the value dimensions of customization ability and adapting to future changes (technology and legal) because this analysis indicates how well the concepts performed seen to the value driver, modularity index.



Spatial: S E :Energy
Information: I M :Materials

AET 1

	Q.ty	AET 1	1 Frame	2 Underrun protection	3 Crossmembers	4 Sensors	5 Battery pack	6 Battery cooling/heating system	7 Charging system	8 Power controlling system	9 DC/DC converter	10 Electric engine
1		Frame	■	S	S	S	S		S			S
2		Underrun protection	S	■								
3		Crossmembers	S		■							
4		Sensors	S			■				I		
5		Battery pack	S				■	S E M	S E		S E	
6		Battery cooling/heating system					S E M	■				
7		Charging system	S				S E		■			
8		Power controlling system				I				■		S I
9		DC/DC converter					S E				■	S E
10		Electric engine	S							S I	S E	■

Figure 4.4: Excerpt of the original DSM matrix with the first 10 components and their connections displayed

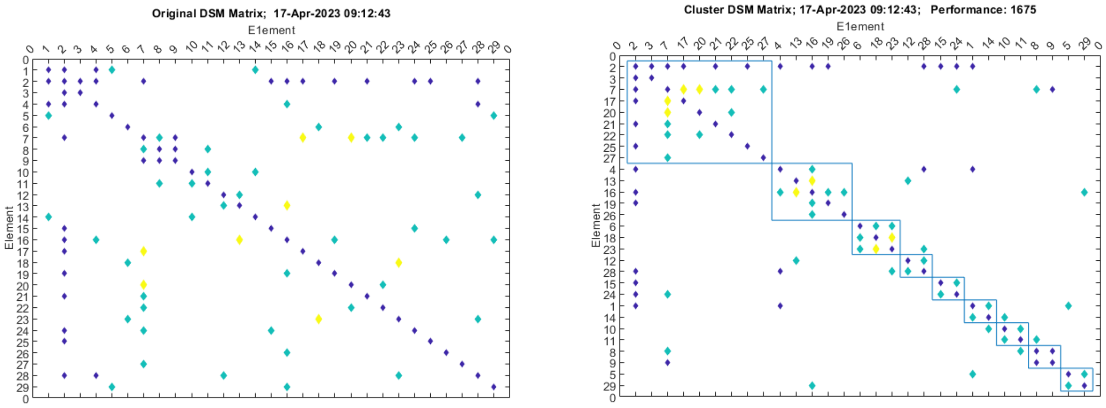
Running the different MATLAB scripts generated different results and visualizations. It resulted in a figure over the original DSM matrix, a figure over the clustered DSM matrix, a cluster list, and a graph of the clustering performance. The original DSM matrix visualizes the connections between the components with a point. The weighting of the connections is displayed by changing the color of the point. Purple indicates one connection between the components (low-weighted), turquoise indicates two types of connections (medium-weighted), and yellow indicates a strong-weighted connection with three or four types of connections (heavy-weighted).

The clustered DSM matrix shows how the points/connections are rearranged to build different clusters. The boundaries for the clustered components and connections are specified with a turquoise square and are listed in the cluster member list.

Models for analyzing the modularity, cost, and adaptability of the different concepts were created to generate insights into the modularity index between the concepts and the different connections. The modularity index retrieved from clustering components based on the different types of connections is presented in the following section. The relation between the cost, adaptability, and modularity index is analyzed and presented in the following sections. Overall a total cost is presented for all six concepts, where the costs for concepts ICE, AET 1, 2, and 3 are specified in more detail. AET 4 and 5 are used as reference points to generate the adaptability index for the other concepts.

4.4.1 ICE with a modularity index of 1675

In concept ICE a total of 144 different connections were identified between the 29 components. Running the clustering for ICE resulted in the original DSM and clustered DSM matrix seen in Figure 4.5, below. The algorithm calculated a modularity performance of 1675 for ICE. The components were divided into nine different clusters, these clusters are presented in the cluster member list seen in Table 4.2, below.



(a) Original matrix **(b)** Clustered matrix

Figure 4.5: Original and clustered DSM matrices for ICE, with the connections mapped out by colored points. Purple = low-weighted connections. Turquoise = medium-weighted connections. Yellow = strong weighted connection.

Table 4.2: Cluster member list of ICE

Cluster #1
Frame (2)
Crossmembers (3)
Combustion engine (7)
Fuel tank (17)
Cooling/heating system engine (20)
Batteries 24V (21)
Fan (22)
Underrun protection (25)
Throttle (pedal) (27)

Cluster #2
Air suspension (4)
Front brakes (13)
Air tank (16)
Air compressor (19)
Brake pedal (26)

Cluster #3
Servo motor (6)
Steering wheel (18)
Steering joint (23)

Cluster #4
Front wheels (12)
Steering axle (28)

Cluster #5
AdBlue tank (15)
Exhaust pipe (24)

Cluster #6
Drive axle (1)
Differential (14)

Cluster #7
Propeller shaft (10)
Transfer gearbox (11)

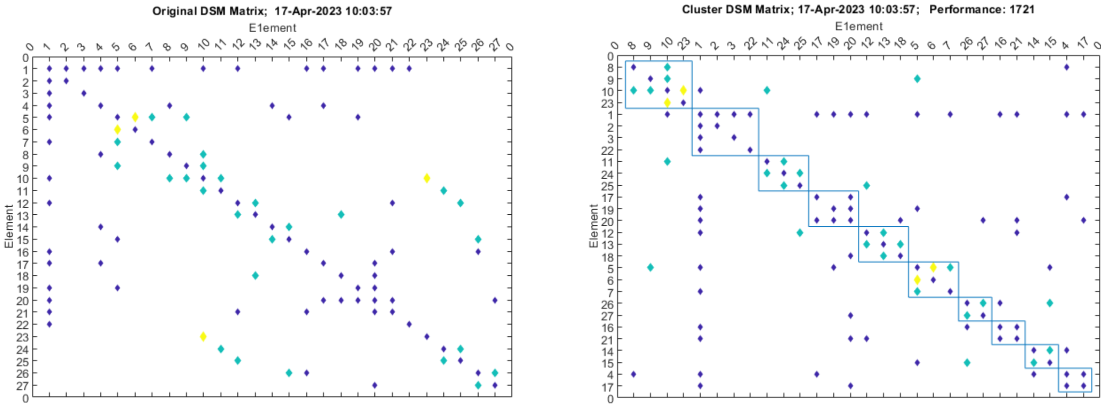
Cluster #8
Gearbox (8)
Clutch (9)

Cluster #9
Rear wheels (5)
Rear brakes (29)

The clustering of ICE resulted in a large cluster #1 which includes a lot of components that provide different functions for the chassis, such as the frame, combustion engine, and cooling/heating system engine. This cluster contains both heavy-weighted connections and some low-weighted connections. On the other hand, clusters #2 and #3 mainly consist of components with high-weighted connections, and no low-weighted connections are included.

4.4.2 AET 1 with a modularity index of 1721

The total number of connections identified for AET 1 resulted in 116 connections based on 27 components. The clustering of the components and connections resulted in a modularity index of 1721. The original and clustered DSM matrix can be seen below in Figure 4.6. Clustering of AET 1 resulted in a cluster member list that contains ten different clusters. The clusters and corresponding components are seen below in Table 4.3.



(a) Original matrix

(b) Clustered matrix

Figure 4.6: Original and clustered DSM matrices for AET 1, with the connections mapped out by colored points. Purple = low-weighted connections. Turquoise = medium-weighted connections. Yellow = strong weighted connection.

Table 4.3: Cluster member list of AET 1

Cluster #1
Power controlling system (8)
DC/DC converter (9)
Electric engine (10)
Cooling system engine (23)

Cluster #2
Frame (1)
Underrun protection (2)
Crossmembers (3)
Electric box (EDS) (25)

Cluster #3
Gearbox (11)
Propeller shaft (24)
Differential (25)

Cluster #4
Breaking control system *(17)
Air compressor (19)
Air tanks (20)

Cluster #5
Driving axle (12)
Rear wheels (13)
Rear brakes (18)

Cluster #6
Battery pack (5)
Battery cooling/heating system (6)
Charging system (7)

Cluster #7
Front wheels (26)
Front breaks (27)

Cluster #8
Steering axle (16)
Air suspension (21)

Cluster #9
Steering control system (14)
Steering motor (15)

Cluster #10
Sensors (4)
Braking control system *(17)

The components of the clusters for AET 1 are evenly distributed between the clusters, cluster #1 to #6 contains three to four components each. It creates more evenly sized clusters compared to the cluster member list of ICE, where the biggest cluster (#1) contains four more components compared to the second largest cluster (#2). The clusters in AET 1 contain components that either have high-weighted connections or low-weighted connections. Clusters #1 and #5 only contains components that have high-weighted connections and clusters #2, #4, #8, and #10 contains components that have low-weighted connections. This is different from the cluster member list of ICE where cluster #1 contains both high- and low-weighted connections. In the clustering of AET 1 the algorithm also chooses to divide component 17 (Braking control system) between two different clusters, #4 and #10. There is therefore an overlapping between the two clusters. All clusters are converted to modules and arranged to form a picture, representing a chassis for AET 1. The interface boundaries and the modules are visualized in Figure 4.7, below.

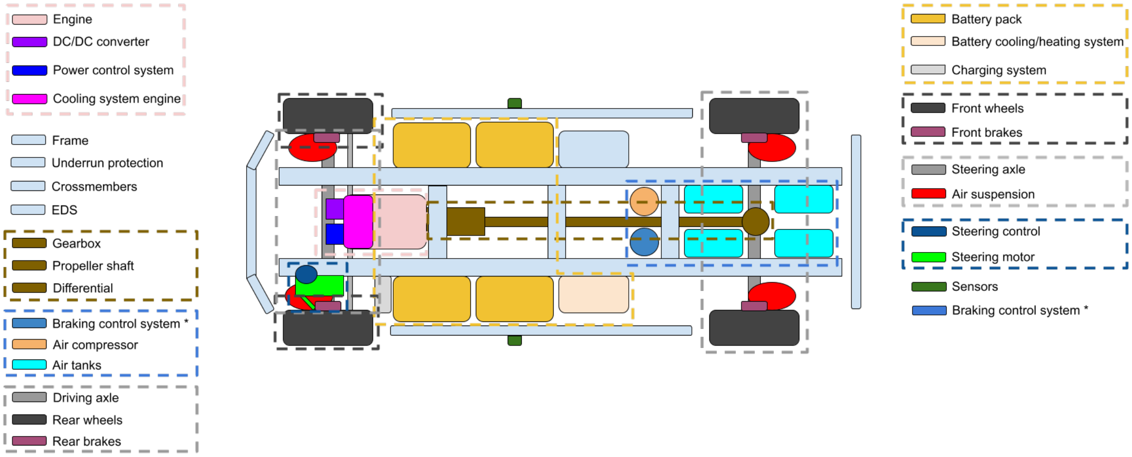
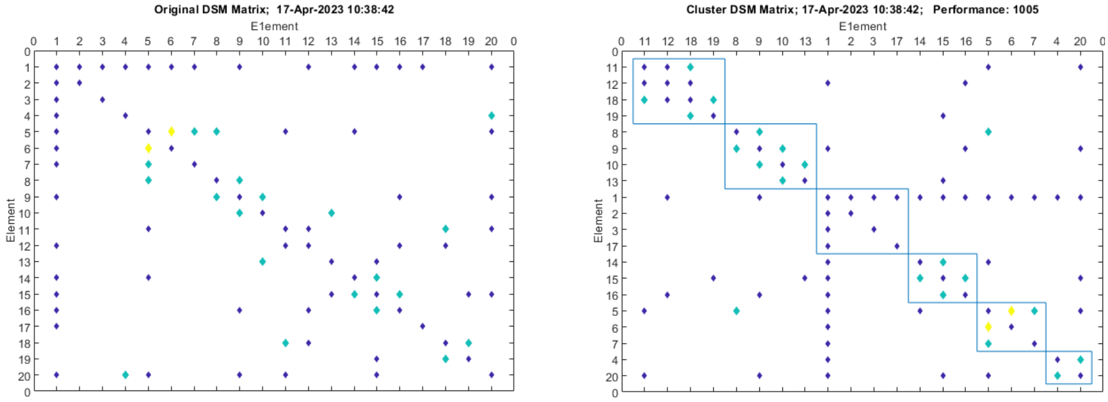


Figure 4.7: Visual representation of the modules and the interface boundaries for AET 1

4.4.3 AET 2 with a modularity index of 1005

AET 2 resulted in a modularity index of 1005, based on 96 different connections identified between the 20 components. The original and the clustered DSM matrix can be seen in Figure 4.8 below. Clustering of AET 2 resulted in a cluster member list with six different clusters and can be seen in Table 4.4, below.



(a) Original matrix **(b)** Clustered matrix

Figure 4.8: Original and clustered DSM matrices for AET 2, with the connections mapped out by colored points. Purple = low-weighted connections. Turquoise = medium-weighted connections. Yellow = strong weighted connection.

Table 4.4: Cluster member list of AET 2

Cluster #1
Steering motor (11)
Steering axle (12)
Front brakes (19)
Front wheels (18)

Cluster #2
DC/DC converter (8)
E-axle (9)
Rear wheels (10)
Rear brakes (13)

Cluster #3
Frame (1)
Underrun protection (2)
Crossmembers (3)
Electric box (EDS) (17)

Cluster #4
Air suspension (16)
Air compressor (14)
Air tanks (15)

Cluster #5
Battery pack (5)
Battery cooling/heating system (6)
Charging system (7)

Cluster #6
Sensors (4)
VCU (20)

The clusters of AET 2 have evenly sized clusters containing two to four components in each cluster. Cluster #5 contains the components that have heavy-weighted connections between each other. This is the only cluster that includes heavy-weighted connections between the components in AET 2. Compared to ICE and AET 1, where several clusters contained heavy-weighted connections. Cluster #3 only contains components that have low-weighted connections. The frame (1) is included in cluster #3 and it is visualized in the clustered matrix that the frame (1) has several connections to components outside of its cluster. This results in a DSM matrix that has a modular bus product architecture, similar to the clustered matrix shown in the Literature review, Figure 2.5. The clusters are converted to modules and arranged to form a picture, representing a chassis for AET 2. The interface boundaries and the modules are visualized in Figure 4.9, below.

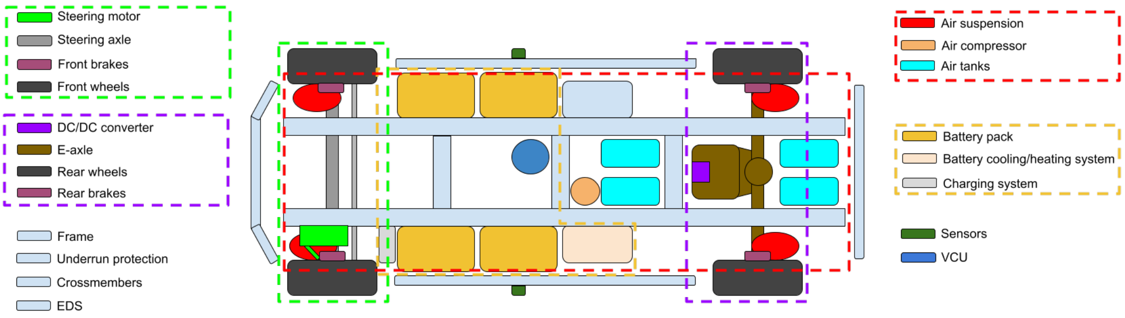
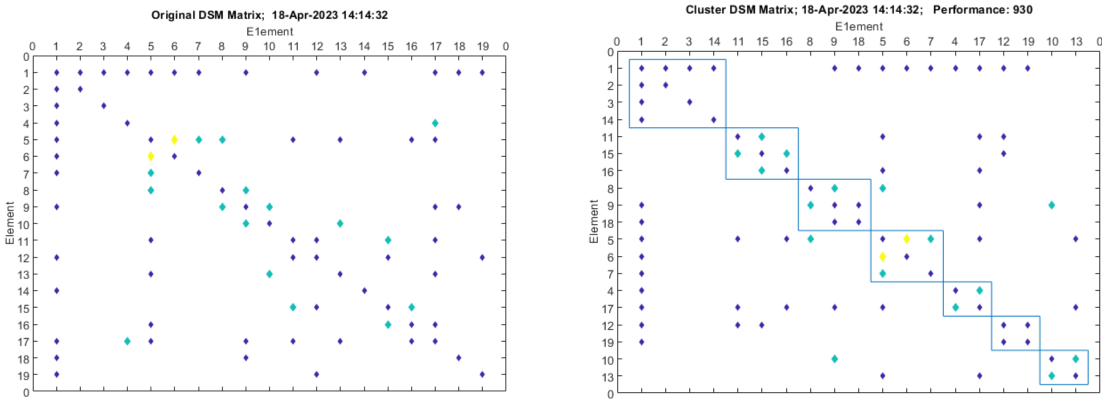


Figure 4.9: Visual representation of the modules and the interfaces for AET 2

4.4.4 AET 3 with a modularity index of 930

Based on the 19 different components in AET 3, 86 connections were identified. The clustered DSM matrix based on AET 3 generated a modularity index of 930. The original and clustered DSM matrices can be seen in Figure 4.10, below. Seven different clusters were generated from the clustering of AET 3. The different clusters and including components can be seen below in Table 4.5.



(a) Original matrix **(b)** Clustered matrix

Figure 4.10: Original and clustered DSM matrices for AET 3, with the connections mapped out by colored points. Purple = low-weighted connections. Turquoise = medium-weighted connections. Yellow = strong weighted connection.

Table 4.5: Cluster member list of AET 3

Cluster #1
Frame (1)
Underrun protection (2)
Crossmembers (3)
Electric box (EDS) (14)

Cluster #2
Steering motor (11)
Front brakes (electro-mechanical) (16)
Front wheels (15)

Cluster #3
DC/DC converter (8)
E-axle (9)
Rear leaf spring (18)

Cluster #4
Battery pack (5)
Battery cooling/heating system (6)
Charging system (7)

Cluster #5
Sensors (4)
VCU (17)

Cluster #6
Steering axle (12)
Front leaf spring (19)

Cluster #7
Rear wheels (10)
Rear brakes (electro-mechanical) (13)

Clustering of AET 3 generated cluster #1 whose components are identical to cluster #2 in AET 1 and #3 in AET 2. This cluster contains the frame (1), underrun protection (2), cross members (3), and EDS (14). The components have a lot of low-weighted connections with each other. The frame (1) in cluster #1 for AET 3, also has a lot of low-weighted connections with components outside of the cluster and can therefore be identified as a modular bus product architecture. Cluster #4 for AET 3 is the only cluster containing components with heavy-weighted connections. The cluster contains battery pack (5), battery cooling/heating system, and charging system which makes the cluster identical to clusters #6 in AET 1 and #5 in AET 2. The clustering for AET 3 shows that cluster #5 also has a lot of low-weighted connections with components outside of the cluster. This is a result obtained from the high number of interactions between the VCU (17) and other components and it also results in a buss product architecture for the VCU (17). The modules and their interfaces for AET 3 are presented in Figure 4.11, below.

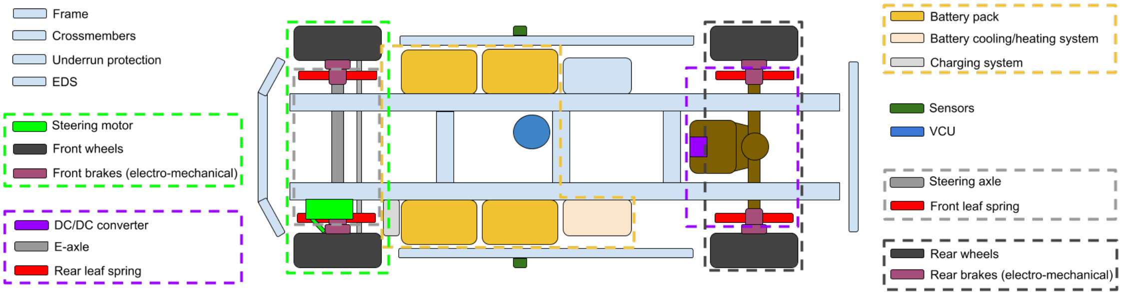
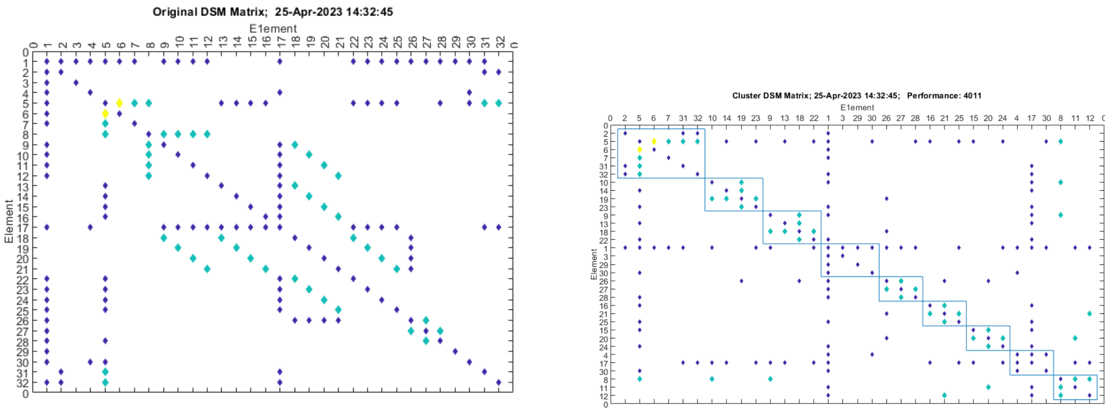


Figure 4.11: Visual representation of the modules and the interfaces for AET 3

4.4.5 AET 4 with a modularity index of 4011

In concept AET 4 a lot of components are added or divided to provide solutions for new functional requirements. This resulted in a DSM matrix containing 32 different components with a total of 202 different types of connections. The clustering of AET 4 generated a modularity index of 4011 and the original and clustered DSM matrices can be seen in Figure 4.12, below. Nine total clusters were created from the original DSM matrix. The clusters with the corresponding components can be seen in the cluster member list in Table 4.6, below.



(a) Original matrix

(b) Clustered matrix

Figure 4.12: Original and clustered DSM matrices for AET 4, with the connections mapped out by colored points. Purple = low-weighted connections. Turquoise = medium-weighted connections. Yellow = strong weighted connection.

Table 4.6: Cluster member list of AET 4

Cluster #1
Underrun protection (2)
Battery pack (5)
Battery cooling/heating system (6)
Charging system (7)
Train connection front (31)
Train connection rear (32)

Cluster #2
In-wheel motor (F-L) (10)
Brakes F-L (electro-mechanical) (14)
Wheel F-L (19)
Steering motor F-L (23)

Cluster #3
In-wheel motor (F-R) (9)
Brakes F-R (electro-mechanical) (13)
Wheel F-R (18)
Steering motor F-R (22)

Cluster #4
Frame (1)
Crossmembers (3)
EDS (29)
Robotic loader/unloader *(30)

Cluster #5
Air suspension (26)
Air tanks (27)
Air compressor (28)

Cluster #6
Brakes R-R (electro-mechanical) (16)
Wheel R-R (21)
Steering motor R-R (25)

Cluster #7
Brakes R-L (electro-mechanical) (15)
Wheel R-L (20)
Steering motor R-L (24)

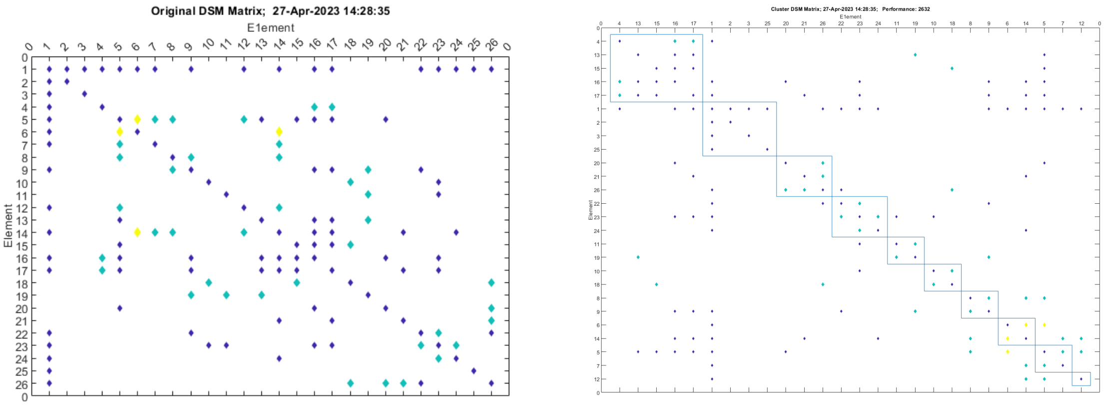
Cluster #8
Sensors (4)
VCU (17)
Robotic loader/unloader *(30)

Cluster #9
DC/DC converter (8)
In-wheel motor (R-L) (11)
In-wheel motor (R-R) (12)

Cluster #1 is the largest cluster, containing six different components. It is also the only cluster with a high-weighted connection. In the clustering results of AET 4 the VCU (17) and the frame (1) are identified as contributors to a modular bus product architecture, similar to the clustering of AET 3. However, cluster #1 contains the battery pack (5) which also contributes to a bus product architecture. An overlapping between clusters #4 and #8 is identified for AET 4 since the robotic loader/unloader (30) is divided over the two clusters. There are a few similarities between the clusters of AET 4 and the previous clusters of AET 1, 2, and 3. Cluster #4 for AET 4 contains the frame (1), cross members (3), and EDS (29), similar to clusters #2 in AET 1, #3 in AET 2, and #1 in AET 3. However, the underrun protection in AET 1, 2, and 3 are also included in this cluster, while the underrun protection (2) for AET 4 is included in cluster #1 together with the new components. Which are the train connection front and rear (31) & (32). Cluster #5 in AET 4 which contains air suspension (26), air tanks (27), and air compressor (28) is identical to cluster #4 in AET 2. The same components in AET 1 are divided into several clusters. There is also another similarity identified for the different concepts. The identical clusters #6 in AET 1, #5 in AET 2, and #4 in AET 3 contain the battery pack, battery cooling/heating system, and charging system. An identical cluster does not exist in AET 4, however, these components are included in cluster #1 with other components.

4.4.6 AET 5 with a modularity index of 2632

The clustering of AET 5 resulted in a modularity index of 2632, based on 166 different types of connections between the 26 components. The original and clustered DSM matrices can be seen in Figure 4.13, below. The clustering of AET 5 resulted in ten different clusters. The different clusters and the corresponding components can be seen in the cluster member list in Table 4.7, below.



(a) Original matrix

(b) Clustered matrix

Figure 4.13: Original and clustered DSM matrices for AET 5, with the connections mapped out by colored points. Purple = low-weighted connections. Turquoise = medium-weighted connections. Yellow = strong weighted connection.

Table 4.7: Cluster member list of AET 5

Cluster #1
Sensors (4)
Rear brakes (electro-mechanical) (13)
Front brakes (electro-mechanical) (15)
VCU 1st (16)
VCU 2nd (17)

Cluster #2
Frame (1)
Underrun protection (2)
Crossmembers (3)
Electric box (EDS) (25)

Cluster #3
Steering motor 1st (20)
Steering motor 2nd (21)
Steering axle (26)

Cluster #4
Air suspension (22)
Air compressor (24)
Air tanks (23)

Cluster #5
Rear wheels (19)
Rear brakes (air) (11)

Cluster #6
Front wheels (18)
Front brakes (air) (10)

Cluster #7
DC/DC converter (8)
E-axle (9)

Cluster #8
Battery cooling/heating system (6)
Lignode batteries 2nd (14)

Cluster #9
Lignode batteries 1st (5)
Charging system (7)

Cluster #10
Receiver power electronics (12)

Similar to the other clustered concepts, frame (1) which is included in cluster #2 is identified as a component that contributes to a modular bus product architecture. There are two heavy-weighted connections identified in AET 5, between the battery cooling/heating system (6) and the Lignode batteries (5) & (14). Since the batteries were divided into two different components, the clustering algorithm decided to place the batteries into two different clusters #8 and #9. This results in a heavy-weighted connection outside of the cluster boundary, between clusters #8 and #9. Cluster #2 containing frame (1), underrun protection (2), cross members (3), and EDS (25) is identical to clusters #2 in AET 1, #3 in AET 2, and #1 in AET 3. The AET 5 chassis was equipped with both air brakes and electro-mechanical brakes. In the clustering results, the different brakes were placed into different clusters. The electro-mechanical brakes (13) & (15) were placed together in cluster #1, while the rear and front air brakes (11) & (10) were divided and placed in clusters #5 and #6. In the previous clustered AET concepts the brakes are always clustered and placed in the same cluster as the corresponding wheels. Whether the concept is equipped with air brakes or electro-mechanical brakes, another similarity between the concepts was identified in cluster #4 in AET 5, which contains air suspension (22), air compressor (24), and air tanks (23), this cluster is identical to cluster #4 in AET 2 and #5 in AET 4.

4.4.7 Modularity index for different types of connections

The original and clustered DSM matrices for concepts ICE, AET 1, 2, and 3 resulted in a variating modularity index. For the different types of connections "S" (spatial), "M" (material), "E" (energy), and "I" (information) concepts AET 4 and 5 were not evaluated. Due to the limited time available for the research, it was determined to focus on concepts ICE, AET 1, 2, and 3. The modularity index, number of connections, and the number of clusters for the concepts with the different connections are presented in Table 4.8, below. For this phase of the result, the value dimensions of Flexibility in adapting to technology changes and Optimized functional placement from the VCS were highlighted since the result showed that the new technology for the AET concept had major impacts on the architecture and thus affected the placement of components. These value dimensions will be presented further in this section.

Table 4.8: Results from individual clustering of the different types of connections for ICE, AET 1, AET 2, and AET 3.

Concept and connection		Number of connections	Modularity index	# Clusters
ICE	S	84	1988	16
	M	18	168	22
	E	32	432	18
	I	10	28	24
AET 1	S	62	874	9
	M	12	48	12
	E	30	330	17
	I	12	128	23
AET 2	S	56	672	7
	M	10	44	15
	E	20	172	13
	I	10	60	15
AET 3	S	50	568	7
	M	2	4	17
	E	22	284	13
	I	12	84	13

A chart displaying the modularity index for each concept and its connections were created to visualize the results from the clustering of the different types of connections. The chart can be seen below in Figure 4.14, where the modularity index (y-axis), and the concepts and the different connections (x-axis). The modularity index for each specific connection ("S", "M", "I", & "E") and the total modularity index previously presented for each generated product architecture are displayed.

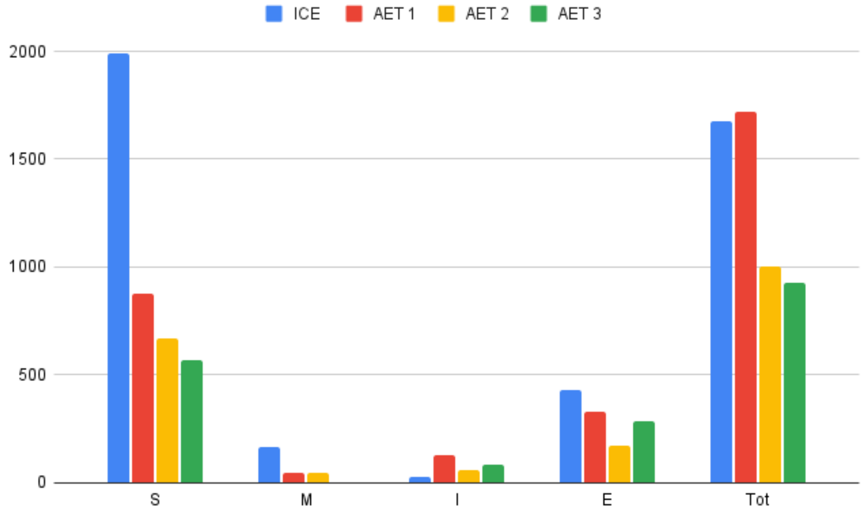


Figure 4.14: Chart of the modularity index for concepts ICE, AET 1, AET 2, and AET 3.

The results from the clustering of the concepts show that the spatial connections have the largest amount of connections and the highest modularity index in all concepts. Energy connections have the second-highest modularity index and the second-largest amount of connections for all concepts. In the clustering of ICE the information connections results in the lowest modularity index. While the lowest modularity index for AET 1, 2, and 3 is the material connections. AET 1 is the concept with the highest total modularity index among the four concepts, even though the modularity index for concept ICE resulted in the highest modularity index for "S", "M", and "E" connections. The connections between concepts ICE and AET 1 increase with two "I" connections, from 10 to 12. However, the modularity index for "I" connections increases by 357% from 28 to 128. This shows the implication of how new technology impacts the types of connections which in turn affects the modularity and the product architecture. Therefore, the value dimensions Flexible in adapting to technology changes and Optimized functional placement are influenced by this result. The connections of "I" and "M" are equal in AET 1 (12 pcs), as well as in AET 2 (10 pcs).

The modularity index for the "I" connections is much higher, resulting in 128 in AET 1 and 60 in AET 2. Compared to the modularity index for "M" which results in 48 in AET 1 and 44 in AET 2. The AET 2 and 3 concepts have similar modularity indexes, and the overall difference is that AET 3 decreases by 7.5 % from 1005 to 930. However, since AET 3 not includes a compressed air system, the number of "M" connections decreases from 10 to 2 connections between AET 2 and 3. This results in a decreased modularity index for "M" by 90% between AET 2 and 3. The number of connections for "E" and "I" increases by 2 connections, for AET 3 compared to AET 2. This generates an increased modularity index of 65% for "E" and 40% for "I" in AET 3.

4.4.8 Cost model

With the created concepts from the DSM, the cost model was designed to estimate the total cost for different concepts, based on different technologies. The costs for the components were estimated and translated into values with an unspecified unit, internally with the manufacturer. Costs of the components are estimated based on off-the-shelf prices from suppliers, this is further explained in the Methodology (subsection 3.4.1). As stated in the VCS, the value dimension of Standardized components have an impact on costs. Therefore, the cost model was established to be able to measure the costs of components and modules. To evaluate the different concepts and their related technologies. The components and cost factors of the concepts ICE, AET 1, AET 2, and AET 3 are summarized in Appendix D. The total costs for each concept are displayed in Figure 4.15, where the ICE concept resulted in the lowest cost (85,5), compared to AET 1, 2, and 3 where the total cost was higher, more than 47,5 %. The ICE concept consists of components that are currently well-developed and can be bought off-the-shelf, at a lower price than the electricity-based components for an AET (The manufacturer, internal communication, 2023).

These components are only applied to the ICE concept and are not used for the different AET concepts. This includes the internal combustion engine, fuel tank, and servo motor. However, there are also common components between the ICE and AET concepts where the cost factor is valued equally because these components are based on existing technology and do not require any specialized development to be used for an AET. These components include, for example, cross members, underrun protection, and wheels. However, the frame is one component that is shared by all the concepts and results in cheaper costs for the AET concepts compared to ICE. Since the frame does not require special extensions to provide space for the internal combustion engine, therefore the beams for an AET are less complex. AET 1, 2, and 3 contain fewer components than the ICE concept, but it is mainly the battery pack that drives the cost factor for these concepts compared to ICE which has a fuel tank as energy storage.

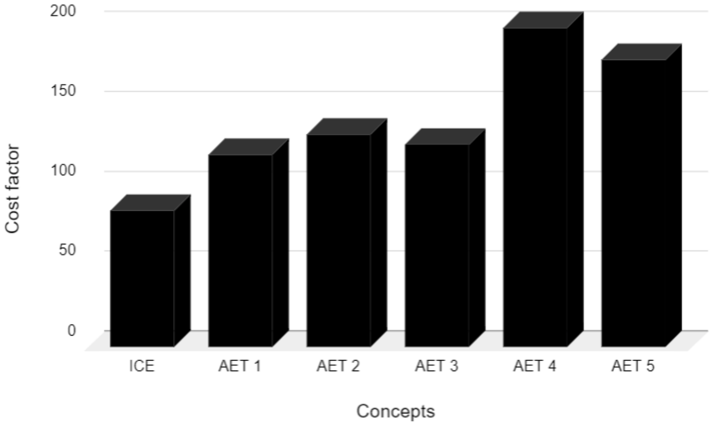
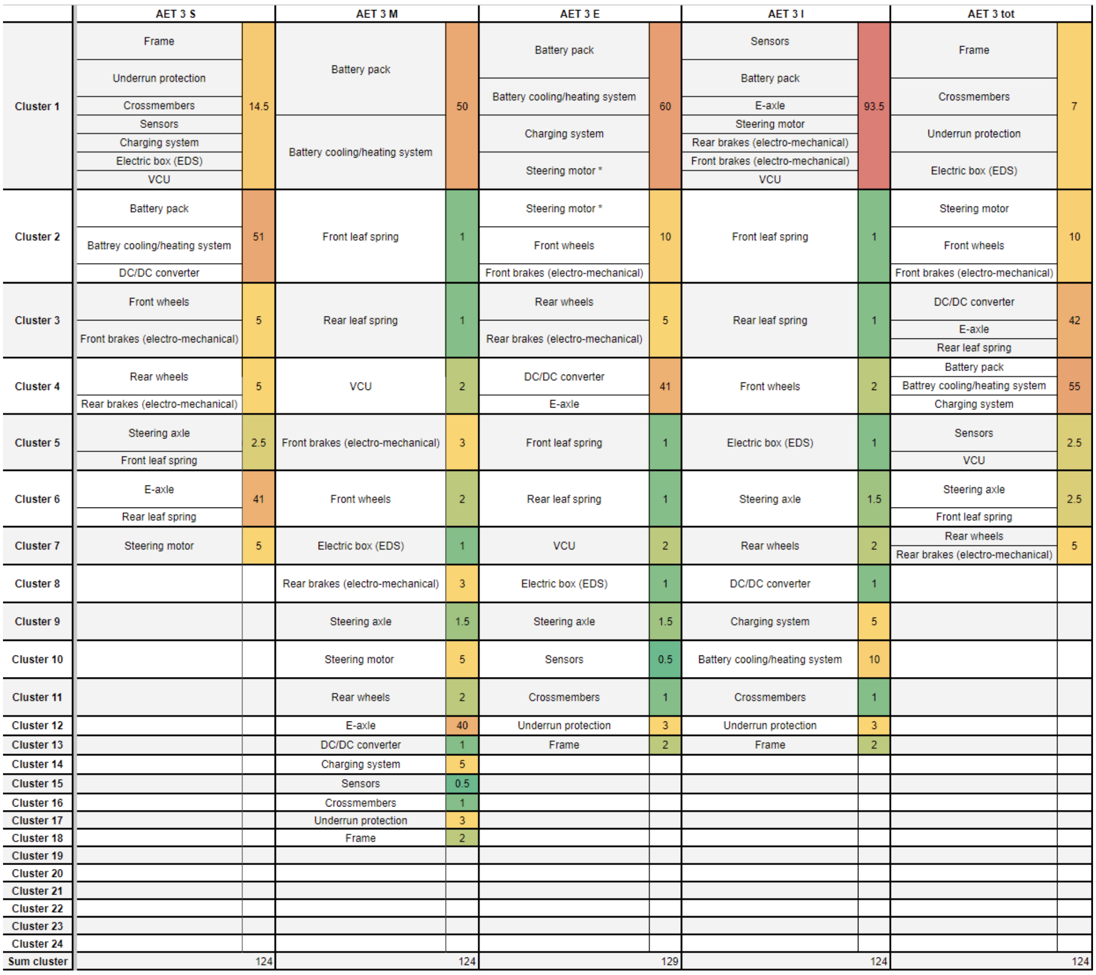


Figure 4.15: Summarized cost factors for the different concepts generated with DSM.

As AET 4 and 5 were based on potential future technological and legal requirements, the cost factor for each specific component was not specified, since there is no available price data. Therefore, the total cost was estimated for AET 4 and 5 respectively. As AET 4 is based on new technological solutions, the total cost factor for the concept is more than 65 % compared to AET 1 as it will require a lot of development to implement these components. Hence, the total cost for AET 4 was estimated at 200. As for AET 5, which was based on future legal requirements, the total increase was not considered to be as large. Due to the fact that the concept has fewer new components, compared to AET 4. Instead, AET 5 contained driving cost factors in the form of double sets of components to ensure redundancy. Hence, a total cost estimate of approximately 50 % compared to AET 1 was decided, and thus the total cost factor for AET 5 resulted in 180.

By combining the results of the clustered member lists from the DSM with the estimated cost factors of the components, an overview of the value of each module was created. Summarized lists of the cost factors for the modules of the concepts ICE, AET 1, and 2 are presented in Appendix section D.2, section D.3, and section D.4, AET 3 are presented below in Figure 4.16. The cost factors were applied for the different types of connections ("S", "M", "E", and "I") as well as the total clustering of all connections.



	AET 3 S		AET 3 M		AET 3 E		AET 3 I		AET 3 tot	
Cluster 1	Frame Underrun protection Crossmembers Sensors Charging system Electric box (EDS) VCU	14.5	Battery pack Battery cooling/heating system	50	Battery pack Battery cooling/heating system Charging system Steering motor *	60	Sensors Battery pack E-axle Steering motor Rear brakes (electro-mechanical) Front brakes (electro-mechanical) VCU	93.5	Frame Crossmembers Underrun protection Electric box (EDS)	7
Cluster 2	Battery pack Battrey cooling/heating system DC/DC converter	51	Front leaf spring	1	Steering motor * Front wheels Front brakes (electro-mechanical)	10	Front leaf spring	1	Steering motor Front wheels Front brakes (electro-mechanical)	10
Cluster 3	Front wheels Front brakes (electro-mechanical)	5	Rear leaf spring	1	Rear wheels Rear brakes (electro-mechanical)	5	Rear leaf spring	1	DC/DC converter E-axle Rear leaf spring	42
Cluster 4	Rear wheels Rear brakes (electro-mechanical)	5	VCU	2	DC/DC converter E-axle	41	Front wheels	2	Battery pack Battrey cooling/heating system Charging system	55
Cluster 5	Steering axle Front leaf spring	2.5	Front brakes (electro-mechanical)	3	Front leaf spring	1	Electric box (EDS)	1	Sensors VCU	2.5
Cluster 6	E-axle Rear leaf spring	41	Front wheels	2	Rear leaf spring	1	Steering axle	1.5	Steering axle Front leaf spring	2.5
Cluster 7	Steering motor	5	Electric box (EDS)	1	VCU	2	Rear wheels	2	Rear wheels Rear brakes (electro-mechanical)	5
Cluster 8			Rear brakes (electro-mechanical)	3	Electric box (EDS)	1	DC/DC converter	1		
Cluster 9			Steering axle	1.5	Steering axle	1.5	Charging system	5		
Cluster 10			Steering motor	5	Sensors	0.5	Battery cooling/heating system	10		
Cluster 11			Rear wheels	2	Crossmembers	1	Crossmembers	1		
Cluster 12			E-axle	40	Underrun protection	3	Underrun protection	3		
Cluster 13			DC/DC converter	1	Frame	2	Frame	2		
Cluster 14			Charging system	5						
Cluster 15			Sensors	0.5						
Cluster 16			Crossmembers	1						
Cluster 17			Underrun protection	3						
Cluster 18			Frame	2						
Cluster 19										
Cluster 20										
Cluster 21										
Cluster 22										
Cluster 23										
Cluster 24										
Sum cluster		124		124		129		124		124

Figure 4.16: Cost factors for the different modules created by DSM for concept AET 3.

Overall, the module with the highest price for all concepts was AET 3 "I", with a total value of 93,5. The module consists of Sensors, battery packs, E-axle, a Steering motor, Rear & front brakes, and VCU. For summarizing AET 3 "tot" modules, the fourth cluster has the highest value of 55, including Battery packs, battery cooling/heating system, and charging system. This is the same for AET 1 "tot" and AET 2 "tot", where both concepts include the same module and value. The highest value in ICE "tot" was the first module with a value of 46,5. The module includes totally nine components, Frame, Crossmembers, Engine, Fuel tank, Cooling system engine, Batteries 24V, Fan cooling, Underrun protection, and Throttle (pedal).

4.4.9 Adaptability model

The adaptability index visualizes the adaptability performance for future changes of the first four concepts of ICE, AET 1, 2, and 3, relatively compared to AET 4 and 5. By differentiating the modularity indexes for concepts ICE, AET 1, 2, and 3 with the modularity index for AET 4 and 5, was the adaptability index calculated. Therefore, no adaptability index for AET 4 and 5 was calculated, as they were references. The Methodology (subsection 3.4.2) explains this in more detail. The adaptability model was created to evaluate the different concepts in relation to the value dimensions of adapting to future changes (technology and legal) from the VCS. In Figure 4.17 are the finalized results of the adaptability index presented. The result shows that the adaptability index for the ICE and AET 1 are higher compared to AET 2 and 3. AET 1 has the highest adaptability index, with a value of 6,2 compared to ICE of 6,0, AET 2: 4,3, and lastly AET 3: 4,2. Therefore, implementing future changes to achieve the product architecture of AET 4 and 5 can be made approximately 1,5 times more efficiently with AET 2 and 3 compared to ICE and AET 1.

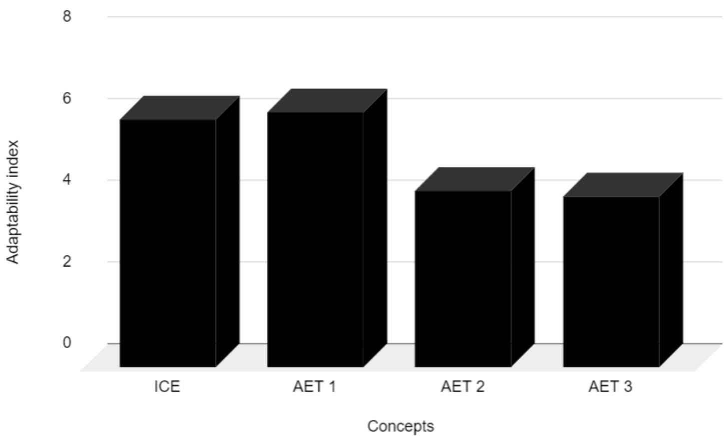


Figure 4.17: Adaptability index of the concepts ICE, AET 1, 2, and 3 relatively compared to AET 4 and 5.

4.4.10 Summarized results for cost, adaptability, and modularity index

The relation between the two different factors was identified by presenting the modularity index and the total cost per concept with a scatter plot, which is visualized in Figure 4.18, for all six concepts. The ideal result of the scatter plot would have been a concept located at the origin of the chart, with as low cost and modularity index as possible. Therefore, the concepts are evaluated related to the distance to the origin point. From the different points of each concept is AET 3 located nearest to the origin seen to both cost and modularity index, followed by AET 2, ICE, AET 1, AET 5, and lastly AET 4. This indicates that the AET 3 concept outperforms the other concepts in terms of the relationship between total cost and the modularity index.

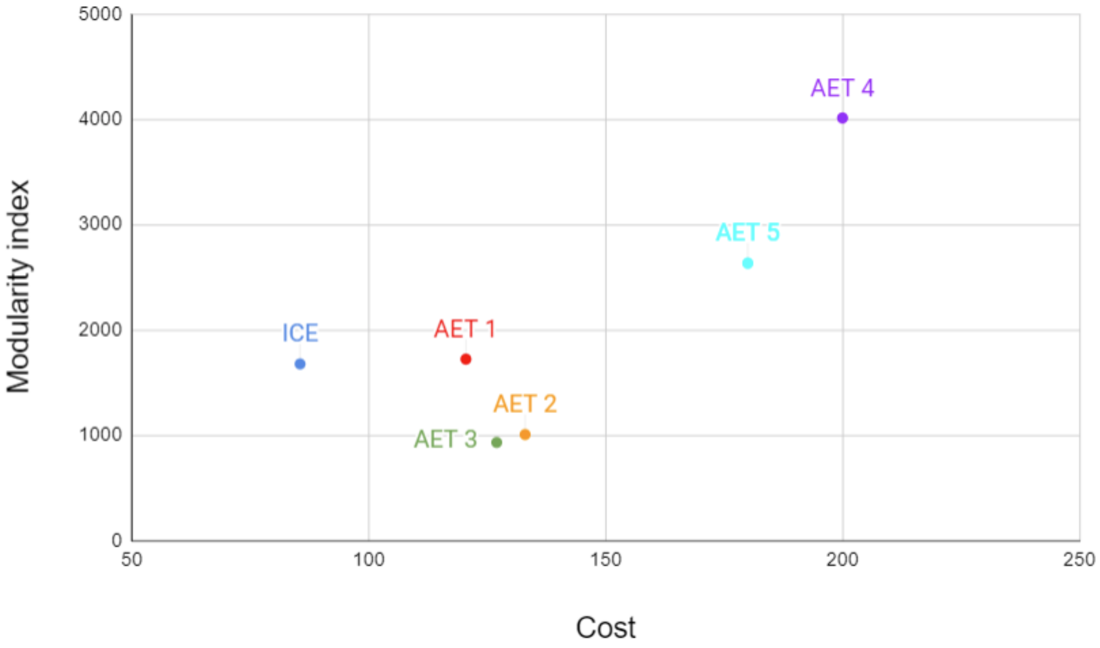


Figure 4.18: Relation between total cost and the modularity index, displayed with a scatter chart for the different concepts.

The third factor of the adaptability index resulted in a 3D chart, displaying all three different factors with their relations (see Figure 4.19). Consequently, the index of adaptability where the concept of ICE, AET 1, 2, and 3 are based on AET 4 and 5, hence AET 4 and 5 have no value in terms of adaptability (z-axis). By comparing the concepts ICE, AET 1, 2, and 3 with the three different factors of adaptability, cost, and modularity index, the different concepts can be ranked according to their performance.

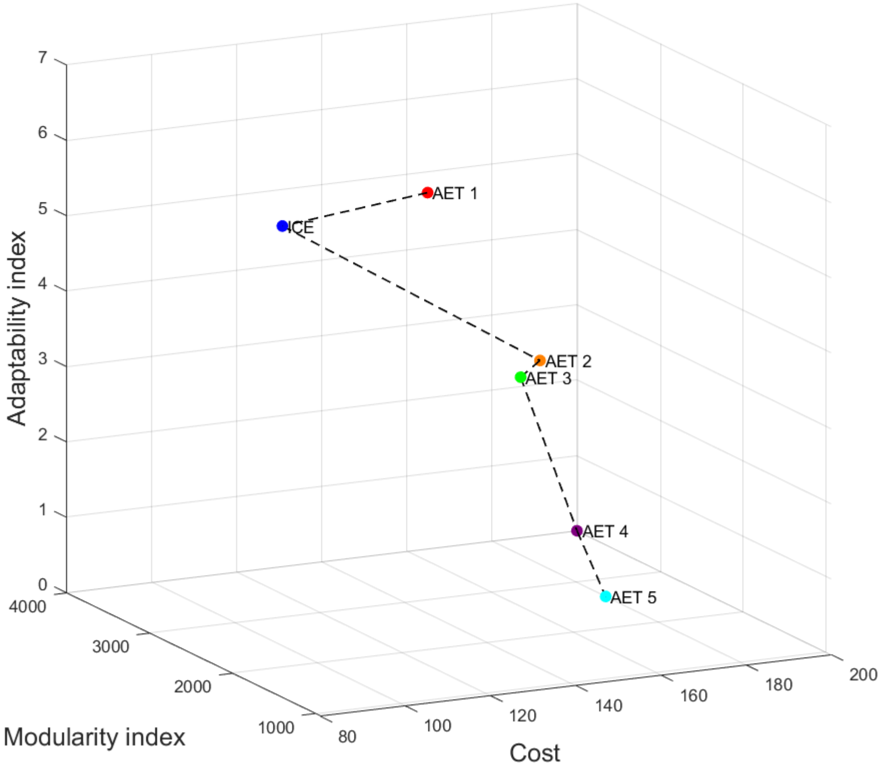


Figure 4.19: 3D-chart with the result of the relation between total cost, adaptability, and modularity index for the concepts.

The total distance between each concept and the origin of the chart was translated into a ranking system in terms of its performance. All measured distances for each concept to the origin are displayed in Table 4.9. The best performing concept was AET 3 and is shown in Figure 4.20. AET 1 has the weakest performance in relation to the three different measurement factors. Since it has the highest modularity index, which leads to the highest adaptability index, while its cost is high compared to ICE. In return, AET 1 is the concept furthest from the chart's origin (1725). Therefore, AET 1 performs poorly with respect to the value dimensions Customization ability, and Adapting to future changes (technology and legal) compared to the other concepts. On the other hand, AET 1 has a similar cost compared to AET 2 and 3 and therefore has an equal performance in the value dimension of Standardized components.

The second weakest result is the ICE concept where the cost is the lowest among all concepts but the concept has a high modularity index compared to AET 2 and 3. This also increases the adaptability index and results in a total distance of 1677. This shows that the ICE concept performs well in the value dimension of standardized components, leading to low cost. However, in the sense of adapting to future changes (technology and legal), the concept performs poorly. The two best concepts are therefore AET 2 and 3. The distance for AET 3 is 939 compared to AET 2 which has 1014. AET 2 and 3 are the most expensive concepts compared to ICE and AET 1. The AET 3 concept is slightly lower in cost compared to AET 2. Since the entire compressed air system is removed and leaf springs are added to AET 3, it reduces components, and the standardized components have a lower cost according to the value dimension Component standardization.

Furthermore, AET 2 and 3 are the concepts that have by far the best modularity index, which also leads to their adaptability index being the best. Regarding the other prioritized value dimensions from the VCS, which were Adapting to technology changes (technology and legal) and Customization ability, AET 2 and 3 are equivalent. However, it is AET 3 that receives the best result even though it is equal and only differs 75 in the distance between the two concepts. This is because AET 3 obtained the best modularity index in terms of the number of connections and the sizes of the modules. This in turn is also linked to the adaptability index where AET 3 is considered best for future changes. Thus, the results show that the AET 3 concept is the most convergent architecture for an AET in terms of cost, modularity, and adaptability.

Table 4.9: The distance between the concepts and the zero point in the 3D plot

Rank	**Concept**	**Measured distance**
1	AET 3	939
2	AET 2	1014
3	ICE	1677
4	AET 1	1725

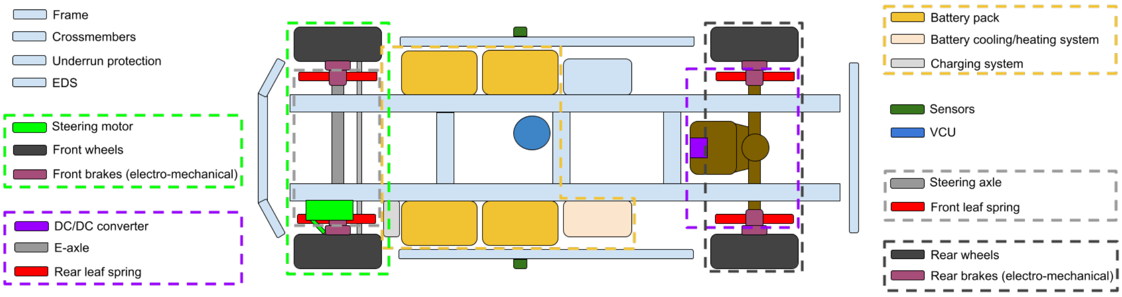


Figure 4.20: Visual representation of the best-performing product architecture AET 3 in relation to cost, modularity, and adaptability

4.4.11 Summarizing results from generated product architectures and modules

The results from the interviews highlighted that the battery packs are by far the most important component or system to make modular. This can be related to the results from the clustering of AET 1, 2, and 3 where the modules containing the battery pack are identical despite having different technologies and product architectures. Identical modules specify that they have the same components clustered together in the different concepts. The identical AET 1, 2, and 3 components modules are visualized in Figure 4.21. Regarding the recurring result of the identical module of the battery pack, battery cooling/heating system, and charging system, the choice of creating a module from these components is verified, regardless of the choice of technology.

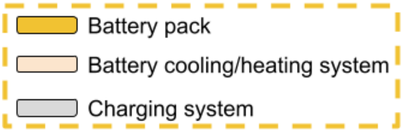
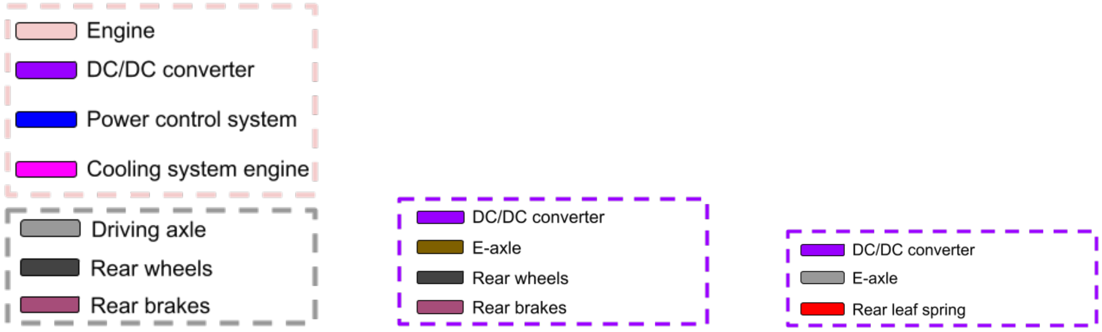


Figure 4.21: The identical module containing the battery pack for AET 1, 2, and 3. Retrieved from Figure 4.7, Figure 4.9, and Figure 4.11.

The powertrain and the axles were also components that employees wished to be modular, to enable the possibility of providing variation in load capacity by offering various powertrains and axles. These components are included in modules that are not identical between the concepts, as seen in Figure 4.22, where the modules for AET 1, 2, and 3 containing the powertrain and the axle are presented. If these components were prioritized in a modularization as wished by the employees, it would affect the future possibilities to adapt to new technologies. According to these three generated product architectures the modules containing the powertrain and the axle needs to be redesigned as the technology changes. The components should therefore not be prioritized to be modular, since technology changes in these components will significantly impact the product architecture.



(a) AET 1 **(b)** AET 2 **(c)** AET 3

Figure 4.22: Overview of the different modules containing powertrain and rear axle for AET 1, 2, and 3. Retrieved from Figure 4.7, Figure 4.9, and Figure 4.11.

By summarizing all results regarding the three identified critical scenarios, Low cost, Adaptability to future changes, and Customization ability, an overview of what the manufacturer should focus on when developing a modular chassis for an AET was created. In the previous section, AET 3 was presented as the concept that performed best in the three scenarios, as seen in subsection 4.4.10. ICE and AET 1 are not relevant to be taken up as potential challengers, given that ICE is not based on electricity and autonomous driving and that AET 1 has a too high modularity index. However, when interpreting the results, it is important to analyze how relatively even the results are between AET 2 and 3. Since AET 3 does not include a compressed air system with connected air suspension, it eliminates the possibility of adjusting the height of the chassis. This was also presented as part of the value dimension Customization ability in the VCS (subsection 4.2.1), where the ability to have a height-adjustable chassis facilitates loading and unloading in different environments. The AET 3 concept can be seen as a chassis that has lower cost, better modularity, and adaptability than all the other concepts, however, it excludes an important part of customization. By developing a product architecture based on the clustering of AET 3 can result in acquiring a smaller part of the market. Therefore, AET 2 can be justified as the most suitable concept to focus on for the manufacturer, which can be seen in Figure 4.23, below. However, it also opens the possibility to explore further developments of AET 3 to accommodate it with a solution that adjusts the chassis height.

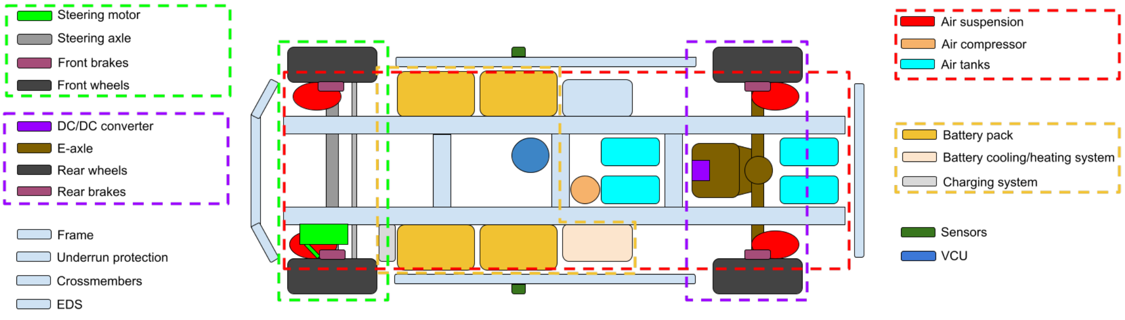


Figure 4.23: Visual representation of the product architecture for AET 2. Concluded as the most suitable concept for the manufacturer

5

Discussion

The Discussion chapter will discuss the presented result and the methodology of the thesis. Within the presented result three different parts are highlighted, Modular product architecture in chassis design, Adapting to technology changes, and Summary of results. Finally, the methods that were applied to the thesis are discussed. To give a nuanced overview of the implications of the selected methods and what could have been done differently.

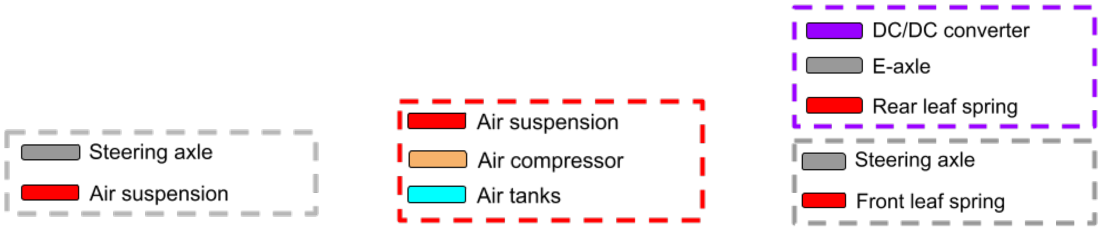
5.1 Modular product architecture in chassis design

The definitions and benefits of having a modular product architecture are presented in the Literature review, chapter 2. The results from the interviews in section 4.1, show that the employees at the manufacturer had a common understanding of what modularity is and how it can be defined, similar to the definitions presented in the Literature review. However, the results also exhibit that the employees had different views on the objective and goals of designing for modularity. This can be identified as a problem when choosing to design a modular product architecture for a chassis. As the results presented in the VCS display that designing the product architecture of a chassis for an AET creates trade-offs between different value dimensions. Therefore it is important for a business or organization to be aligned in which value dimensions are more important. As well as identifying the goals and objectives for designing a modular product architecture.

Strengths and opportunities mentioned in the SWOT analysis are a simplified assembly process, easier system verification and testing, and flexibility of use for modules. Achieving these aspects with a modular design would probably affect the value dimensions' priority during the design process. With the trade-offs in the VCS, design decisions regarding the modular chassis architecture need to be made. Although many different strengths and opportunities can be stated, achieving all the positive aspects can be difficult. Therefore, performing a SWOT analysis for a modular chassis architecture would be better based on one of the three scenarios stated in the VCS. This would result in a more reasonable SWOT analysis, where the strengths and opportunities can be specified as goals and objectives for the design of the chassis.

The fact that there is no market with full-scale production of chassis for AET today and the need to define a chassis adaptable to possible future changes, developing a modular product architecture for a chassis can be beneficial. As motivated by Ulrich, the possibility of changing components within modules is made possible (1995), the focus of the first product architecture would be a chassis that is adaptable to further changes. Once a product architecture has been established, the next priority could therefore be to develop a modular product platform to enable variation for different use cases (Alvin P Lehnerd & Marc H Meyer, 1997). This could also be supported by using carryover-Common and carryover-Modified components within the platform (Suh et al., 2007).

In concept generation, the connections in the DSM matrices were affected when functions and design solutions were selected. For some functions, the design solutions were divided into several components. One example of this can be seen between the components of AET 1, 2, and 3, where the suspension in AET 1 and 2 is mapped out as a single component, and in AET 3 it is divided into front and rear suspension. This has an impact on the results as the product architectures and the clusters for the different concepts vary. In AET 3 the suspension is divided between two modules compared to AET 1 and 2 where the suspension is included in one module, as seen in Figure 5.1. In return, it is more difficult to compare the concepts and the generated clusters to each other. Some components should be divided based on their placement on the chassis to draw more conclusions regarding similarities between clusters. The components that should be divided are the wheels, brakes, and suspension, for example, by specifying them individually as front-right, front-left, rear-left, and rear-right. This could create more synergies between the concepts, and more clusters might be identified as identical clusters.



(a) AET 1 **(b)** AET 2 **(c)** AET 3

Figure 5.1: Overview of modules containing suspension for AET 1, 2, and 3.

The generated concepts were simplified and did not contain certain systems and specific components that a more detailed concept needs. This is done to quickly generate results and understand the difference between the product architectures and their modularity. Clustering concepts based on different objectives, can generate useful insight into the product architecture (Eppinger & Browning, 2012). Therefore, it was decided not to create too detailed concepts, but rather several varying concepts. However, it would be suitable for future research to define a final concept, specifying technical solutions, components, and connections.

To build a product architecture, it is necessary to specify the arrangement of functional requirements (K. Ulrich, 1995). It is therefore beneficial to perform clustering on a more detailed concept, to specify the functional arrangement in the chassis product architecture more accurately. The question is then what is a sufficiently detailed concept? In the context of this work, more specific knowledge about each component and its function would have been required. Therefore, more competence would have been needed, which could have been obtained from one or more employees with specific knowledge.

Because it was stated in the Literature review that spatial connections are the most important connections to map out and analyze when performing a DSM analysis (Helmer, Yassine, & Meier, 2007), it was decided to focus more on identifying and mapping the spatial connections for each concept. Furthermore, the thesis was limited to focusing on the mechanical properties of a chassis design and it was decided to disregard other properties to a certain degree, such as software and electrical functions. The results from the clustering show that information and energy connections increased when switching from the ICE concept to AET 1, 2, 3, 4, and 5. The market is transitioning from trucks powered by ICE to electrical-powered trucks (ACEA, 2022a). This will probably result in fewer spatial connections and more energy and information connections. Due to the reduced number of traditional components for an ICE, such as exhaust system and transmission (Truett, 2022).

It is proven in the analysis of AET 2 and 3, where AET 3 is equipped with electric-powered brakes instead of air brakes. This results in an increase in both the number of connections and the modularity index for "E" and "I". Therefore, switching to more electrical-powered solutions from material-powered solutions, the connection complexity for "E" and "I" increases while it decreases for "S" and "M". This implies that the chassis of an AET is more than only a mechanical product and the importance of electronics and software plays a major role. This can also be motivated by the emergence of new electronics and software innovations within the automotive industry (Pelliccione et al., 2017). Therefore it would be reasonable to focus more on the "I" and "E" connections, as further DSM clustering of the chassis product architecture is performed. Focusing more on "I" connections results in a need to investigate further modularity in software and its impact on the product architecture. A short explanation was presented in section 2.4, however for future work it would be required to investigate the topic further.

The results of the clustering and analysis show that the frame acts as a common bus for all concepts. This means that the product architecture for the chassis should be designed around the frame. Where other components and modules will be connected to the frame with an identical interface (Doe, 2020). If it were decided to specify the frame as an individual module, the components clustered with the module of the frame in AET 1, 2, 3, and 5 (underrun protection, cross-members, EDS), would not be required to have identical standardized interface as the other modules.

Since these components only have connections with the frame and not with any other components. Future research should explore the possibility of having a sectional-modular or slot-modular architecture for the chassis. The result from the patent search in section B.1, shows several examples of different modular chassis, where the frame is divided into different segments. Compared to current concepts, the frame was viewed as one solid component. Therefore, it needs to be explored how the modularity index is affected by dividing the frame into different segments, and whether it would result in another type of modular architecture.

Concepts AET 4 and 5 were created with the purpose of analyzing the modularity of concepts based on possible future technology and legal changes. The modularity index for AET 4 and 5 is much higher compared to the other clustered concepts. An explanation for this could be that the added or changed components for the concepts contribute to much more complexity in establishing the connections. Analyzing the results from clustering of AET 4 shows that three components are identified as common bus components (frame, VCU, and battery pack), which leads to connections outside of the cluster. Because the clustering algorithm penalizes connections outside of clusters, having more common bus components results in an increased modularity index for AET 4. AET 5 on the other hand is the only clustered concept that generates a cluster with a heavy-weighted connection outside of the cluster. It is also the concept with the most amount of medium-weighted connections outside of the clusters. Compared to the other concepts, having high- and medium-weighted connections outside of the clusters increases the modularity index significantly for AET 5.

As the modularity index of the individual connections was analyzed, AET 1 had the highest total modularity index of the concepts. AET 1 had fewer components compared to ICE, resulting in a decrease in the total number of connections from 144 to 116. The total clustering index for "S" also decreases by more than 1000 in the modularity index, from 1988 to 874. Considering these aspects the total clustering index for AET 1 is still higher compared to ICE. However, the modularity index for "I" increases by 357%, from 28 to 128. This explains why the total modularity index is higher for AET 1 compared to ICE. Looking at these results it can be concluded that decreasing the number of connections and components does not necessarily mean that it will result in a better modularity index. Concepts AET 3 and AET 1 both have twelve "I" connections, however, the modularity index for "I" are different. It is therefore the relation of the connections between components that impact the modularity index and not the number of components or connections that are specified in the DSM matrix.

5.2 Adapting to technology changes

Accordingly, to the SWOT analysis, there are a lot of strengths and opportunities identified for the business case of having a modular chassis architecture. However, if something is not accounted for when designing a modular chassis architecture, the specified strength or opportunity can quickly turn into a weakness or a threat. It is stated that a modular chassis architecture can decrease the complexity of future upgrading/developments and also make it easier to meet changing market demands. This is accurate if the chassis's modular product architecture is considered a robust product architecture (Krause et al., 2017), where predictions of the future technology and the changing elements have been considered. Failing to design a robust product architecture will increase complexity when performing upgrades or executing design changes to meet changing market demands. Therefore, the positive aspects of designing a modular chassis might quickly turn into negative effects and create a certain risk.

Presented in the patent search, the Literature review, and the first round of interviews, the importance of new technology and potential legislative changes are highlighted. According to the patent search, new technological solutions are continuously emerging. These solutions could provide new benefits that are not currently possible. For example, individual wheel mounting could mean that an AET can move more flexibly than using a traditional wheel axle (William J. Bluethmann et al., 2013). From the first round of interviews, in section 4.1, the battery pack is mentioned as the main part of the chassis that should be made modular. According to the preparation of the AET 5 concept, potential new legal requirements were identified that would affect the battery pack and its functioning. Both by new technology to not have lithium batteries and to enable inductive charging (Storaenso, 2022; Power-Circle, 2021). This demonstrates that batteries and other technologies can change a lot and which leads to increased justification as to why the business scenario of adapting to future changes should be prioritized by the manufacturer.

5.3 Summary of result

The cost model shows that the AET concepts have significantly higher costs than the ICE concept (section 4.4). This indicates that the cost of an AET today is difficult to compete with an ICE. However, it is important to remember that the ICE concept is intended to be operated with a driver and powered by an internal combustion engine, which will also have an impact on the operating costs in terms of fuel consumption and driver salary compared to the AET.

Looking at the total cost of the different modules, it is interesting to see how the most expensive module on ICE results in 46,5 while the most expensive for AET 1, 2, and 3 is 55. Which is significantly higher and the module for the AET concepts contains only 3 components where the battery pack is included. Compared to the most expensive module for the ICE which contains 9 components. Therefore, a lot of components will not necessarily result in an expensive module.
Another module that stands out for AET 2 and 3 is the module containing the E-axle, which has a high value. This indicates that the battery pack and powertrain represent the largest driving costs for both concepts. This indicates the possibility of focusing on offering these two modules in different varieties. It would mean that the overall cost of an AET could be reduced if a lower-capacity battery pack and E-axle were available. At the same time, higher capacities could be offered to meet the needs of other customers. This is linked to the literature by Ulrich, where the value of modularity is highlighted by Component economy of scale and Product variety (1994). These two benefits of modularity are achieved by offering a chassis with standardized components that can be adapted to different needs in terms of battery and powertrain capacity. We, therefore, believe that the entire chassis should be modularized to facilitate future changes, as previously mentioned. But also, the focus should be on offering a product variation of these two modules to be able to influence the price of the product.

Furthermore, the relevance of the estimated costs can be highlighted as an important factor of the result to be taken into account. As the cost data is based on internal data from the manufacturer, the results show how it indirectly affects the company itself and may not necessarily be indirectly relatable to other companies. But what can be determined is the cost distribution between an ICE and AET, as there is a difference in maturity in the technology between these two concepts. Hence a cost difference is difficult to avoid, regardless of which company would be interested in developing an AET compared to an ICE. As mentioned earlier in the literature by Ulrich, modularity is motivated by Component economics of scale, which means that the total production volume increases while standardized components are used over several variations (1994). This is linked to the future development of a chassis for AET, where standardized components can contribute to profitability and reduce the gap in total cost.

The importance of the adaptability model is a factor that plays an essential role. In order to determine the relevance of a chassis in terms of the possibility of future changes. The literature motivates the increased possibility of product change through a modular design (K. Ulrich, 1994). At the same time, it is stated that modularity can lead to a limitation of product innovation (Ethiraj & Levinthal, 2004). In terms of the chassis of an AET, adaptability will therefore be crucial for future changes.

There are significant differences in the product architecture between the two developed concepts, AET 4 and 5, and the remaining concepts that were chosen to be compared in the area of adaptability. The fact that AET 2 and 3 are the most adaptable is therefore considered reasonable as it mainly offers a more modular architecture. But also in accordance with its compatible architectures, such as the fact that the powertrain is more comparable between the architectures, however, further research would be necessary to investigate how much of the architecture is adaptable to future changes. Or if it is actually the case that the required changes are too extensive and result in limited product innovation or a new product architecture.

5.4 Discussion about the chosen Methodology

This section discusses the different methodological choices made for the thesis and their impact in terms of the work and results. In the course of the thesis, the scope has been revised. In the early stages, the idea was initially to develop a detailed concept of a modular chassis for an AET. Given the scope and complexity of creating this concept, the focus was switched to determining critical factors and how a general product architecture of a chassis for AET could be defined. The authors realized at an early stage that there are many elements to consider and that designing a chassis requires special expertise in different areas. In order to then focus on a complete solution for an AET chassis, the results of the work were based on a more general level than initially intended.

5.4.1 Exploratory phase

Overall, the exploratory phase was very important in laying a foundation for the work. This is also the goal of an exploratory phase, collecting data to create an idea of a problem at an early stage (section 3.1). The Literature review provided a broad base of data on modularity. The goal was to find different types of definitions of modularity and related terms such as product architecture and platform design, and further how it can be applied. This also resulted in a Literature review that was broad with many different mindsets, but at the same time contained consistent definitions between different publications. Which also strengthens the credibility of the various sources used. In terms of credibility, mainly publications from journals have been used and checked in terms of who published the work.

The material used for the Literature review has a very high spread in which year the material was published, from 1990 to 2022. Consideration was made to see if the material used should be focused on up-to-date state-of-the-art within the scope. However, using material from the previous century was considered necessary as these publications have played a major role in the subject and are today recurring among new publications. The patent search only focused on the automotive industry. However, since the focus of the Literature review was not only to search for literature in the automotive industry, patents in other industries could have been explored as well.

By conducting the two rounds of interviews, different types of data were collected. From the first round of semi-structured interviews, the interviewee was given the opportunity to fill in the discussed topic according to their personal interest and knowledge (Knott et al., 2022). This gave a clear picture of how the manufacturer works with developing AET and facts about modularity. For the second round of the structured approach to the interviews, a clear framework was created for the questions to be asked depending on who was being interviewed. This gave very specific answers and also specific data about AET. The specific data could not be used to the full extent for the work presented in this thesis as it was considered to be sensitive information.

To ensure that information published from the interviews would not be traceable to a specific person in this report, the roles of who said what could not be shared. Hence, it was necessary only to express that information generally came from the interviews. The fact that all interviews were conducted internally with the manufacturer may have had some implications for the results presented. Since the company has a structured way of thinking about how AET should be developed, produced, and operated has also permeated the answers to the interviews. In order to get other mindsets and perspectives on AET, it could have been relevant to interview people from other companies. However, this was impossible due to difficulties accessing competing companies that work with similar products.

5.4.2 Value creation strategy (VCS)

The use of the VCS gave an interesting result, in terms of the priorities that should be made based on the business scenario to be followed. A primary interesting reason for the successful result is that the choice of the three business scenarios fit very well with the manufacturer. A different outcome of the overall result could have occurred by selecting other business scenarios. The highlighted trade-offs between the different scenarios were based on the prioritization matrices created by us and discussed internally. To get an even more accurate view, it would have been possible to involve more people with different responsibilities in the creation of the prioritization matrices. Overall, the input for the VCS was based on a few specific areas within the company. This laid the foundation for both value dimensions and value drivers. The specific value drivers can later be analyzed as very important factors to be able to drive each specific value dimension further. Therefore, it would have been beneficial if another round of interviews had been conducted with each value dimension's specific areas of the company.

The Literature review highlighted two methods that are applicable to the development of modular products, Modular function deployment (MFD) and Design for variety (DFV). According to the VCS, it would have been interesting to apply the MFD method after the results of the VCS had been compiled. The VCS could have been a basis for further developing concepts. Since DFM is a method for developing specific concepts and takes into account how modularity should be applied within the concepts (Erixon, 1998).

Furthermore, DFV could also have been applied, especially for this work as the importance of focusing on adaptability for future changes has been motivated by the VCS. After the VCS showed what should be prioritized within the future changes scenario, future requirements could have been developed with the DFV. This is motivated by the fact that DFV is used to specify which specific parts of a product are most likely to be subjected to future changes. As well as defining how relationships between different components of a product are affected (Martin & Ishii, 2002).

5.4.3 Concept generation

The EF-M tree and the DEBAS tool were used to create the concepts and the DSM matrices. After the concept creation, the EF-M tree was considered a great method for visualizing and creating new concepts creatively. The DEBAS tool was also easy to use for creating and visualizing connections. In return, this made the process of creating the DSM matrices more efficient. The tool and method were also deemed to be efficient in highlighting critical systems and components of the chassis, based on the stated functional requirements. However, it can be difficult and time-consuming to use the tool and method for identifying a more detailed view of the chassis, including all the necessary components if the purpose is to create a more detailed view of the product architecture. Using another tool or mapping the components and connections in the DSM matrix could be more reasonable.

The concepts that were created had big differences from each other and this in turn generated differences in the clustered product architecture. This was beneficial in order to show how the product architecture changed due to different technologies. However, it would have been interesting to create more concepts based on the same components and technology, with a variation in how the connections are mapped out. This could generate insights into how the specifications of connections and systems can impact the modularity index. It could result in the optimal mapping of the connections, with the purpose of enabling a modular product architecture.

5.4.4 DSM clustering

The DSM clustering was effective in generating clusters and a modularity index. As the algorithm only allowed to cluster connections based on values the connections were assigned a weighting based on the amount of different types of connections. This might not be the optimal way of weighing the connections between components. Another possibility for weighting the connections would be to assign a weighting based on the importance of a connection. This was difficult to do since we had limited knowledge of the components and their structure in a chassis. It could be interesting to create new DSM matrices with an expert in chassis design, where the connections are weighted based on their importance.

Another way of changing the weighting of the connections could be to assign larger weightings to connections that include "I" and "E". Because it is concluded that converting to electrically powered systems will increase complexity for "I" and "E" connections. It could therefore be reasonable in future analysis to specify a larger weighting for those connections. The clustering algorithm had a feature where it was possible to extract a specific component and force it not to be grouped with other components in a cluster, presented in subsection 3.3.3. It was decided not to use this feature during the clustering of the concepts, to have similar inputs in the algorithm for the different concepts. In hindsight, the frame proved to be a common bus component for all clustered concepts. Therefore, extracting the frame in the algorithm for all concepts would be reasonable. This can result in a better modularity index with new clusters that might be more optimized for a modular product architecture of a chassis.

A new function would be interesting to implement for future work on the DSM clustering and the algorithm: the ability to pre-define the clusters with the included components and the connections, to only generate a modularity index without the clustering function. This would make it possible to specify clusters for the different concepts based on certain functions and analyze how the modularity index changes based on the concepts.

6

Conclusion

This work aimed to investigate the possibility of developing a modular chassis architecture for an AET and its various implications. This leads to a proposal on how a chassis should be designed. As well as what should be focused on for the manufacturer in the development, both in terms of preliminary work to lay a foundation and the actual development. The conclusion of the work is presented in relation to how well the three objectives have been achieved and summarizes the results for the two research questions. Finally, a recommendation for further future work is presented.

The following three objectives were stated for the thesis:

Objective 1 "*Identify the components and the product architecture of a chassis for an AET, by exploring existing solutions and performing interviews within the company.*" Achieved with the patent search (in section B.1) and the first round of the interviews (in section 4.1).

Objective 2 "*Define modularity on a chassis for an AET and identify critical modular components by implementing theoretical methods for product development projects within the design of modularity. This objective will be based on existing research on modularity as well as the internal needs of the company.*" This was achieved first of all through the Literature review on the definition and methods to apply modularity (in chapter 2), then different concepts are generated with an EF-M Tree (in section 4.3) and applied in DSM matrices (in section 4.4), according to the material presented in the Literature review.

Objective 3 "*Create a schematic design proposition on how modularity should be implemented in a chassis for an AET.*" From the clustered material in DSM, a result was created in different formats, both as matrices, cluster member lists, and a visual representation of concepts AET 1, 2, and 3 (in section 4.4).

The concluding answers to the stated research questions for this thesis are as follows:

RQ1: "What are the critical factors and functions to take into consideration when designing a modular architecture for a chassis of an AET?"

The presented work highlights three critical business scenarios regarding the modular architecture of an AET chassis. From these scenarios, adapting to technology changes is concluded to be the most critical factor to focus on.

This is discussed in detail in section 4.4. To apply an architecture that is modular and adaptable to future changes the focus must be applied to the connections that manage information and energy within the chassis, as these increase significantly in the transition to electrified and autonomous trucks. In terms of the cost factor, the battery packs and powertrain components must be taken into account, as these components are by far the most expensive on the chassis and drive the overall cost. The most critical functions in the product architecture for the chassis are steering, braking, suspension, and acceleration. Changes to these technologies have a greater impact on the intended product architecture. In conclusion, the focus must therefore be on building a robust modular product architecture that is adaptable to future changes in terms of these functions.

RQ2: “How can a modular architecture for a chassis of an AET be designed?”

The modular architecture of a chassis for an AET should be designed according to the specified modules and interfaces presented in AET 2, seen in Figure 4.9. The reasoning as to why this architecture was selected is discussed in section 5.3. The frame of the chassis has by far the most connections to the components outside its cluster and must be considered a common bus component. It is, therefore, necessary to design a bus modular architecture for the chassis of an AET. The two most important modules to create a standardized interface for are modules #3 containing the frame and module #5 containing the battery pack. Because these modules are identical for all clustered concepts regardless of the chosen technology for solving the critical functions. Removing the compressed air system from the chassis of an AET could impact the possible acquired market share. Therefore it is concluded that including the compressed air system is necessary.

Recommendations for future work

Three future recommendations are presented to continue the work that this thesis has been the foundation for.

Firstly, prioritize the most important value dimensions for the desired business scenario. Continue to develop the different value drivers using specific competencies in the different areas.

Focus on defining an initial architecture. By specifying a specific area of application for the AET. Assigning technical solutions and estimating the intended lifetime of the architecture.

Thirdly and finally, develop a final concept in detail with specified components and their connections. Conduct DSM analysis on the concept with a focus on "I" and "E" connections. Evaluate and further develop the concept to achieve the desired architecture according to the chosen business scenario.

References

ACEA. (2022a, 11). *The EU needs a holistic policy approach to zero-emission mobility.* ACEA. Retrieved from `https://www.acea.auto/message-dg/the-eu-needs-a-holistic-policy-approach-to-zero-emission-mobility/`

ACEA. (2022b, 11). *Fact sheet: trucks - ACEA.* Retrieved from `https://www.acea.auto/fact/fact-sheet-trucks/`

ACEA. (2022c, 1). *Report – Vehicles in use, Europe 2022.* Retrieved from `https://www.acea.auto/publication/report-vehicles-in-use-europe-2022/`

ACEA. (2023, 1). *VEHICLES IN USE EUROPE 2023.* Retrieved from `https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2023.pdf`

Agrawal, T., Sao, A., Fernandes, K. J., Tiwari, M. K., & Kim, D. Y. (2013, 1). A hybrid model of component sharing and platform modularity for optimal product family design. *International Journal of Production Research*, *51*(2), 614–625. doi: 10.1080/00207543.2012.663106

Almefelt, L., Berglund, F., Nilsson, P., & Malmqvist, J. (2006, 11). Requirements management in practice: findings from an empirical study in the automotive industry. *Research in Engineering Design*, *17*(3), 113–134. doi: 10.1007/s00163-006-0023-5

Alvin P Lehnerd, & Marc H Meyer. (1997). *The power of product platforms: Building value and cost leadership.* New York: Free Press.

Anderson, J. J., Kuhl, T. A., & Roberts, D. W. (2019). *Motor vehicle modular construction.* Retrieved from `https://patents.google.com/patent/US11161560B2/en?oq=US11161560B2+`

Babbie, E. (2007). *The Practice of Social Research* (11th ed.). Belmont CA: Thompson - Wadsworth.

Bajpai, S., Eppinger, S. D., & Joglekar, N. R. (2019, 9). The Structure of Agile Development Under Scaled Planning and Coordination. In *Proceedings of the 21st international dsm conference.* The Design Society. doi: 10.35199/dsm2019.3

Bråtegren, K. (2023, 1). *Software Modularity.* Retrieved from `https://www.modularmanagement.com/blog/software-modularity`

Church, R. M. (2002, 2). February). The effective use of secondary data. *Learning and Motivation*, *33*(1), 32–45. doi: 10.1006/lmot.2001.1098

Clark, K. B., & Fujimoto, T. (1991). Product development performance : strategy, organization, and management in the world auto industry. *Harvard Business School Press.*

Culp, K. I., Eastwood, C., Turner, S., Goodman, M., & Ricketts, K. G. (2016, 5). *Using a SWOT Analysis: Taking a Look at Your Organization Using a SWOT*

Analysis: Taking a Look at Your Organization [2016] [2016] (Tech. Rep.). University of Kentucky. Retrieved from `https://uknowledge.uky.edu/ced_reports/3`

Daniilidis, C., Enßlin, V., Eben, K., & Lindemann, U. (2011). A Classification Framework for Product Modularization Methods. In *International conference on engineering design, iced11.*

Denman, J., Kaushik, S., & de Weck, O. (2011). TECHNOLOGY INSERTION IN TURBOFAN ENGINE AND ASSESSMENT OF ARCHITECTURAL COMPLEXITY. In *Proceedings of the 13th international dsm conference.*

Denscombe, M. (2010). *The Good Research Guide For small-scale social research projects* (4th ed.). Berkshire: Open University Press.

DiCicco-Bloom, B., & Crabtree, B. F. (2006, 4). The qualitative research interview. *Medical Education*, *40*(4), 314–321. doi: 10.1111/j.1365-2929.2006.02418.x

Dickinson, M., Thornton, A., & Graves, S. (2001). Technology portfolio management: optimizing interdependent projects over multiple time periods. *IEEE Transactions on Engineering Management*, *48*(4), 518–527. doi: 10.1109/17.969428

Doe, R. (2020). SENSMOD - Computational Design through the lens of Henri Lefebvre's Spatial Theory. In (pp. 701–710). doi: 10.52842/conf.caadria.2020.1.701

Eppinger, S. D., & Browning, T. R. (2012). *Design Structure Matrix Methods and Applications.* The MIT Press. doi: 10.7551/mitpress/8896.001.0001

Erens, F., & Verhulst, K. (1997). Architectures for product families. *Computers in Industry*, *33*(2-3), 165–178. doi: 10.1016/S0166-3615(97)00022-5

Ericsson, A., & Erixon, G. (1999). *Controlling Design Variants : Modular Product Platforms.* Society of Manufacturing Engineers.

Erixon, G. (1998). *Modular function deployment* (Doctoral dissertation, Production system). Retrieved from `http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-2619`

Ethiraj, S. K., & Levinthal, D. A. (2004). Modularity and Innovation in Complex Systems. *Management Science*, *50*(2). doi: 10.2139/ssrn.459920

European-Union. (2023a). *2050 long-term strategy.* Retrieved from `https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en`

European-Union. (2023b). *Paris Agreement.* European Comission. Retrieved from `https://climate.ec.europa.eu/eu-action/international-action-climate-change/climate-negotiations/paris-agreement_en`

Franzen, H., Wieschemann, A., Hegewald, M., & Moutsokapas, J. (2009). *Floor-bound heavy-duty transport vehicle, in particular driverless heavy duty transport vehicle for ISO containers.* Retrieved from `https://worldwide.espacenet.com/patent/search/family/042357582/publication/DE102009025051A1?q=DE102009025051A1`

Gao, H., & Zhang, Y. (2020). Application of Modular Design Method in Product Design. In *International conference on intelligent design (icid)* (pp. 292–297). doi: 10.1109/ICID52250.2020.00068

Garud, R., & Kumaraswamy, A. (1995). Technological and organizational designs for realizing economies of substitution. *Strategic Management Journal*, *16*(S1), 93–109. doi: 10.1002/smj.4250160919

Gaussin. (2021, 4). *Road Truck Skateboard [Video File].* Retrieved from `https://www.youtube.com/watch?v=IHaG1LXXGuI`

Gaussin, C. (2004). *Chassis frame for trailer, has mounting unit comprising semi-trailer king pin for forming semi-trailer or running gear for forming trailer, and allowing rotation of king pin or gear with respect to frame.* Retrieved from `https://patents.google.com/patent/FR2875779A1/en?oq=FR2875779A1`

Grant, R. M. (1996). Toward a knowledge-based theory of the firm. *Strategic Management Journal*, *17*(Special Issue), 109–122. doi: https://doi.org/10.1002/smj.4250171110

Habib, T. (2014). Multidisciplinary Product Decomposition and Analysis Based on Design Structure Matrix Modeling. In (pp. 409–423). doi: 10.1007/978-3-319-04271-8{_}35

Hackl, J., & Krause, D. (2016). *EFFECTS OF MODULAR PRODUCT STRUCTURES ON LIFE PHASES AND ECONOMIC FACTORS* (Tech. Rep.).

Hare, E., & Kaplan, A. (2016, 10). *Designing Modular Software: A Case Study in Introductory Statistics* (Tech. Rep.). Iowa State University. Retrieved from `https://arxiv.org/pdf/1608.02533.pdf`

Helmer, R., Yassine, A., & Meier, C. (2007, 10). *MODULE AND INTERFACE IDENTIFICATION AND DEFINITION-A COMPREHENSIVE APPROACH USING DSM* (Tech. Rep.). Munich. Retrieved from `http://www.iese.uiuc.edu/pdlab/`

Hirano, T. (2012). *In-wheel motor drive device.* Retrieved from `https://patents.google.com/patent/US8596395B2/en?q=(wheel+motor)&oq=in+wheel+motor`

International Organization for Standardization. (2015, 5). *ISO/IEC/IEEE 15288:2015.* Retrieved from `https://www.iso.org/standard/63711.html`

Isaksson, O., Kossmann, M., Bertoni, M., Eres, H., Monceaux, A., Bertoni, A., ... Zhang, X. (2013, 6). Value-Driven Design - A methodology to Link Expectations to Technical Requirements in the Extended Enterprise. *INCOSE International Symposium*, *23*(1), 803–819. doi: 10.1002/j.2334-5837.2013.tb03055.x

Jiao, J., Simpson, T. W., & Siddique, Z. (2007, 2). Product family design and platform-based product development: A state-of-the-art review. *Journal of Intelligent Manufacturing*, *18*(1), 5–29. doi: 10.1007/s10845-007-0003-2

Knott, E., Hamid Rao, A., Summers, K., & Teeger, C. (2022, 9). Interviews in the social sciences. *Nature Reviews Methods Primers*, *73*. doi: 10.1038/s43586-022-00150-6

Kotabe, M., Parente, R., & Murray, J. Y. (2007, 1). Antecedents and outcomes of modular production in the Brazilian automobile industry: a grounded theory approach. *Journal of International Business Studies*, *38*, 84–106. doi: 10.1057/palgrave.jibs.8400244

Krause, D., Gebhardt, N., & Oltmann, J. (2017). *New Trends in the Design Methodology of Modularization* (Tech. Rep.). Retrieved from `https://www.researchgate.net/publication/315808585`

Kulkarni, A., Jennings, C., Hoffman, M., Blanco, E., Terpenny, J., & Simpson, T.

(2018, 4). Clustering Design Structure Matrices: A Comparison of Methods Using Minimum Description Length..

Langlois, R. (2002). Modularity in Technology and Organization. *Journal of Economic Behavior & Organization*, *49*(1), 19–37. doi: 10.1016/S0167-2681(02)00056-2

Langlois, R. N., & Savage, D. A. (2001). Standards, Modularity, and Innovation: The Case of Medical Practice. In P. Karnoe & R. Garud (Eds.), *Path dependence and creation* (1st ed.). New york: Taylor & Francis. Retrieved from `https://doi.org/10.4324/9781410600370` doi: 10.4324/9781410600370

Mack, S. (2013, 7). The Importance of the Trucking Industry. *Small Business - Chron.com.* Retrieved from `https://smallbusiness.chron.com/importance-trucking-industry-71922.html`

Martin, M., & Ishii, K. (2002). Design for variety: developing standardized and modularized product platform architectures. *Research in Engineering Design*, *13*, 213–235. doi: 10.1007/s00163-002-0020-2

Mather, H. (1987). *Logistics in Manufacturing: A Way to Beat the Competition* (Vol. 7). Assembly Automation.

McGrath, M. E. (1995). *Product Strategy for High-technology Companies: How to Achieve Growth, Competitive Advantage, and Increased Profits.* Irwin Professional Pub.

Meyer, M. H., & Utterback, J. M. (1993). The Product Family and the Dynamics of Core Capability. *Sloan Management Review*, 29–47.

Namugenyi, C., Nimmagadda, S. L., & Reiners, T. (2019). Design of a SWOT analysis model and its evaluation in diverse digital business ecosystem contexts. In *Procedia computer science* (Vol. 159, pp. 1145–1154). Elsevier B.V. doi: 10.1016/j.procs.2019.09.283

Nature. (2021, 7). Lithium-ion batteries need to be greener and more ethical. *The international journal of science*, *595*(7865), 7–7. doi: 10.1038/d41586-021-01735-z

Nevins, J. L., & Whitney, D. E. (1989). *Concurrent Design of Products and Processes: A Strategy for the Next Generation in Manufacturing.* McGraw-Hill Education.

Orlov, H., Sardes, A., Segev, T., Doron, N., & Chioclea, S. (2021). *Brake systems integrated into vehicle corner modules and methods of use thereof.* Retrieved from `https://patents.google.com/patent/US11524667B2/en?oq=ree+automotive`

Panarotto, M., Isaksson, O., Habbassi, I., & Cornu, N. (2020). Value-Based Development Connecting Engineering and Business: A Case on Electric Space Propulsion. *IEEE Transactions on Engineering Management*, *69*(4), 1650–1663. doi: 10.1109/TEM.2020.3029677

Pandremenos, J., Paralikas, J., Salonitis, K., & Chryssolouris, G. (2009). Modularity concepts for the automotive industry: A critical review. *CIRP Journal of Manufacturing Science and Technology*, *1*(3), 148–152. doi: 10.1016/j.cirpj.2008.09.012

Pelliccione, P., Knauss, E., Heldal, R., Magnus Ågren, S., Mallozzi, P., Alminger, A., & Borgentun, D. (2017, 6). Automotive Architecture Framework: The experience of Volvo Cars. *Journal of Systems Architecture*, *77*, 83–100. doi: 10.1016/j.sysarc.2017.02.005

Peschansky, L. V., Von Knorring, D. L., Norton, R. F., Burger, F., Herrick, T. J., & Jayroe, R. E. (2008). *Vehicle Frame Assembly And Method Having Flexible Modular Architecture.* Retrieved from `https://patents.google.com/patent/US20090236877?oq=Modular+truck+chassis`

Power-Circle. (2021, 12). *Elvägars möjligheter* (Tech. Rep.). Stockholm.

Rodgers, L., Hoff, N., Jordan, E., Heiman, M., & Miller, D. (2005). A Universal Interface for Modular Spacecraft. Proceedings of the 19th Annual AIAA/USU Conference on Small Satellites.

Rothwell, R., & Whinston, T. G. (1990). *Design, innovation and corporate integration* (3rd ed., Vol. 20). Retrieved from `https://doi.org/10.1111/j.1467-9310.1990.tb00709.x` doi: 10.1111/j.1467-9310.1990.tb00709.x

Sako, M. (2003). Modularity and Outsourcing: The Nature of Co-evolution of Product Architecture and Organization Architecture in the Global Automotive Industry. *The Business of Systems Integration*, 229–253. doi: 10.1093/0199263221.003.0012

Sanchez, R., & Mahoney, J. T. (1996). Modularity, Flexibility, and Knowledge Management in Product and Organization Design. *Strategic Management Journal*, *17*(Special issue), 63–76. doi: 10.1002/smj.4250171107

Sardes, A., Starik, E., Dekel, R., Segev, T., Aknin, A., Avigur, E., & Boaz, A. (2021). *Vehicle chassis platform.* Retrieved from `https://patents.google.com/patent/US11260909B2/en?oq=ree+automotive`

Sattler, S., Hintereder, J., Kondic, D., Burger, N., Jahn, D., Kusch, W., & Leisch, A. (2018). *Structural and preferably functionally modular commercial vehicle chassis.* Retrieved from `https://patents.google.com/patent/DE102018117094A1/en?q=(Modular+truck+chassis)&q=(Modular)&q=(Truck)&q=(B62D21%2f12)`

Scania. (2021, 11). *Next-level modularity in Scania's new chassis programme [Video File].* Retrieved from `https://www.youtube.com/watch?v=E3HsMDGvs9Y&t=1s`

Schachinger, P., & Johannesson, H. L. (2000, 12). Computer modelling of design specifications. *Journal of Engineering Design*, *11*(4), 317–329. doi: 10.1080/0954482001000935

Shirley, G. V. (1990). Models for Managing the Redesign and Manufacture of Product Sets. *Journal of Manufacturing and Operations Management*, *3*, 85–104.

Simpson, T. W., Maier, J. R., & Mistree, F. (2001). Product platform design: Method and application. *Research in Engineering Design - Theory, Applications, and Concurrent Engineering*, *13*(1), 2–22. doi: 10.1007/s001630100002

Stewart, I., McBurney, C., Mcbride, B., Steele, D., & Brayshaw, R. (2016). *Chassis for electric vehicles.* Retrieved from `https://patents.google.com/patent/GB2546535A/en?oq=GB2546535A`

Storaenso. (2022, 11). *In the future, car batteries can be made from trees – and this is why European EV and battery manufacturers should care.*

Suh, E. S., De Weck, O. L., & Chang, D. (2007, 8). Flexible product platforms:

Framework and case study. *Research in Engineering Design*, *18*(2), 67–89. doi: 10.1007/s00163-007-0032-z

Sun, H., Ha, W., Teh, P. L., & Huang, J. (2017, 8). A Case Study on Implementing Modularity in Software Development. *Journal of Computer Information Systems*, *57*(2), 130–138. doi: 10.1080/08874417.2016.1183430

Sutton, R., Toledano, R., Stauber, O., & Layevski, E. (2021). *Control systems for vehicle corner modules and methods of operation.* Retrieved from `https://patents.google.com/patent/US11465636B2/en?oq=ree+automotive`

Sverdlov, D., & Saint, G. (2017). *Autonomous container transportation vehicle.* Retrieved from `https://worldwide.espacenet.com/patent/search/family/056410800/publication/EP3464159A1?q=EP3464159A1`

Thebeau, R. (2001). *Knowledge management of system interfaces and interactions for product development processes* (Unpublished doctoral dissertation). Massachusetts Institute of Technology.

Truett, R. (2022, 9). EV skateboard chassis history. *Automotive News.* Retrieved from `https://www.autonews.com/manufacturing/ev-skateboard-chassis-its-history-and-future`

Ulrich, K. (1994). Fundamentals of Product modularity. In *Management of design* (1st ed., pp. 219–231). Springer. doi: 10.1007/978-94-011-1390-8{_}12

Ulrich, K. (1995). The role of product architecture in the manufacturing firm. *Research Policy*, *24*(3), 419–440. doi: 10.1016/0048-7333(94)00775-3

Ulrich, K., Eppinger, S., & Yang, M. (2020). *Product Design and Development* (7th ed.). New York: McGraw-Hill Education.

Ulrich, K. T., Eppinger, S. D., & Yang, M. C. (2019). *Product Design and Development.* McGraw-Hill Education.

Wheelwright, S., & Clark, K. (1992). *Revolutionizing Product Development: Quantum Leaps in Speed, Efficiency, and Quality.* New York: Free Press.

Wilhelm, B. (1997). Platform and Modular Concepts at Volkswagen — Their Effects on the Assembly Process. In K. Shimokawa, U. Jürgens, & T. Fujimoto (Eds.), *Transforming automobile assembly: Experience in automation and work organization.* Berlin Heidelberg: Springer. doi: 10.1007/978-3-642-60374-7{_}12

William J. Bluethmann, Thomas M. Waligora, Nathan Fraser-Chanpong, Ryan Reed, Akinjide Akinniyi Akinyode, Ivan Spain, … Raymond Guo (2013). *Multi-functional electric module for a vehicle.* Retrieved from `https://patents.google.com/patent/US9102331B2/en?oq=US9102331B2`

A

Appendix A

A.1 First round of interviews

- What is your title at the company and what are your main responsibilities?
- Which components would you describe as the major parts of the chassis for the AETs?
- What are the major differences between a chassis for an AET compared to a traditional truck with ICE, according to your experience?
- How would you describe the term modularity?
- How would you describe the term modularity within the context of the manufacturer?
- Which of the mentioned components would you prefer to be modular and in what way?
- Would you see a modular design as a benefit for you and the company? And for which department would it be beneficial?

A.2 Second round of interviews

In this section are the interview questions for the secound round of interviews presented. The questions asked in each interview differentiate depending on the interviewees competence. All interviewees are asked to answer the general questions presented in the following section. Thereafter the interviewees are asked to answer questions from one or two of the following subjects, frame, axles, brakes, steering, power train, battery package, User experience, manufacturing or business case.

A.2.1 General questions

- What are the main functions that the chassis have to fulfill? Not components or systems, just functions?
- Are there any functions that today's chassis are missing?
- Which specific user cases would you like the chassis to be modularized after, and how will it impact the different components?
- What don't you like with the chassis that are used today?
- What are your main goals when looking to develop a chassis or buy a chassis from suppliers?
- How much of the chassis are you developing and designing, and how much of a say do the suppliers have in the design and development?

- How would you describe the development phase/cycle in terms of pace, quality, and verification?
- How do you think the development internally/externally will look in the future, and how would you prefer it to be?
- What do you wish to change or develop further but are unable to change because of today’s restrictions?
- Is there any component or system that is required today, which might not be necessary in the future? Or can be substituted to something else in the future?
- How important is the placement of the center of gravity?
- Could you name a key benefit that you wish for, from the result of having a modular chassis?

A.2.2 Frame

- What are your expectations of the frame for a new chassis?
- Are there any specific requirements for the frame?
- Are there different types of interfaces between the frame and other components?
- In view of serviceability, how could the frame be further improved?
- What are the legal requirements to follow for designing the frame?

A.2.3 Axles

- What are your expectations of the axles?
- Are there any specific requirements for the shaft/axles?
- How would the connection of the axle with the frame be designed according to your experience?
- How would the connection of the axle with the energy source be designed according to your experience?
- Which other systems are the shaft/axles interacting with the most?
- In view of serviceability, how could the shaft/axles be further improved?
- What are the legal requirements to follow for the shaft/axles?

A.2.4 Brakes

- What are your future expectations for the design of the brakes?
- Which are the necessary components used today that are included in the braking system?
- How is braking controlled in an autonomous system?
- Are there any specific requirements for the brakes?
- Is there a specific type of break that you would like to use?
  - How can it be integrated or re-designed in the future?
  - Will air compressor and air tanks be required in the future?
- If an extra fail operation is necessary, can it be built into the braking system? How could it be integrated into the system?
- Which other systems is the braking system interacting with the most?

- In view of serviceability, how could the brakes be further improved?
- What are the legal requirements to follow for the brakes?

A.2.5 Steering

- What are your expectations of the steering system?
- Which are the necessary components used today that are included in the steering system?
- Are there any specific requirements for the steering system?
- Could you mention a few pros and cons for different types of steering systems?
- Which other systems are the steering system interacting with the most?
- In view of serviceability, how could the steering be further improved?
- What are the legal requirements to follow for the steering?

A.2.6 Powertrain

- What are your expectations of the power train?
- What are the components necessary and used today that are included in the power train?
- Are there any specific requirements for the power train?
- To what extent is it possible to switch components in today's power train?
- Which other systems is the power train system interacting with the most?
- In view of serviceability, how could the power train be further improved?
- What are the legal requirements to follow for the power train?

A.2.7 Battery packs

- What are your expectations of the battery package?
- Which are the main components in the battery pack?
- Are there any specific requirements for the battery package?
- How do you specify the design of the battery pack?
- Where would you specify the interface/boundary for a modular battery pack?
- How well does the cooling/heating system for the batteries work today?
- Implement cooling and heating of batteries? Can it be integrated into the battery pack?
- Is there any specific position necessary for the charging port?
- Any specific wishes for the placement of batteries?
- Which other systems is the battery package system interacting with the most?
- In view of serviceability, how could the battery package be further improved?
- What are the legal requirements to follow for the battery packages?

A.2.8 User experience

- What are your expectations of different use cases for an AET?
- Which different use cases do you think will be relevant for an AET in the nearest future?

- In the far future, which different use cases will an AET be used in? Compared to the near future.
- What are the requirements for an AET from the use cases perspective?
- What are the foreseen problems in the near future when switching to electric and autonomous transportation?
- In view of serviceability, how would you describe it and how could it be further improved for users?

A.2.9 Manufacturing

- Could you shortly explain a simplified version of the manufacturing process today?
- Is there any process step that is extra difficult in today's manufacturing process?
- What are your future expectations of the manufacturing process?
- Are there any specific requirements for the manufacturing process?

A.2.10 Business case

- What are your expectations on a modular chassis seen from a business perspective?
- What are the requirements for a modular chassis seen from a business perspective?
- Are there any trade-offs between the business unit and engineering requirements when developing a chassis?
- Would it be possible and beneficial to find an agreement with a supplier on a co-development level?

B

Appendix B

B.1 Patent search

Twelve different patents from the patent search were selected to be presented since they showed interesting solutions for how modularity could be applied to the chassis architecture of vehicles. All the patents were located in the IPC group of "B" except one that was in "H", where "B" covers performing operations; transporting, and "H" covers electricity. Several different concepts have similarities and cover similar areas. The different patents are presented in the following categories, Frame of chassis, Transport solution, and Individual wheel mounting.

Frame of chassis

Different patents with relation to the frame in chassis for different vehicles were founded. From the patent search, it was concluded that modular frames are something that is highly relevant among different vehicle manufacturers. Firstly, the three presented patents are based on assembling the frame for the vehicle by dividing it into different modules. Arbo Speciality Veichles LLC published a patent in 2019, named Motor Veichle modular construction and it is stated as active. The patent is based on having different pre-assembled subassemblies that are assembled with mechanical interfaces to build the entire vehicle (see Figure B.1), in this example, a chassis of a bus is presented. The different subassemblies can be configured in various setups with a familiar product architecture. The construction is motivated by reducing the assembly time and welding processes (Anderson et al., 2019).

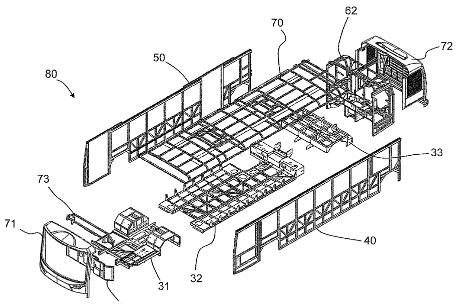


Figure B.1: Patent US11161560B2 created and published by Arboc Speciality Vehicles LLC in 2019 (Anderson et al., 2019).

Furthermore, another presented patent is one by the company MAN Truck and BUS SE, named Structural and preferably functionally modular commercial vehicle chassis, which was published in 2018 and has the status of pending. The presented patent can be seen in Figure B.2 and consists of one front axle and a rear axle module. Including the possibility to add various numbers of modules in between the front and rear modules, with modules named as function-modules. This enables the possibility of having a varying longitudinal length of the vehicle depending on preferences. All the modules are constructed with supporting structures and assembled with defined mechanical interfaces (Sattler et al., 2018). Another similar patent was published in 2008 by GM Global Technology Operations LLC and has the status of abandoned. The idea of the patent is the same as the previously mentioned with defined front and rear modules, having a flexible length of a single middle module (Peschansky et al., 2008). The main difference between the two patents is the structural design, where the patent by MAN Truck and BUS SE consists of middle modules structured as boxes and wheels mounting integrated into the front and rear axle modules (Sattler et al., 2018). While the patent by GM Global Technology Operations LLC is based on only having one left and right beam for the frame, linked together with crossmembers to stabilize the chassis (Peschansky et al., 2008).

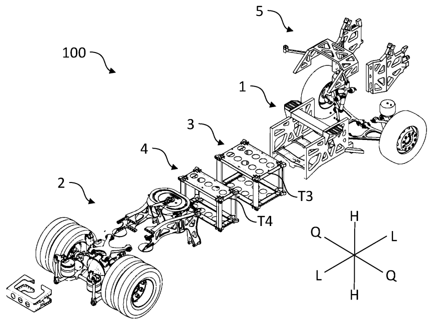


FIG. 1

Figure B.2: Patent DE102018117094A1 created and published by MAN Truck and Bus SE in 2018 (Sattler et al., 2018).

A similar patent with beams that was identified was a patent by Gaussin SA published in 2004, with an anticipated expiration in 2024. This patent is based on a trailer for a truck, with independent frames constituting the structure for the chassis of the trailer. While modules of wheels and mountings are interchangeable (Gaussin, 2004). Lastly, a patent within the chassis for electric vehicles is presented. The patent was published by Wrightbus LTD in 2016 and has now the status of being withdrawn. The chassis in this case is designed for a bus and has modular placement for the batteries. Placement spots for batteries are located between the front and rear axles with rectangular areas for each battery module. Depending on the number of battery modules the number of spots can be relegated, i.e. if space is required for a middle door on the bus, two spots for battery modules can be removed for enabling space (Stewart, McBurney, Mcbride, Steele, & Brayshaw, 2016).

]

Autonomous transport solutions

In the case of autonomous transportation where a driver cab is not included in the solution, it leads to changes compared to a traditional truck. Therefore, one part of the patent research was to discover this specific transport solution. This resulted in presenting two different patents, where both solutions are developed for transporting containers. Container transport is a significant segment of the transportation industry and was therefore investigated further. The first presented patent was published by Demag Cranes and Components GmbH in 2009 and has the status of being withdrawn. Additionally, the patent is based on a heavy-duty truck with the capacity of carrying a total weight of 40 tons (see Figure B.3). The vehicle is constructed on a frame with two axles, one front, and one rear. Power for the vehicle is sourced by a battery pack mounted under the frame in the middle, between the front and rear axle. This enables the possibility of loading and unloading the entire battery pack in the direction of "E", visualized in Figure B.3 (Franzen et al., 2009).

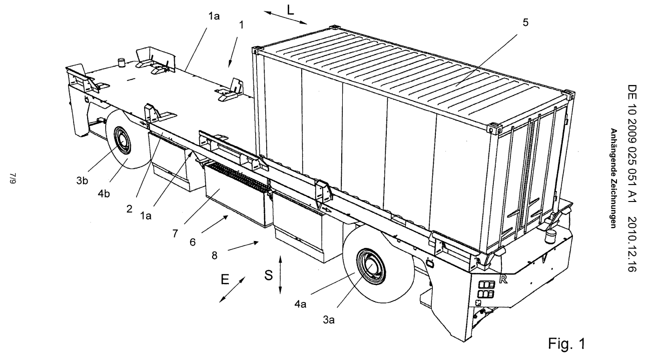


Figure B.3: Patent DE102009025051A1 created and published by Demag Cranes and Components GmbH in 2009 (Franzen et al., 2009).

Another identified patent that includes an autonomous transportation solution for containers is published by Arrival LTD in 2016. The patent is named, Autonomous container transportation vehicle and has the status of pending. Having one module of two wheels, one axle, and an attachment for lifting a container (see Figure B.4), which is required for the solution. Combining two of the mentioned modules on each side of the short ends of a container and providing at least one module with an electric powertrain enables the transportation of a container. This shows the possibility of transporting goods autonomously without being restricted to designing vehicles with a frame connecting the front and rear axle (Sverdlov & Saint, 2017).

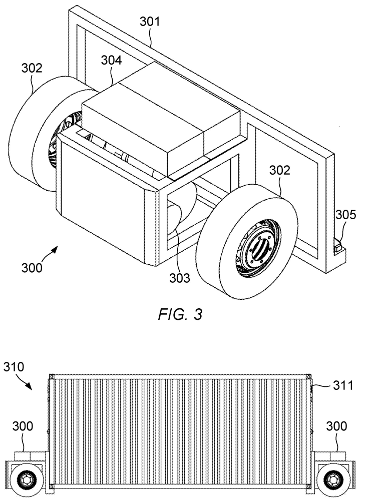


Figure B.4: Patent EP3464159A1 created and published by Arrival UK Ltd in 2017 (Sverdlov & Saint, 2017).

Individual wheel mounting

From the conducted patent search a specific area of chassis for vehicles was discovered, specifically vehicles with individual wheel mounting. Instead of having a vehicle with two wheels linked to a common axle, one possibility could be to have two separate wheels and no linking axle in between. By having a solution dependent on individual wheel mountings another type of chassis architecture would be required, compared to a traditional frame with beams and axles with two wheels. A proposed solution for this was found in a patent published by REE Automotive Ltd in 2021, with the status of active. The patent is named Vehicle chassis platform and is based on having a rectangular flat frame with a vehicle corner module (VCM) in each corner, visualized in Figure B.5. The VCM is designed with the possibility to include a powertrain, steering, and suspension system. Each VCM is assembled to the frame with mechanical connections and with connections for controlling each function. Batteries are proposed as the source of power and these are mounted between the bottom and top layer of the frame (Sardes et al., 2021). Another active patent linked to the vehicle, presented as a brake system was published by Ree Automotive Ltd in 2021. A brake actuator controlled by a fluid-based power source is proposed to regulate the rotation of each wheel. Each VCM has a mounted braking system and there is no fluid communication among the other VCMs' or the chassis (Orlov, Sardes, Segev, Doron, & Chioclea, 2021). Additionally, a separate patent for controlling the system in operations was also published by Ree Automotive Ltd in 2021 and is active. The purpose of the patent is to have a control network for the entire vehicle, by having separate VCM controllers on each VCM and connecting these together by a common unit placed on the frame (Sutton, Toledano, Stauber, & Layevski, 2021).

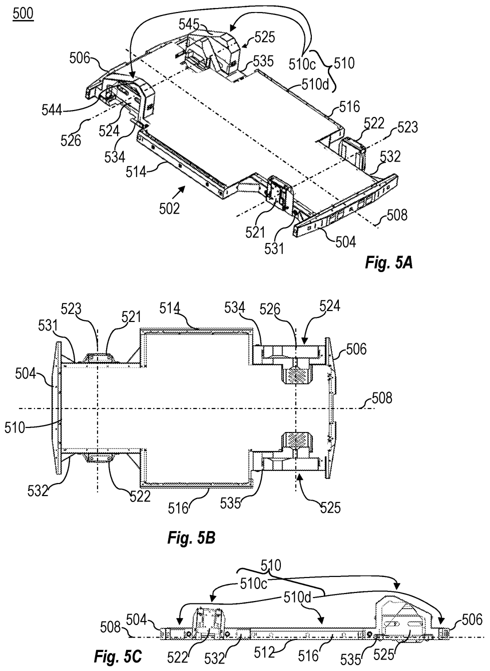


Figure B.5: Patent US11260909B2 created and published by REE Automotive Ltd in 2021 (Sardes et al., 2021).

Furthermore, two other patents within the area of individual wheel mounting were identified. Firstly, an active patent published by Aisin AW Co Ltd in 2012 was explored. The patent is named, In-wheel motor drive device and covers an entire solution for having a motor mounted directly to a wheel. The solution will enable more space in the vehicle compared to a traditionally placed motor in the front and middle of the frame. As well as improve the efficiency of the motor (Hirano, 2012). Secondly, a patent named, Multi-functional electric module for a vehicle, was published in 2013 by GM (Global Technology Operations LLC) and NASA (National Aeronautics and Space Administration). The patent is based on a multi-functional electric module (eModule) that can be connected to a chassis and provide steering, braking, transferring, and suspension in a wheel module (see Figure B.6). Electricity is powering the eModule powertrain and is sourced from the chassis. Each eModule has a control system for the different operations, which is simultaneously connected with the vehicle and other eModules. Having the flexibility of steering on each eModule is motivated by increasing the maneuvering efficiency of the vehicle. Additionally, a traditional conventional powertrain constructed with a driveline is not seen as an optimal solution in the sense of providing increased maneuvering (William J. Bluethmann et al., 2013).

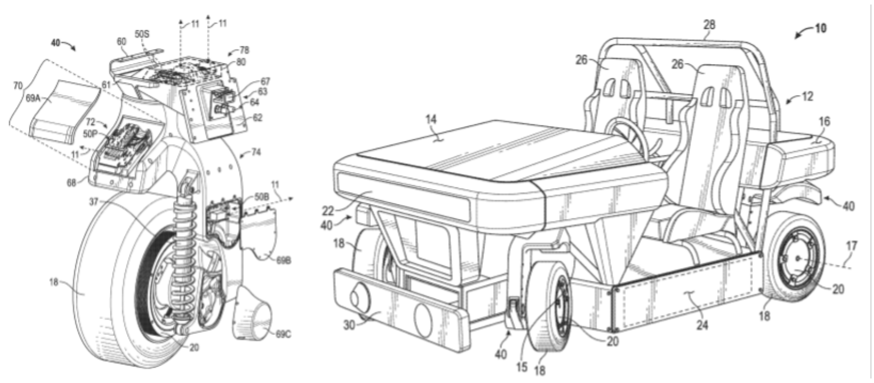
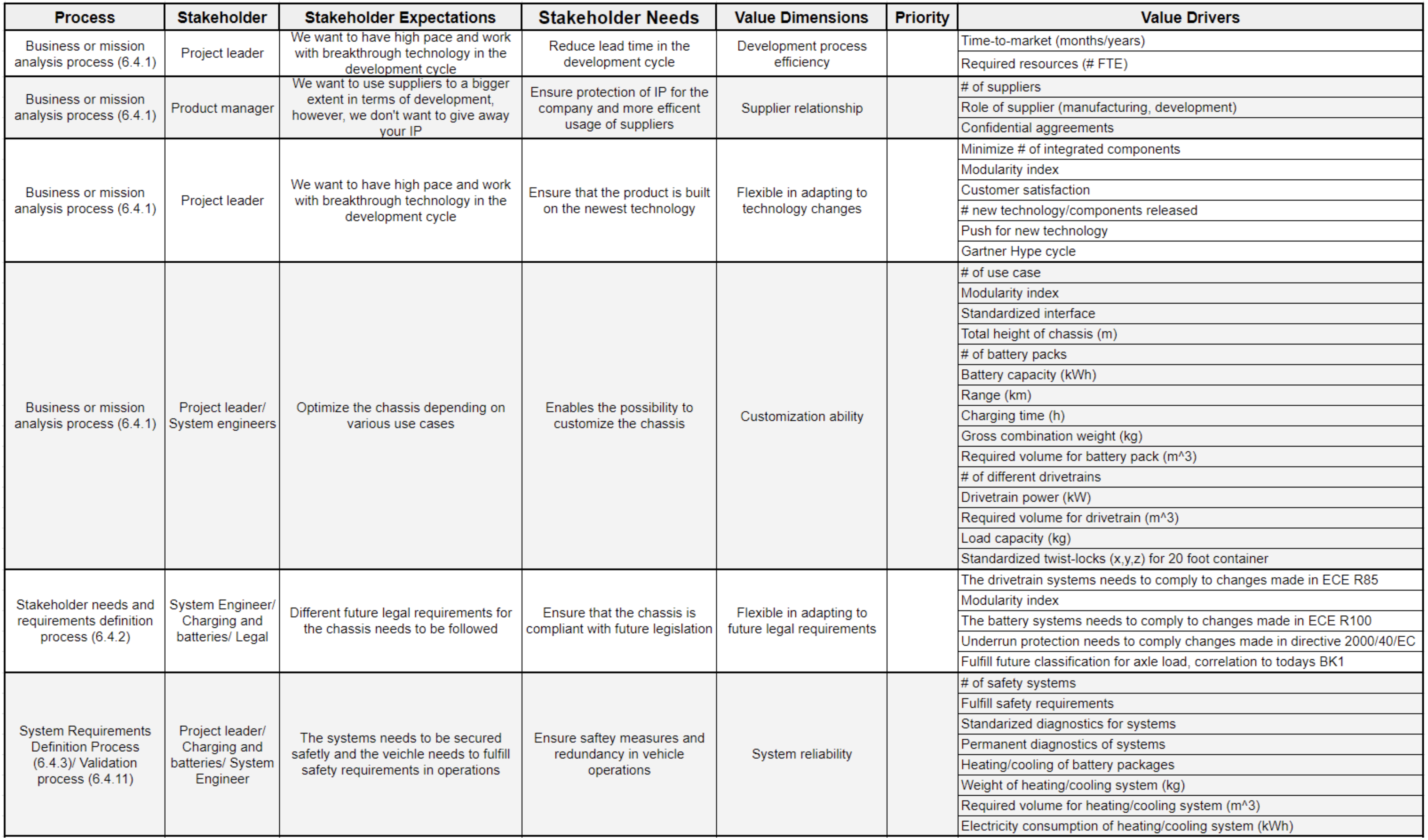


Figure B.6: Patent US9102331B2 created and published by GM Global Technology Operations LLC and NASA in 2013 (William J. Bluethmann et al., 2013).

C

Appendix C

C.1 Value Creation Strategy (VCS)



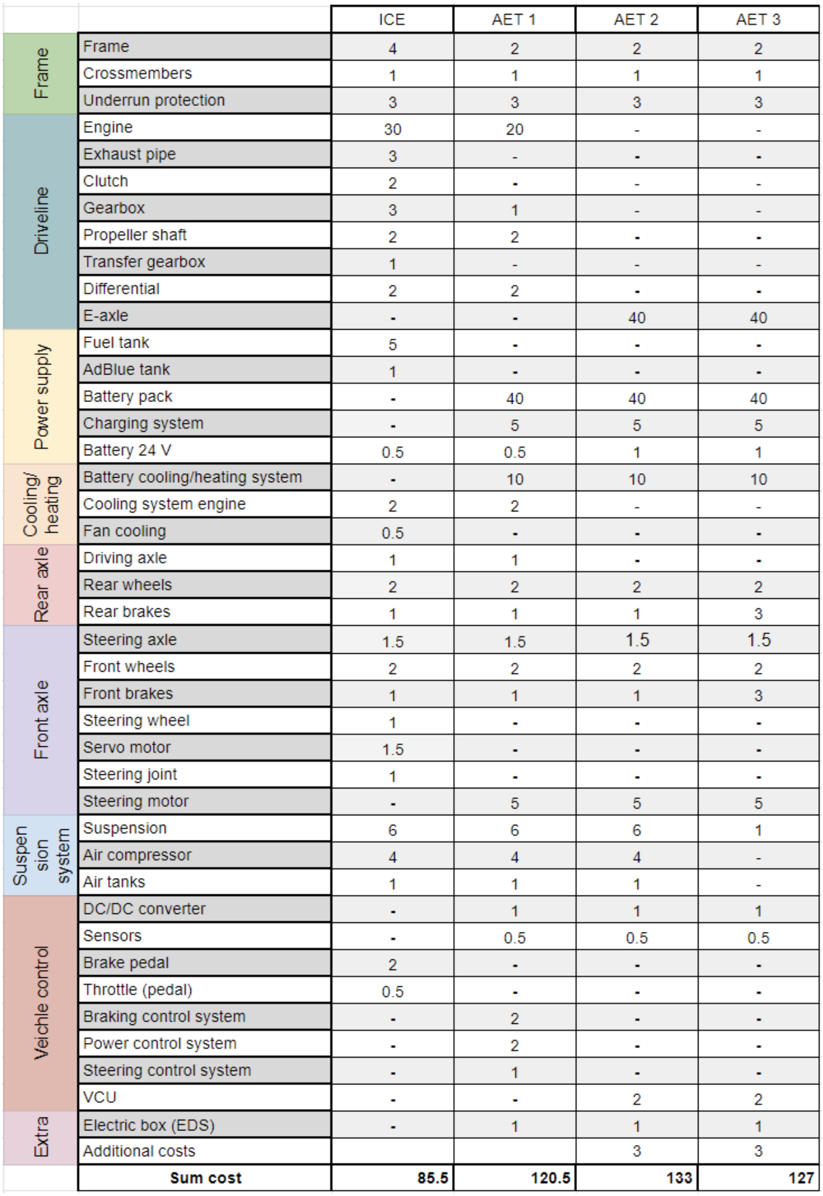
Process	Stakeholder	Stakeholder Expectations	Stakeholder Needs	Value Dimensions	Priority	Value Drivers
Business or mission analysis process (6.4.1)	Project leader	We want to have high pace and work with breakthrough technology in the development cycle	Reduce lead time in the development cycle	Development process efficiency		Time-to-market (months/years)
						Required resources (# FTE)
Business or mission analysis process (6.4.1)	Product manager	We want to use suppliers to a bigger extent in terms of development, however, we don't want to give away your IP	Ensure protection of IP for the company and more efficent usage of suppliers	Supplier relationship		# of suppliers
						Role of supplier (manufacturing, development)
						Confidential aggreements
Business or mission analysis process (6.4.1)	Project leader	We want to have high pace and work with breakthrough technology in the development cycle	Ensure that the product is built on the newest technology	Flexible in adapting to technology changes		Minimize # of integrated components
						Modularity index
						Customer satisfaction
						# new technology/components released
						Push for new technology
						Gartner Hype cycle
Business or mission analysis process (6.4.1)	Project leader/ System engineers	Optimize the chassis depending on various use cases	Enables the possibility to customize the chassis	Customization ability		# of use case
						Modularity index
						Standardized interface
						Total height of chassis (m)
						# of battery packs
						Battery capacity (kWh)
						Range (km)
						Charging time (h)
						Gross combination weight (kg)
						Required volume for battery pack (m^3)
						# of different drivetrains
						Drivetrain power (kW)
						Required volume for drivetrain (m^3)
						Load capacity (kg)
						Standardized twist-locks (x,y,z) for 20 foot container
Stakeholder needs and requirements definition process (6.4.2)	System Engineer/ Charging and batteries/ Legal	Different future legal requirements for the chassis needs to be followed	Ensure that the chassis is compliant with future legislation	Flexible in adapting to future legal requirements		The drivetrain systems needs to comply to changes made in ECE R85
						Modularity index
						The battery systems needs to comply to changes made in ECE R100
						Underrun protection needs to comply changes made in directive 2000/40/EC
						Fulfill future classification for axle load, correlation to todays BK1
System Requirements Definition Process (6.4.3)/ Validation process (6.4.11)	Project leader/ Charging and batteries/ System Engineer	The systems needs to be secured safetly and the veichle needs to fulfill safety requirements in operations	Ensure saftey measures and redundancy in vehicle operations	System reliability		# of safety systems
						Fulfill safety requirements
						Standardized diagnostics for systems
						Permanent diagnostics of systems
						Heating/cooling of battery packages
						Weight of heating/cooling system (kg)
						Required volume for heating/cooling system (m^3)
						Electricity consumption of heating/cooling system (kWh)

Process	Stakeholder	Stakeholder Expectations	Stakeholder Needs	Value Dimensions	Priority	Value Drivers
Architecture definition process (6.4.4)	Project leader/ System engineer	Reduce components to decrease complexity and allow for more space	Ensure that components are reduced and free space is enabled	Reduce system complexity		# of components
						Unit cost
						Weight reduced (kg)
						Placement of components (x,y,z)
						Space availability (m^3)
Design definition process (6.4.5)	Project leader/ Charging and batteries	The battery cells needs to be protected and not exposed for vibrations	Ensure protection for battery cells	Battery safety and reliability		Displacement (mm)
						Tensile strength (MPa)
						Architectural placement (x,y,z)
						Absorbed vibrations (Hz)
Design definition process (6.4.5)	System Engineer	We want to place the steering motor on the component XX and not on the component YY	Enable optimal placement of components in terms of functionality	Optimized functional placement		Placement of components (x,y,z)
						Braking efficiency (m/s^2)
						Powertrain efficiency (%)
						Steering efficiency (degrees, rad/s)
Implementation process (6.4.7)	Manufacturing/ Chapter lead	The production needs to be simple and efficient	Ensure standardized production	Manufacturbility		# standarized components
						Unit cost
						Standardized process (main/sub processes)
						# reduced components
						Placement of cables (x,y,z)
Integration process (6.4.8)	System engineer	Using same axles for different use cases	Ensure the ability to use components for multiple use cases	Component standardization		Standardized interface
						# of standardized components
						# of attachments/interfaces
						Posibility to integrate with new components
Operation process (6.4.12)	System Engineer/ Project leader/ Product manager	It is important to have reliable operations	Ensure operational stability in vehicle	Opertational reliability		Vibrations (Hz)
						Power usage (kW)
						Placement center of gravity (x,y,z)
						Placement of components (x,y,z)
						Up-time (%)
						Component life expectancy (years)
Operation Process (6.4.12)	Project leader	Remove energy conversion used for hydraulics and compressed air	Energy consumption reduction	Energy efficiency		Electricity consumption (kWh)
						Friction (COF)
						Air resistance (Drag coefficient, Cd)
						Powertrain efficiency (%)
						Compressor efficiency (%)
						Thermal efficiency (%)
						# of energy conversion
Maintenance process (6.4.13)	Project leader/ manufacturing	We want the possibility of attaching and detaching components, and acces the cables.	Enable easy service of components and cables	System serviceability		Placement of components (x,y,z)
						# integrated components
						# standarized maintnace processes
						# standarized components
						# of steps to access specific components
						Minimized service time (h)

D

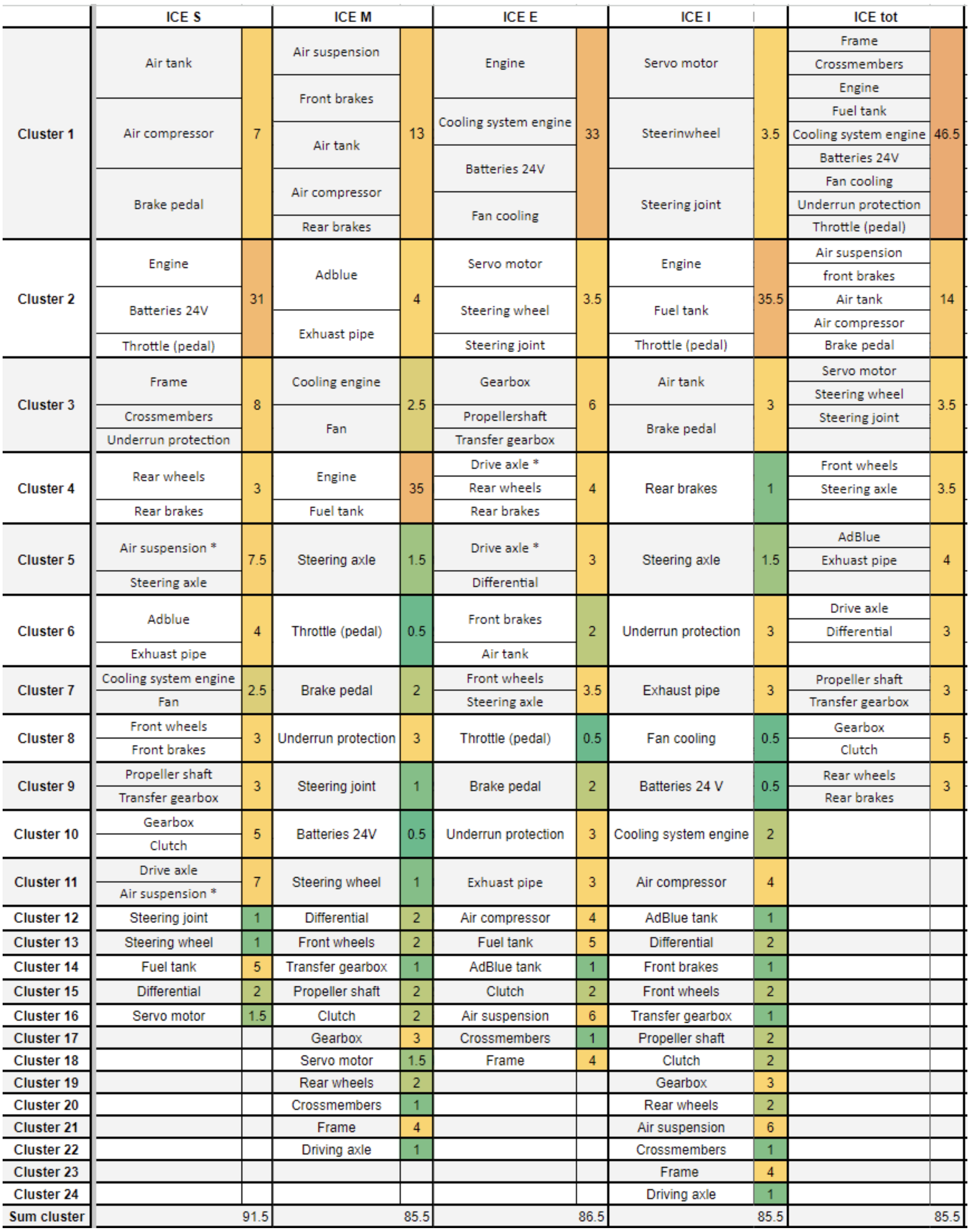
Appendix D

D.1 Costs factors for components



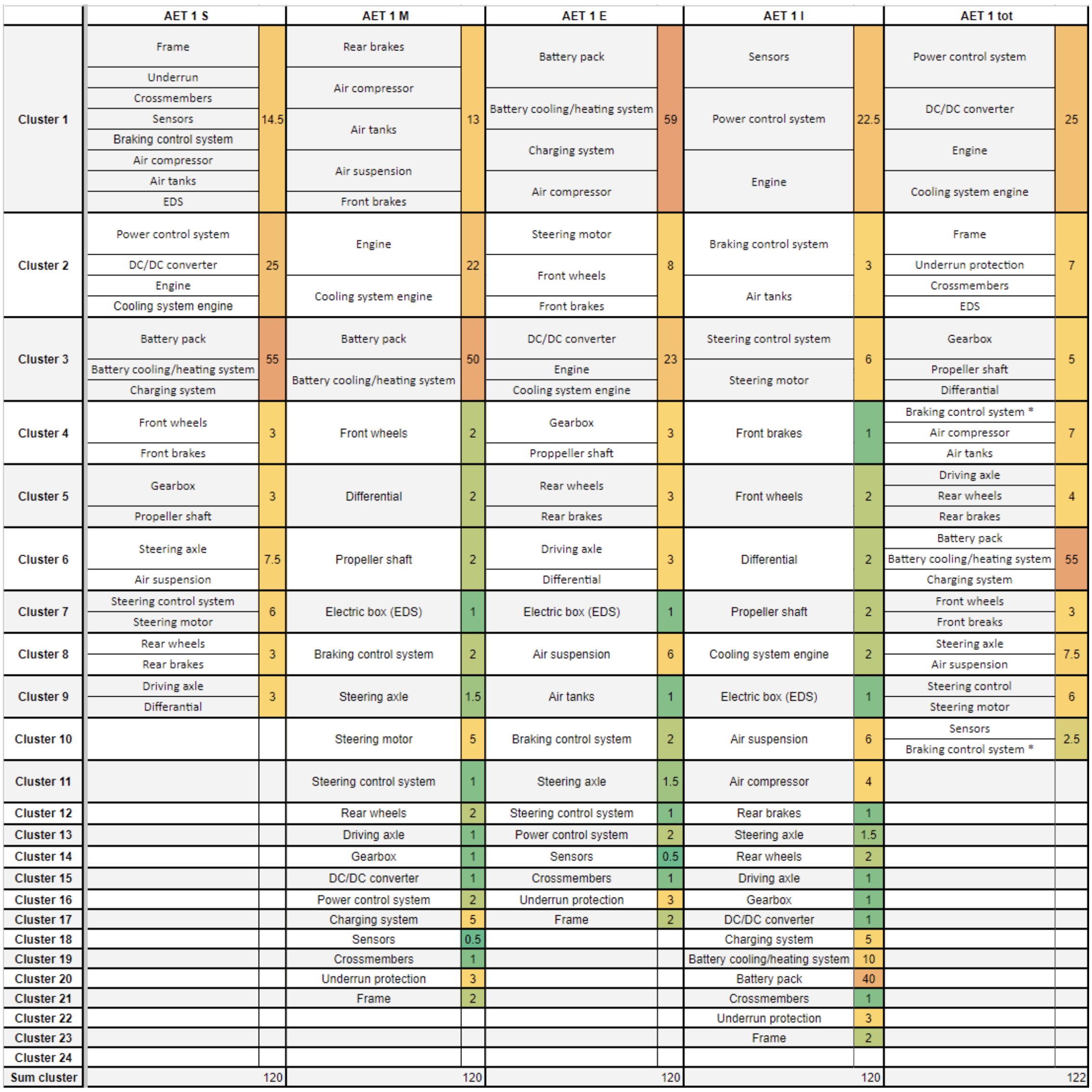
		ICE	AET 1	AET 2	AET 3
Frame	Frame	4	2	2	2
	Crossmembers	1	1	1	1
	Underrun protection	3	3	3	3
Driveline	Engine	30	20	-	-
	Exhaust pipe	3	-	-	-
	Clutch	2	-	-	-
	Gearbox	3	1	-	-
	Propeller shaft	2	2	-	-
	Transfer gearbox	1	-	-	-
	Differential	2	2	-	-
	E-axle	-	-	40	40
Power supply	Fuel tank	5	-	-	-
	AdBlue tank	1	-	-	-
	Battery pack	-	40	40	40
	Charging system	-	5	5	5
	Battery 24 V	0.5	0.5	1	1
Cooling/ heating	Battery cooling/heating system	-	10	10	10
	Cooling system engine	2	2	-	-
	Fan cooling	0.5	-	-	-
Rear axle	Driving axle	1	1	-	-
	Rear wheels	2	2	2	2
	Rear brakes	1	1	1	3
Front axle	Steering axle	1.5	1.5	1.5	1.5
	Front wheels	2	2	2	2
	Front brakes	1	1	1	3
	Steering wheel	1	-	-	-
	Servo motor	1.5	-	-	-
	Steering joint	1	-	-	-
	Steering motor	-	5	5	5
Suspen sion system	Suspension	6	6	6	1
	Air compressor	4	4	4	-
	Air tanks	1	1	1	-
Veichle control	DC/DC converter	-	1	1	1
	Sensors	-	0.5	0.5	0.5
	Brake pedal	2	-	-	-
	Throttle (pedal)	0.5	-	-	-
	Braking control system	-	2	-	-
	Power control system	-	2	-	-
	Steering control system	-	1	-	-
	VCU	-	-	2	2
Extra	Electric box (EDS)	-	1	1	1
	Additional costs			3	3
	Sum cost	**85.5**	**120.5**	**133**	**127**

D.2 Summarized cost factors for the ICE concept



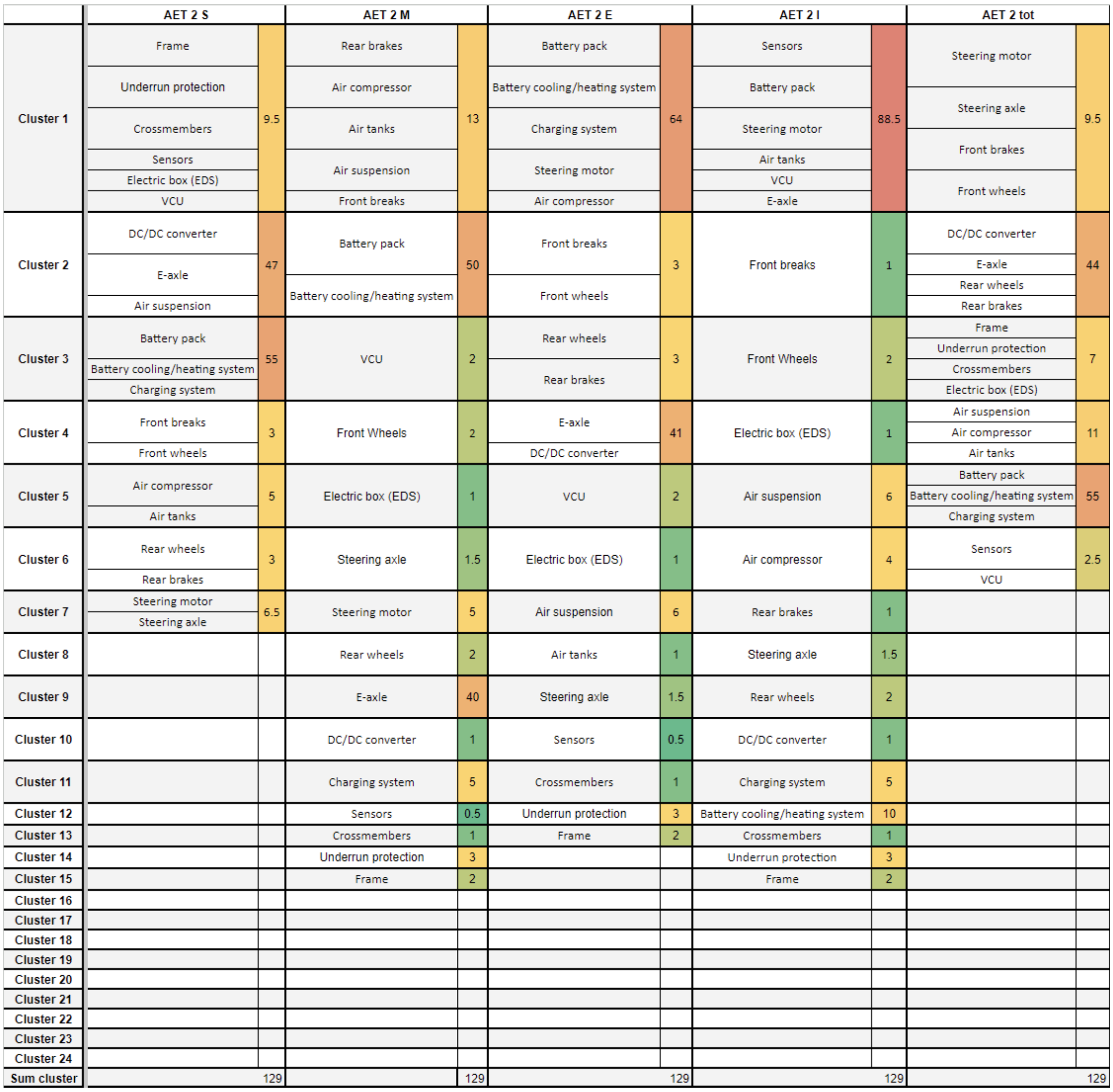
	ICE S		ICE M		ICE E		ICE I		ICE tot	
Cluster 1	Air tank Air compressor Brake pedal	7	Air suspension Front brakes Air tank Air compressor Rear brakes	13	Engine Cooling system engine Batteries 24V Fan cooling	33	Servo motor Steerinwheel Steering joint	3.5	Frame Crossmembers Engine Fuel tank Cooling system engine Batteries 24V Fan cooling Underrun protection Throttle (pedal)	46.5
Cluster 2	Engine Batteries 24V Throttle (pedal)	31	Adblue Exhuast pipe	4	Servo motor Steering wheel Steering joint	3.5	Engine Fuel tank Throttle (pedal)	35.5	Air suspension front brakes Air tank Air compressor Brake pedal	14
Cluster 3	Frame Crossmembers Underrun protection	8	Cooling engine Fan	2.5	Gearbox Propellershaft Transfer gearbox	6	Air tank Brake pedal	3	Servo motor Steering wheel Steering joint	3.5
Cluster 4	Rear wheels Rear brakes	3	Engine Fuel tank	35	Drive axle * Rear wheels Rear brakes	4	Rear brakes	1	Front wheels Steering axle	3.5
Cluster 5	Air suspension * Steering axle	7.5	Steering axle	1.5	Drive axle * Differential	3	Steering axle	1.5	AdBlue Exhaust pipe	4
Cluster 6	Adblue Exhaust pipe	4	Throttle (pedal)	0.5	Front brakes Air tank	2	Underrun protection	3	Drive axle Differential	3
Cluster 7	Cooling system engine Fan	2.5	Brake pedal	2	Front wheels Steering axle	3.5	Exhaust pipe	3	Propeller shaft Transfer gearbox	3
Cluster 8	Front wheels Front brakes	3	Underrun protection	3	Throttle (pedal)	0.5	Fan cooling	0.5	Gearbox Clutch	5
Cluster 9	Propeller shaft Transfer gearbox	3	Steering joint	1	Brake pedal	2	Batteries 24 V	0.5	Rear wheels Rear brakes	3
Cluster 10	Gearbox Clutch	5	Batteries 24V	0.5	Underrun protection	3	Cooling system engine	2		
Cluster 11	Drive axle Air suspension *	7	Steering wheel	1	Exhaust pipe	3	Air compressor	4		
Cluster 12	Steering joint	1	Differential	2	Air compressor	4	AdBlue tank	1		
Cluster 13	Steering wheel	1	Front wheels	2	Fuel tank	5	Differential	2		
Cluster 14	Fuel tank	5	Transfer gearbox	1	AdBlue tank	1	Front brakes	1		
Cluster 15	Differential	2	Propeller shaft	2	Clutch	2	Front wheels	2		
Cluster 16	Servo motor	1.5	Clutch	2	Air suspension	6	Transfer gearbox	1		
Cluster 17			Gearbox	3	Crossmembers	1	Propeller shaft	2		
Cluster 18			Servo motor	1.5	Frame	4	Clutch	2		
Cluster 19			Rear wheels	2			Gearbox	3		
Cluster 20			Crossmembers	1			Rear wheels	2		
Cluster 21			Frame	4			Air suspension	6		
Cluster 22			Driving axle	1			Crossmembers	1		
Cluster 23							Frame	4		
Cluster 24							Driving axle	1		
Sum cluster		91.5		85.5		86.5		85.5		85.5

D.3 Summarized cost factors for the AET 1 concept



	AET 1 S		AET 1 M		AET 1 E		AET 1 I		AET 1 tot	
Cluster 1	Frame Underrun Crossmembers Sensors Braking control system Air compressor Air tanks EDS	14.5	Rear brakes Air compressor Air tanks Air suspension Front brakes	13	Battery pack Battery cooling/heating system Charging system Air compressor	59	Sensors Power control system Engine	22.5	Power control system DC/DC converter Engine Cooling system engine	25
Cluster 2	Power control system DC/DC converter Engine Cooling system engine	25	Engine Cooling system engine	22	Steering motor Front wheels Front brakes	8	Braking control system Air tanks	3	Frame Underrun protection Crossmembers EDS	7
Cluster 3	Battery pack Battery cooling/heating system Charging system	55	Battery pack Battery cooling/heating system	50	DC/DC converter Engine Cooling system engine	23	Steering control system Steering motor	6	Gearbox Propeller shaft Differantial	5
Cluster 4	Front wheels Front brakes	3	Front wheels	2	Gearbox Proppeller shaft	3	Front brakes	1	Braking control system * Air compressor Air tanks	7
Cluster 5	Gearbox Propeller shaft	3	Differential	2	Rear wheels Rear brakes	3	Front wheels	2	Driving axle Rear wheels Rear brakes	4
Cluster 6	Steering axle Air suspension	7.5	Propeller shaft	2	Driving axle Differential	3	Differential	2	Battery pack Battery cooling/heating system Charging system	55
Cluster 7	Steering control system Steering motor	6	Electric box (EDS)	1	Electric box (EDS)	1	Propeller shaft	2	Front wheels Front breaks	3
Cluster 8	Rear wheels Rear brakes	3	Braking control system	2	Air suspension	6	Cooling system engine	2	Steering axle Air suspension	7.5
Cluster 9	Driving axle Differantial	3	Steering axle	1.5	Air tanks	1	Electric box (EDS)	1	Steering control Steering motor	6
Cluster 10			Steering motor	5	Braking control system	2	Air suspension	6	Sensors Braking control system *	2.5
Cluster 11			Steering control system	1	Steering axle	1.5	Air compressor	4		
Cluster 12			Rear wheels	2	Steering control system	1	Rear brakes	1		
Cluster 13			Driving axle	1	Power control system	2	Steering axle	1.5		
Cluster 14			Gearbox	1	Sensors	0.5	Rear wheels	2		
Cluster 15			DC/DC converter	1	Crossmembers	1	Driving axle	1		
Cluster 16			Power control system	2	Underrun protection	3	Gearbox	1		
Cluster 17			Charging system	5	Frame	2	DC/DC converter	1		
Cluster 18			Sensors	0.5			Charging system	5		
Cluster 19			Crossmembers	1			Battery cooling/heating system	10		
Cluster 20			Underrun protection	3			Battery pack	40		
Cluster 21			Frame	2			Crossmembers	1		
Cluster 22							Underrun protection	3		
Cluster 23							Frame	2		
Cluster 24										
Sum cluster		120		120		120		120		122

D.4 Summarized cost factors for the AET 2 concept



	AET 2 S		AET 2 M		AET 2 E		AET 2 I		AET 2 tot	
Cluster 1	Frame Underrun protection Crossmembers Sensors Electric box (EDS) VCU	9.5	Rear brakes Air compressor Air tanks Air suspension Front breaks	13	Battery pack Battery cooling/heating system Charging system Steering motor Air compressor	64	Sensors Battery pack Steering motor Air tanks VCU E-axle	88.5	Steering motor Steering axle Front brakes Front wheels	9.5
Cluster 2	DC/DC converter E-axle Air suspension	47	Battery pack Battery cooling/heating system	50	Front breaks Front wheels	3	Front breaks	1	DC/DC converter E-axle Rear wheels Rear brakes	44
Cluster 3	Battery pack Battery cooling/heating system Charging system	55	VCU	2	Rear wheels Rear brakes	3	Front Wheels	2	Frame Underrun protection Crossmembers Electric box (EDS)	7
Cluster 4	Front breaks Front wheels	3	Front Wheels	2	E-axle DC/DC converter	41	Electric box (EDS)	1	Air suspension Air compressor Air tanks	11
Cluster 5	Air compressor Air tanks	5	Electric box (EDS)	1	VCU	2	Air suspension	6	Battery pack Battery cooling/heating system Charging system	55
Cluster 6	Rear wheels Rear brakes	3	Steering axle	1.5	Electric box (EDS)	1	Air compressor	4	Sensors VCU	2.5
Cluster 7	Steering motor Steering axle	6.5	Steering motor	5	Air suspension	6	Rear brakes	1		
Cluster 8			Rear wheels	2	Air tanks	1	Steering axle	1.5		
Cluster 9			E-axle	40	Steering axle	1.5	Rear wheels	2		
Cluster 10			DC/DC converter	1	Sensors	0.5	DC/DC converter	1		
Cluster 11			Charging system	5	Crossmembers	1	Charging system	5		
Cluster 12			Sensors	0.5	Underrun protection	3	Battery cooling/heating system	10		
Cluster 13			Crossmembers	1	Frame	2	Crossmembers	1		
Cluster 14			Underrun protection	3			Underrun protection	3		
Cluster 15			Frame	2			Frame	2		
Cluster 16										
Cluster 17										
Cluster 18										
Cluster 19										
Cluster 20										
Cluster 21										
Cluster 22										
Cluster 23										
Cluster 24										
Sum cluster		129		129		129		129		129

DEPARTMENT OF INDUSTRIAL AND MATERIALS SCIENCE
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY