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Flexibility of platforms and its impact on platforms lifecycle - a review and a focused case

Master's thesis in Product Development

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
www.chalmers.se

Master's thesis 2021

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Master's Thesis 2021
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Typeset in LaTeX
Printed by Chalmers Reproservice
Gothenburg, Sweden 2021

Abstract

The market demand for differentiated product variants keeps increasing. A platform strategy is followed by companies to develop differentiated products to adapt to the forever changing customer needs while cutting the development lead times. In the automotive industry, this strategy has been used for decades to produce different variants of vehicles based around a common architecture. The longevity of platforms is expected to decrease due to the faster changing market. To fulfil the customer needs with minimal changes to the production architecture, a modular platform is a good candidate. This eliminates the hefty cost of completely redesigning a new platform or heavily modifying an existing platform architecture and its associated production setup. There is currently a lack awareness in practice of how modularisation methods can enhance the flexibility of platforms and companies generally rely on subjective approaches.

This thesis was carried out in collaboration with Volvo Cars, with the goal to investigate the flexibility of the current platforms, the trade-offs required to achieve a highly flexible platform, and the role of geometry and space allocation of components regarding flexibility level. In-depth interviews were conducted with employees working at different departments at Volvo Cars. The interviews provided insights into the company's way of working with regards to modularisation, the drawbacks with it and expected future challenges.

The interview data was analysed in detail using reflective thematic analysis, comparing and categorising the data according to the relevant themes associated with the research questions. Furthermore, a case study of a component was conducted to get an understanding of the design and interfaces across vehicles of different variants. The practices followed for modularisation is at different levels of sophistication between departments at Volvo Cars, and generally trailing behind the state-of-the-art. The trade-offs identified were well understood and the qualitative analysis showed that the modularisation of pure mechanical modules is better defined and documented in comparison to electrical and software modules. The new developments like the electrification of cars pose challenges affecting the decision-making process and modularisation strategy at Volvo Cars.

Keywords: Platforms, Modularisation, Modules, Interfaces.

Acknowledgements

The master thesis was done in cooperation with Volvo Cars. During the work several people have contributed by providing guidance and assistance along the way. The authors would like to thank all the parties involved in the thesis. Especially Thomas Krusell who has been the supervisor from Volvo Cars and supported us with all the knowledge and material. Moreover, thanks to Iñigo Alonso Fernandez for being supervisor from Chalmers and was always there for feedback and meetings.

We would like to thank Daniel Norell for giving us training for Teamcenter and helping us throughout the project. We would also like to thank Volvo Cars for giving us access to necessary tools and software for our thesis. Finally, we would thank all the interviewees who participated in research at Volvo Cars . Your help has been of a great value.

Hamza Hassan & Motasom Ibrahim, Gothenburg, 2021

Nomenclature

BEV - Battery Electric Vehicle

CCB - Cross Car Beam

CMA - Compact Modular Architecture Platform

DFMA - Design For Manufacturing And Assembly

DSM - Design Structure Matrix

HUD - Head-Up-Display

HDD - Head-Down-Display

LCD - Liquid Crystal Display

LED - Light-Emitting Diode Display

PCF - Pedal Column Frame

SPA - Volvo Scalable Product Architecture Platform

SPA 2 - Volvo Scalable Product Architecture Platform, Secound Generation

TC - Team Center

TCVis - Team Center Visualization Software

VISP - Value and flexibility Impact analysis for Sustainable Production

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1
Introduction

This chapter presents the background, aim and objectives are defined, along with the brief introduction to Volvo Cars as a company. The research questions are elaborated while keeping ethics and sustainability in view.

1.1 Context

The customer demands and desires in the automotive industry are changing rapidly. Volvo Cars ambition is to establish a market-leading position by offering their customers personal, sustainable, and safer cars accross all of the models [2]. An excellent way to effectively manufacture a variety of products is to utilize product platforms. Volvo Cars is one of many industries that have applied a product platform strategy and achieved successful results [3]. The concept of a product platform is to increase efficiency in the development process and production through the sharing of core elements between the different models [4]. Thus, multiple variants can be derived from the base consisting of the shared core elements. Currently, Volvo Cars has two different platforms in the market, Compact Modular Architecture (CMA) and Scalable Product Architecture (SPA). The CMA platform is used for the smaller car models while the SPA platform is utilized for the larger ones. Both platforms have helped Volvo Cars to produce many premium models and reach their targets. Since the market demand and desires are constantly changing, there is always a need for improvements. Thus, the flexibility level must be considered to increase the life cycle of platforms.

A flexible product platform can be defined as a system that can undergo changes relatively easy and does not require a whole new redesign process [5]. This will allow a company to quickly make desirable adjustments and hence decrease the lead time as well as costs. Although flexible platforms have their benefits, it is very challenging to develop such a system. Furthermore, predicting where the design changes occur, and the level of flexibility requires continuous research and consultation of experts [6]. Volvo Cars are working together with the System Engineering Design group at Chalmers to develop the flexibility of product platforms. Therefore, this thesis is a collaboration between the authors, researchers from Chalmers, and Volvo Cars group. Additionally, the System Engineering Design Group are already working on a project called VISP "*Value and flexibility Impact analysis for Sustainable Production*" which is connected to this thesis. The VISP project is funded by VINNOVA and aims to develop a model that helps to increase the flexibility of the current platforms without affecting production negatively.

In the automotive industry, the product variants have more than doubled in the past 30 years while the life cycle has decreased by 20 %. This indicates that the market needs are changing at a rapid pace and this is expected to continue in industries for several years. Even though flexibility comes with its benefits, there are many common challenges that industries face. There is a lack of strategic guidance when developing a flexible platform for a specific case, and industries are having problems such as low production volume due to uncertainty or a specific way of developing a product [7].

Volkswagen being the leader in the automotive industry has succeeded in producing 4 different cars on a single flexible platform called MQB. Volvo Cars ambition is to compete at the highest level and this thesis will contribute to increasing the flexibility in Volvo Cars future platform [8].

1.2 Company background

Volvo Cars is an established Swedish automobile industry and they are known for producing premium vehicles. The manufacturing plants of Volvo Cars are located in Sweden, Belgium, China, and the United States of America. Moreover, Volvo Cars is a company with an international market and had 96,194 employees worldwide in 2020 [9]. Currently, Volvo Cars produces vehicles based on two platforms, Scalable Product Architecture (SPA) and Compact Modular Architecture (CMA). A thorough description of the term "platform" can be found in chapter 2. The automotive industries are currently focusing on developing Battery Electrical Vehicles (BEV) and Volvo Cars has already started producing electrical vehicles but aims to further invest in the BEV concept. Volvo Cars production of current platforms and the future platforms under development are explained below.

1.2.1 Scalable Product Architecture (SPA)

The manufacturing of Scalable Architecture Platform (SPA) started in 2015 at the plant in Torslanda (Gothenburg, Sweden). Volvo's SPA platform includes front overhang, cabin, rear luggage space, and rear overhang. Additionally, the engine bay and bulkhead are the only fixed components. This structure allows variation in all longitudinal dimensions except for pedals to the front axle [10]. SPA produces vehicles attracting customers from the D and E segment, examples of models that the platform produces are XC90, S60, and Polestar 1. The description of the different customer segments is presented in Table 1.1

Table 1.1: Description of customer segments

Segment	Description
B	Small cars
C	Medium cars
D	Large cars
E	Saloon cars
F	Luxury cars

1.2.2 Compact Modular Architecture (CMA)

Compact Modular Architecture (CMA) is another platform produced by Volvo Cars together with China Euro Vehicle Technology (CEVT), both Volvo Cars and CEVT are owned by a Chinese company called Zhejiang Geely Holding Group (Geely). CMA and SPA are flexible in most of the dimensions but SPA is more scalable and could produce larger bandwidth of cars. The manufacturing of CMA started in 2017 at the plant in Gent, Belgium. CMA produces vehicles targeting the customer segment C and different variants for both Volvo Cars and Geely are derived from CMA [11]. The distance between the pedal box and the center of the front wheels is fixed in the CMA platform, while the remaining parts can be adjusted [12]. CMA has produced cars such as XC40, C40, and Polestar. Furthermore, the platform supports BEV.

The future of BEV looks promising and the global market is expected to grow. Volvo Cars are currently aiming to continue investing in the BEV concept and only producing electrical vehicles by 2030. Volvo Cars have produced their first BEV car (XC40 recharge) from the CMA platform in 2020 [13].

The CMA platform does not support the development of complete bandwidth of Vehicles at Volvo cars for BEV as initially it was designed for combustion engine vehicles. Volvo Cars are currently in the development process of launching new vehicles built on an upgraded version of the SPA platform, called SPA 2. This new platform will support Battery Electrical Vehicles and would be optimised for larger vehicles covering a greater bandwidth while meeting the energy efficiency targets.

1.3 Aims and objectives

The purpose of this thesis is to investigate the flexibility level of Volvo Cars current platforms and the challenges to achieve a highly flexible platform. Furthermore, a case study on a part called "*Head Up Display*" was conducted to further analyse the flexibility level of the platforms and to analyse the product architecture of the platforms at Volvo cars.

1.4 Research questions

Research questions are prepared in order to identify the flexibility of current platforms and challenges to achieve a highly flexible platform.

1. How flexible are the current platforms at Volvo Cars?
2. What are the challenges to achieve a highly flexible platform?

1.5 Ethics and sustainability

Ethics plays an important role when developing a new process, product or a platform as it may affect society. To understand the ethical consequences of implementing new technologies is critical to understand the effects on society as well as on the individual. The new platform developed would affect the people, since a more efficient platform might result in lower maintenance and thus fewer number of people which could lead to unemployment [14]. This would mean better utilization of resources and could save energy as well by having more flexible architecture where more number parts and components could be fixed in a single platform, hence minimizing the need for transporting the parts/components from one platform to another.

1.6 Limitations

This project will mostly investigate about the research topic from a product development perspective. Although the production will partly be considered, it is not intended to conduct an analysis about the production. Furthermore, a case study was executed on only one of the components and the analysis was based on mechanical integration. The current situation with Covid-19 also affected the project by limiting physical activities and face-to-face meetings.

2
Framework

This section presents the process of retrieving literature relevant to the topic of this thesis through different databases.The retrieved literature was studied and reviewed.

2.1 Systematic literature review

A systematic literature review was conducted using the database called ‘’Scopus”. It was used to get a relative understanding of the platforms, flexibility, modularity, and their application in the automotive industry. A thorough search was initially conducted to find the synonym of the keywords. The following string was used to get initial results of 1336 articles;

TITLE-ABS-KEY *("Product Modularity" OR "Platform Flexibility" OR "Production Modularity" OR "Modular Platform" OR "Modular Production" OR " Modular Adoption")*

To further narrow down the scope, a new string was applied which resulted in a total of 131 articles as shown below.

TITLE-ABS-KEY *(("Product Modularity" OR "Platform Flexibility" OR "Production Modularity" OR "Modular platform" OR "Modular Production" OR " Modular Adoption") AND ("Automotive" OR "Automobile" OR "Vehicle"))*

The retrieved literature is dependent on the keywords accuracy and relevancy. A better quality of keywords used in the search would result in better efficiency of literature retrieval. The keywords might not have the same meaning across all publications, and this can be misleading. Therefore, the abstract of each paper was examined to retrieve data related to the subject including platform and modularity in the automotive industry. After studying the abstracts, most of the papers studied platform and modularity in fields unrelated to the automotive industry. The papers did not offer useful insights and were not considered for further analysis. Through this process, 19 papers were regarded as beneficial to get a better understanding of platform and modularity in general but also their application in the automotive industry. Other databases as Google Scholars and Chalmers Library were also used. The reference list of the selected papers were inspected to find other relevant publications. Thus, additional papers were added, and the details of all used articles are presented in Table 2.1.

In the initial phase, the meaning of platform and modularity, as well as its benefits and challenges, were studied. There are several interpretations of these terms and they are addressed across the literature. Muffatto [15] describes the platform process as a technical-, strategic-, and organisational issue. A technical issue refers to the product architecture. While a strategic and organisational issue affects the product development, and coordination as well as engineering activities within the platform team respectively. Modularity is referred to as one-to-one mapping where each functional element is mapped to one component. Thus, the changes in product functionality can be performed by changes in individual components rather than the entire product [16].

The main benefits of platforms include reducing costs by increasing efficiency both in design and production. The cost for development and production will indeed be reduced by sharing parts across the products. As the demand for a higher product variety is rising, it is very challenging for companies to satisfy all customer needs and produce numerous models from a single platform. Most of companies need to redevelop the entire product platform strategy to meet the customer needs which is very costly. The increasing demand for product variety has caused a need to find new design approaches [17].

Many companies are turning to a modular strategy to accommodate more models in a single platform and hence avoiding redeveloping costs. Ulrich highlighted the benefits of modularity which include: (1) efficient management of changes in a product since manufactures can change functions by simply chaining modules, (2) improved product variety management as multiple varieties can be derived by different module combinations, (3) effective product development process as design activities is independent and can be performed simultaneously [18].

Furthermore, the definition of platform and modularity in the automotive industry was studied. The evolution of platform strategy and common challenges in the automotive industry were addressed in the literature. The platform strategy is well known and has been used in the automotive industry for many years. But it was not until 2010 that most of the vehicle companies started developing modular thinking. The product architecture of most vehicles in Europe has transited from integral product architecture to modular product architecture. The reason behind this transition is the rapid change in customer needs, as well as higher demand for product variety [19]. The modular platform enables the companies to develop and produce models for different segments in a single platform, contrary to the integrated platform which only produced one segment per platform.

Moreover, new systems and technologies have emerged in the last decade and have caused changes in the product architecture. The demand for a higher variety is expected to grow and companies are aiming to increase modularity to be competitive in the market. The concept of modularity can be classified into two categories: modularity in design and modularity in production. Both categories are dependent on each other as modularity in design leads to modularity in production [19]. There are some trade-offs that the product developers must consider for example material choice and product structure to not affect the production negatively [17].

The selected articles were read thoroughly, and a content analysis was conducted. The content analysis was performed by searching for content specifically related to the research questions, hence allowing to extract and categorize data accordingly. Thus, enabling a comparison of the answers between the retrieved literature.

Table 2.1: Literature list

Literature	Reference	Scope
Papers about platforms	[16], [19], [20] [21]	General definition of platform and common challenges
Papers about platforms in automotive industry	[16], [19], [22], [20] [23] [21] [24]	The application of platform strategy in the automotive industry
Papers about product architecture	[16], [19], [25], [22], [26], [20], [27] [28] [29] [30] [31]	Identifying the common architectures in a platform
Papers about Product and Production Modularity	[19], [22], [26] [32] [20] [19] [26] [17] [33] [31] [34] [35] [36] [33] [37]	The flexibility in platforms in automotive industry
Papers about platform modularity	[19], [22], [38], [20], [27] [39], [40] [8] [25] [41]	The modular architecture of a platform in automotive industry

2.2 Key concepts

In this section, the general meaning of a platform is described and its application in the automotive industry is addressed. The definitions of modules and interfaces are also presented in this section.

2.2.1 Platforms

Nowadays, the market needs are changing very quickly as customers are settling into new patterns of behaviors and industries are facing a lot of challenges. The challenges are decreasing lead time, increasing product volumes and variants, attain high-cost efficiency, etc. To overcome these challenges, many big engineering companies including Volvo Cars, Apple, Tetra Pak, etc. have applied the product platform strategy. Product platforms can be defined differently across the industries but commonly the main idea is about sharing [24]. The platform usually shares components, tools, development processes, workers, machines, etc. within a company. A platform can be defined as a collection of core elements implemented among various products in a product family [21]. The interfaces in a platform are also an important factor to consider. Mahmoud-Jouini and Lenfle mention that the interfaces connecting the components in a platform are standardized [42]. The product platform strategy allows the companies to improve quality and reliability in their products, streamline their manufacturing, and most importantly offering customers a variety of products while decreasing the lead time.

Although the product platform has numerous benefits, there are also several drawbacks. According to Robertson and Ulrich, it is a challenge to balance the commonality and distinctiveness when deriving products from the platform. To have a high distinctiveness would be too expensive for the companies while a higher commonality is more cost-efficient. But the customers care a lot about the distinctiveness, meaning a lower commonality which in turn increases the customer value, to find a balance is therefore a challenge for the product designers [43].

Within the different function teams, trade-offs must be taken to develop a successful platform. Function teams such as marketing and sales put a high emphasis on customer experience by prioritizing the user experience. While function teams such as production and engineering want to attain a cost-effective product. It is therefore important that the top managers are participating and improving the communication between the different teams so that decisions are taken wisely. The issues stated above are reasons to consider the level of flexibility when developing a platform to deal with uncertainties. Flexibility refers to performing changes relatively easily and at a low cost instead of redeveloping the whole product [44]. Most of the automotive industries apply the product platform strategy which has led to successful outcomes but new challenges affecting the lead time, customer value, and cost are constantly emerging as the market is changing at a rapid pace.

2.2.2 Platforms in automotive industry

The customer demands in the automotive industries have changed significantly since the 1950s and the need for product variety has increased. As as the demands increased the companies needed an efficient method to satisfy customer needs while reducing the cost. Therefore, the automotive industries have turned to the platform strategy by sharing core elements across a range of products. Although the automotive industries applied a platform strategy in 1960's, it did not evolve significantly until the 1990's. The platforms were developed in a way to accommodate multiple models. Since 2010, companies are focusing more on introducing decoupled interfaces, meaning one component can be changed without affecting other surrounding components. The definition of the platform among the automotive industries differs. Gosh and Morita [45] defines a platform in cars as a system that includes floor plan, drive, train, and axles. While Muffatto [46] argues that a platform is usually defined as the sum of suspension, underbody, axles, and powertrain. This is a general description of what is included in a platform and the development process varies among the different companies.

The expected number of vehicle models per platform is expected to grow in the future due to new customer needs. Keeping that in check, a platform needs to should be flexible enough to produce products satisfying the customer needs [10]. It is important to develop a platform in a flexible way to increase its lifetime. Flexibility reduces risks such as economical loss, inefficient resource utilization, etc. Furthermore, a highly flexible platform helps to deal with future uncertainties, and it will favor the designers, operators, and system owners. When developing a flexible platform, it will initially cost more than a traditional platform as it includes features developed after uncertain customer needs that are not needed at the moment, but the investment will be worth it if the prediction is correct [6]. To develop and attain a highly flexible platform is challenging as it is relatively hard to predict where the flexibility is needed and how much flexibility is needed. The R&D managers who are responsible for improving existing products and examining the potential of new products, usually delay decisions when the market is unknown in case to react to new market information. As new information emerges, the managers should invest in increasing in flexibility to avoid major costs. In markets that require high performance and have uncertain requirements, high flexibility is required to effectively respond to the market. The uncertainties should be reviewed regularly and thus gather the necessary information to determine where the flexibility is needed [47]. A flexible platform aims to change parts of the system relatively easily and attain an efficient production as well as assembly process. The production and manufacturing process is affected by design changes. Therefore, it is important to early consider the requirements and constraints from the production as well as manufacturing perspective when developing new concepts. Factors such as the material, structure, and number of products must be taken to account for the platform to be produced concerning the production as well as manufacturing [17].

2.2.3 Modular vs integral architecture

There are two types of architectures to consider when developing product platforms, product architecture and production architecture. The product architecture dictates the commonality and distinctiveness of the product. A trade-off has to be made between both, and the market has to be studied before implementing the platform development strategy. The second type of architecture is the production architecture, which determines the range of products on a single platform.

The product architecture can be classified into two main categories; integral and modular architecture [18] [48] [49]. Nevertheless, a noteworthy point is that architecture can have both very integrated parts and some that are completely modular. Moreover, a product architecture is said to be integral if a single block(subsystem or part) maps to multiple functions or when a function maps to multiple blocks of the products. The interfaces between the blocks are also not well defined. The main goal is to achieve high performance of the product. It is really hard to identify the interfaces and they might not even exist in some products. A single change in a part or component of a product may require a complete redesign due to being integral. For an architecture to be modular, a single block maps to one or multiple functions. The interactions among blocks are made via well-defined interfaces [50]. In a modular design, a change in a module could be made independently without affecting other modules in a product. Computers are one of the classic examples used to explain what modular architecture looks like, each part for example hard drive, monitor, processor, graphics card, and many other parts are produced by different vendors and are finally assembled by different companies [51].

A car could be considered as an integral product according to some authors, as several functions are distributed across the vehicle. And in one of the articles, the author stresses the system to be more integral as a single function, e.g. noise or vibration, is not linked to a single part [52].

A product could not be classified to be fully integral or modular, but the degree of modularity could be defined relative to other products. Most of the platforms in the automotive industry developed in 2010 have a modular approach, where the interfaces are fixed and decoupled. Furthermore, the modules are not dependent on each other and this approach entails an increased number of variants derived from a single platform. Moreover, the modular platforms are more versatile and allow several models from different segments to be assembled. This lies in contrast with the majority of the platforms developed before 2010 which only was able to produce a platform from a single segment.

Platforms affect how the company's manufacturing network operates. The models assembled on the production plant are the ones that share the same platform. By implementing a platform strategy the company could share production across the different plants and cut down cost greatly by utilizing resources globally [53]. The older platforms were not flexible enough, so only one or two models were able to be produced on a single platform. It also limited the production mobility as only models in the same segment could be produced [54]. Today the companies could reap the benefits of the new platforms by achieving Economies of Scale, Economies of Scope, and Operational Flexibility.

Economies of Scope: In a manufacturing network many advantages are gained by introducing several variants that could be produced on a single platform [55].

Economies of Scale: Due to increased modularity common manufacturing resources could be used across plants that are geographically spread out in different regions [56] [57] . It is defined as the production capacity of the plant's platform in million units/year.

Operational Flexibility: The greater the number of plants, the greater the operational flexibility as a large number of resources could be shared internationally between them [58].

Economies of scope could be achieved with modular platforms as a variety of products could be added to portfolios from a single platform. The modularity would result in more efficient utilization of the resources and globalization of the processes involved. On the other hand, by efficiently utilizing the shared resources, increasing the number of produced models in different segments would increase economies of scale [35].

2.2.4 Standardisation vs modularisation

Standardisation is not the same as Modularisation. Standardisation is a process to reduce the number of required components in a product yielding reduced manufacturing and purchasing costs. Reducing the number of parts may put the company at disadvantage by reducing external variety if the process is not handled correctly. The goal of standardisation is to find a product that fits in all required segments in a limited time.

Modularisation on the other hand, is a process in which a product is defined into several modules. Each module can be mass-produced, reducing the manufacturing cost and cutting the delivery lead time. The modules could be strategically designed to make different variety of products that fit different customer segments in the company [59].

2.2.5 Modularisation methods

When an attempt is made to modularise a product, the most relevant methods must be identified to establish the best strategy. The process is still not well defined and sometimes oversees important key aspects.

Due to advancement and technology, the new innovative products usually have several complex systems which are needed to be integrated (e.g., mechanical, and electrical). It is impossible to have a simple, cost-effective and flexible modular architecture without implementing the right strategy.

The modularisation strategy or methods are a process to classify a product into different modules and defining each functional block with a module that has decoupled interfaces. But to do so a team is required with a great understanding of the product and what the company expects from the process itself as the modularisation would affect the whole company strategic position in the market and the product development process in general as well.

The existing product could be modularised if requirement specification is in place. For a new product to be developed from scratch, a modularity strategy could be put in place in the early stages of development resulting in an uncoupled design which makes it easier in designing modular products.

Several methods such as function-mean's tree, knowledge integration matrices, Modular function deployment, and design structure matrix could be used as methods for modularisation. For analysis of the product required for this thesis the most relevant method is DSM.

2.2.5.1 DSM

The Design Structure Matrix (DSM) was first introduced in 1994 to give an understanding of the product structure [60]. Later it was used to describe the product architecture via adding relations between different functions and technical solutions into a product architecture DSM. Many successful companies have used the product architecture DSM for developing new concepts e.g. when a hybrid vehicle architecture was developed by BMW in Germany [61]. In this report, the product architecture DSM will be referred to as DSM, as it is the only relevant method that is going to be used.

DSM a square matrix, where relationships between components could be categorised into four types. As shown in the Table 2.2.

Table 2.2: Relationship between components

Type of relation	Two technical solution (or function) needs to:
Geometry(g)	Physically be connected or oriented to each other
Signal(s)	Exchange all types of signal between each other
Energy(e)	Transfer energy between each other
Material(m)	Transfer material between each other

By adding the above relations into the matrix, it simplifies a complex system clearly and compactly, making it easier to understand the complex systems. This method aims to create clusters that have the fewest relations between them and have complex and more relations within each cluster. Figure 2.1 shows the relationship between different components, the arrows show the relation from/to the component, and the text above the lines shows what type of relationship each component has with the other.

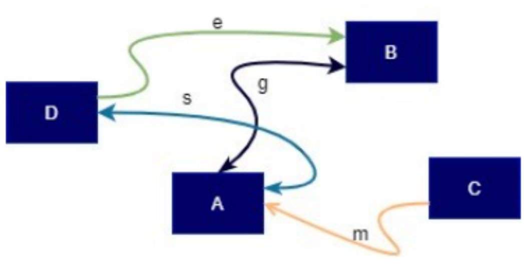

Figure 2.1: Relation between four components

From Figure 2.2 it could be observed that the matrix is not symmetric as A$\neq$A^T so each component could show the relation in two directions.

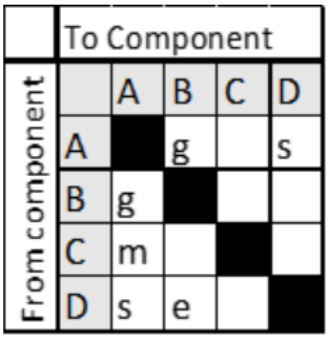

Figure 2.2: Example of a DSM

Clustering Figure 2.2 yield the matrix shown in Figure 2.3. The above examples show that if the components are defined as modules, component "C" could be one of the modules as it only has one relation with "A". A simple interface could be defined to connect the parts. For large systems, the complexity increases where there is no concrete solution, so the clustering method plays a big role in modularising a product.

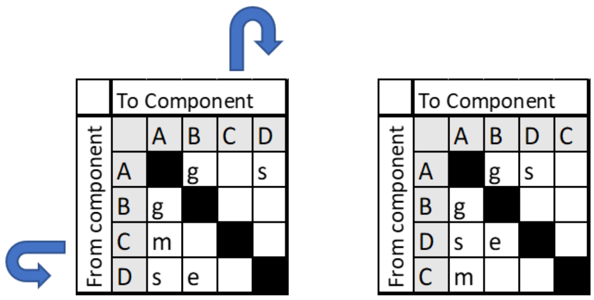

Figure 2.3: Clustering of the DSM

In Figure 2.3, each relation has been given the same weight. It might look way different, some relations would have more importance over the others, for example, a signal relation might have four times more important than the other relations since the electrical interface might be harder to design. The DSM is a tool that allows the product to be divided into well-defined modules which are connected to each other via a well designed interfaces as seen in Figure 2.4. Though the importance/weight of each relation defines the modularisation strategy of the product.

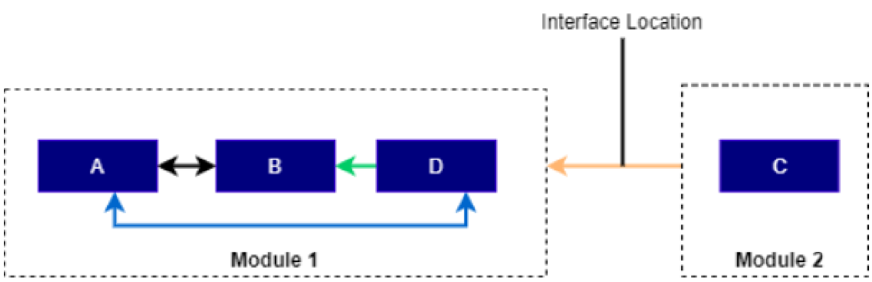

Figure 2.4: The modular design

2.2.6 Modules interfaces

An interface is defined as a surface or volume that creates a common boundary between two modules, allowing an exchange of information between them mostly through signals, material, and energy [62]. The interfaces should be simple in design and robust enough. Careful consideration must be placed when designing modules and suitable methods should be selected to avoid high complex interfaces creating problems later in the development process.

Design for manufacturing and assembly (DFMA) methods could be implemented when designing the interfaces. Many modules are involved in the design of the complex product. The only point of communication between them is an interface. Hence, they should design and documented to lower the chances of confusion or misinterpretation among different design teams working on the product. Module interfaces that are not optimally designed would result in a more costly and time-consuming product development process.

Interfaces could be categorized into different types [62]:

- ***Spatial***; an interface where space is defined between two modules e.g., the length and volume each module could move within the space
- ***Transfer*** , where it allows the transfer of energy or material
- ***Command and control***; an interface allowing transfer of the information most commonly the signals
- ***Attachment***: where the geometry of interface is defined for the two modules

2.2.7 Product architecture

At system level design the product architecture is defined, where each function is linked to its relevant module, part, or subsystem. A function element is described as the perceived function expected from a part e.g., accelerating the car, cooling the engine, heating the room, etc. These relations and functions are usually described in a diagram which later defines the product architecture.

The parts are mapped to functional elements, the interactions, and functions performed by each component could be seen in Figure 2.5. It is said to be an uncoupled design. If each function element is mapped to one component.

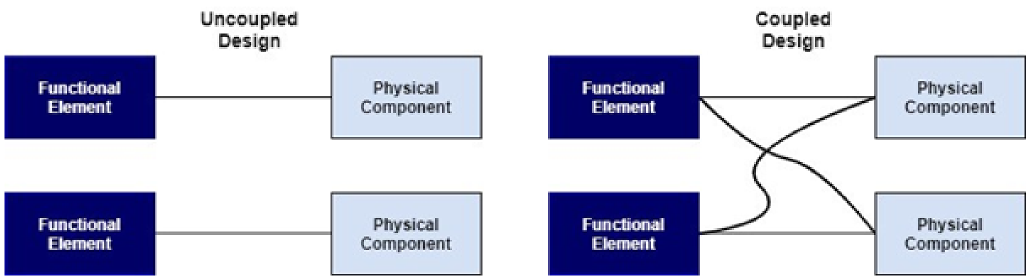

Figure 2.5: Coupled design vs uncoupled design

A simple example of uncoupled design is the modern tap water where temperature and flow rate are controlled independently. In the older coupled design of water taps, where two control valves are used to control the flow and temperature of the water, making the solution more complicated. The uncoupled design is easy to redesign as there is a one-to-one mapping. The axonometric design theory also suggests that it is easier to have an uncoupled design as it keeps interdependency down and a malfunction in one component would not affect the entire system [63].

Furthermore, Figure 2.6 presents the task sequence of dependent tasks, uncoupled tasks, and coupled tasks in function to the development time. The colored boxes represent different tasks, and the area of the boxes represents the design time. The dependent task must be executed in a specific order and thus take a longer time to develop. While the uncoupled tasks and coupled tasks can be executed in a specific sequence. In the uncoupled tasks, the information does not need to be exchanged since all tasks are independent of each other. Even though coupled tasks can be executed independently to an extent, there is still needed to exchange information since one functional element is connected to more than one physical component.

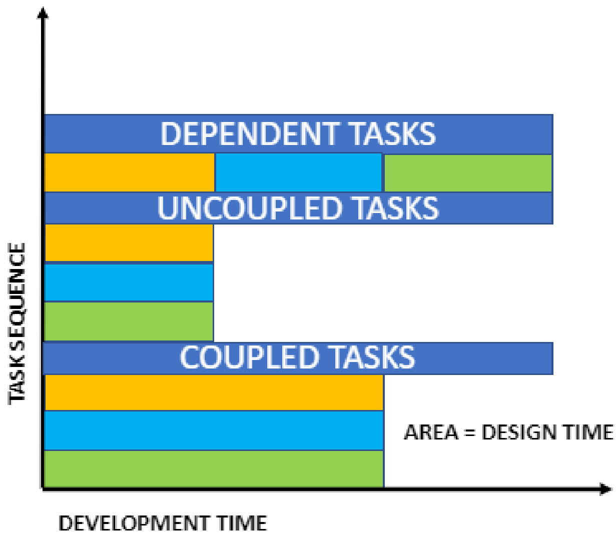

Figure 2.6: Task sequence effect on development time

The product architecture could be further categorized into two: integral and modular. Hybrid integral and modular architecture exists as it is hard to reach a complete integral or modular architecture, see Figure 2.7.

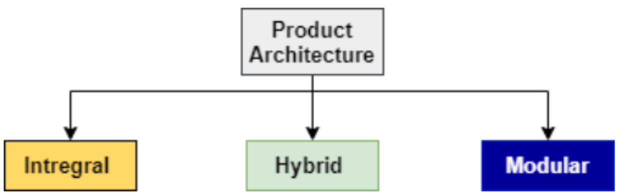

Figure 2.7: Diffrent types of Product Architecture

2.2.8 Modularity in design vs Modularity in production

Modularity in design is a method to reduce design process complexity [64]. The design boundaries are defined for the product or components. The procedure is followed to divide a complete system into modules, the system is divided in such a way that each module task is interdependent within and independent across the modules [65]. The modularity in design would define the product architecture, a key aspect is to find common modules across different platforms.

Modularity in production is to define the plant's boundaries to assist manufacturing and assembly to reach the required product variety, production flow, cost, and quality [65]. Production modularity enables the company to produce the components independently before the final assembly process of the components [66].

2.2.9 Modules carry-over

A carryover is described as a module or a part of a product that is carried over to the next generation of product or platform without any major changes. The company's modular strategy, image, the new customer requirements decide how to proceed with the carry-over. The development costs, lead time of the product are directly affected by how efficiently the carryover module is used. The feasibility of the carry-over is analysed by evaluating different concepts against the development cost [67]. Figure 2.8 shows how carryovers are used in different generations and platforms. Generations refer to the life-cycle of a design for a specific model.

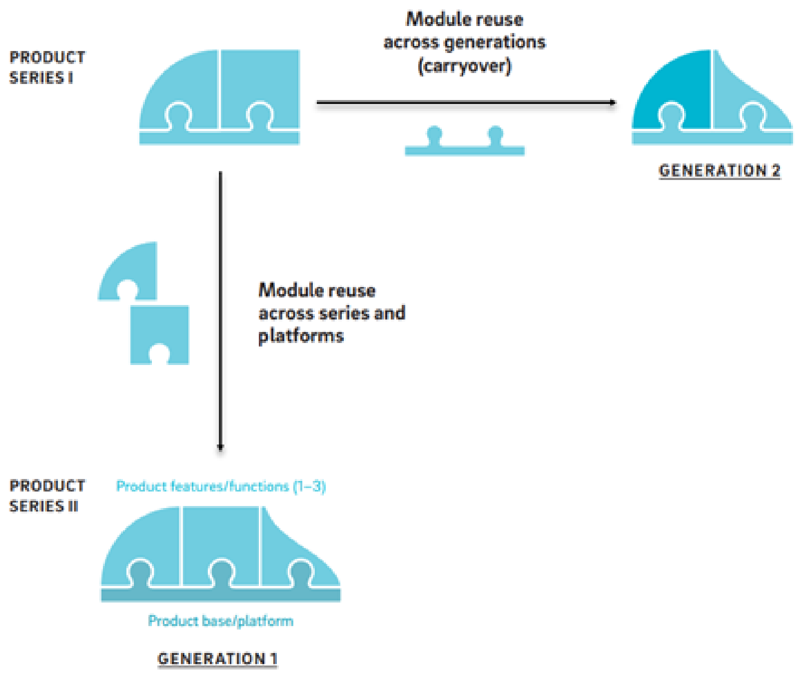

Figure 2.8: Modules carryovers [1]

2.3 Modularity and sustainability

The automotive industries are facing challenges to produce vehicles with better performance without affecting the environment. The main challenge for the automotive industries is to develop sustainable vehicles and thus minimizing emissions. Sustainable products are in demand by more customers in recent times, and also by national and local authorities encourages drivers to purchase environmentally friendly cars [68]. A sustainable design is related to sustainable solutions, finding a balance between the interests of a company against economic, social, and environmental concerns [69]. Additionally, the product lifecycle must be considered to produce environmentally friendly products. The product lifecycle refers to all activities being executed from the start till the end of the product's life. This includes manufacturing, remanufacturing, assembly, operation, testing, reuse, recycling, etc. The strategies for developing environmentally friendly products emphasize the importance of a long lifespan [68] and has been mentioned by Yang et al. citeyang as one of the pillars of developing more sustainable products.

Modularity has in recent times gained attention across many industries due to its impact on the life cycle and sustainable characteristics. As discussed previously, modularity increases the product flexibility by implementing modules and thus allowing changes to occur with relative ease. In addition, the use of modules can contribute to an improvement of repair and maintenance activities, which can increase the product lifecycle [68]. Modules also facilitate the disassembling process and many valuable components can be reused. Apart from providing the opportunity to produce more variants and avoiding additional costs, modular design reduces huge costs in production equipment used in the assembly plants. Resources are utilized more efficiently by reusing modules and the production of new components and equipment can be avoided [70]. The module concept is also beneficial for the users since the user can buy modules to upgrade or replace another module instead of buying a new vehicle. This concept does not only have a better impact on the environment but also could increase profits for the companies [68]. However, there are limitations with modularity and the concept could decrease customer acceptance.

Modular products could be seen as less durable and reliable in contrast to entirely new products. Customers may perceive that the new system upgrades do not have a similar performance level and aesthetics as a completely new product. Introducing the concept of modules to customers and gaining their acceptance could be a challenge for many companies. The benefits from implementing modules are not as obvious for the customer, even though customers value certain characteristics of modularisation such as delivery, product variety, and customer service. The companies need to understand how customers value their modular products before launching them to ensure customer satisfaction [68]. The product value is discovered during the use of products and it is further generated from interactions between all stakeholders according to Biggemann et al. [71]. The benefits of sustainable products are hence strongly related to the behaviors of the customers. The companies can improve their reparation and maintenance activities but it is customers who decide whether to utilize the aforementioned activities or not. If the customers do not return their products, then the activities cannot be executed. Modules can have an increased impact on the environment if they cause overdesigned products. The utilization of energy and material is inefficient in overdesigned products [72]. Furthermore, the production of many components is to a large extent undertaken by suppliers among many automotive industries. Thus, the suppliers have a greater impact on the design and production of environmentally friendly components [68].

2.4 Head Up Display (HUD)

Head-Up-Display (HUD) is a well-known technology in the automotive industry and is used for conveniently projecting information without requiring the drivers to divert their sight from the road. The technology was first invented for military aviation and enabled the pilot to effectively maintain awareness of important information while also observing landmarks and potential risks [73]. It was not until the late 1980s that the HUD was introduced in the automotive industry to improve driver safety [74]. Many dangerous events can occur in the road environment. Displaying relevant information such as velocity, fuel level, road accidents, navigation, etc is essential for the driver. Technologies displaying such information include HUD and Head Down Display(HDD) [75]. In Figure 2.9, the positioning of the HUD in the vehicle can be seen.

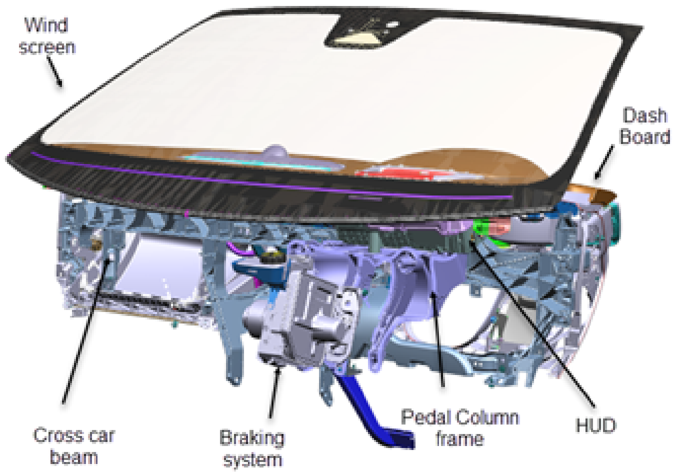

Figure 2.9: Isometric view of S90 model

The HUD technology projects an image of information on the windscreen in front of the driver. This allows the driver to avoid looking at a dashboard display or so-called Head Down display. Vehicle supporting HUD contributes to better vehicle control, less mental stress, faster response time for perceiving information, and faster reaction to road events than vehicles applying with HDD [76] [75]. Additionally, the HUD will display relevant information which helps the driver to reduce the number of glances and hence become less distracted. By displaying too much information, the HUD would become a distraction for the user, and a balance is needed to achieve the benefits of the technology. The HUD does not have a static background in contrast to HDD, since the frame of reference changes when the car moves due to changing background. The positioning of the HUD can harm driving, in some cases, the projected image could obstruct a clear vision of the road environment and distract the driver [76].

2.4.1 Design of HUD

Projector, Combiner, and electronic circuit are the three main components in the HUD. The projector displays the image of the information and is typically an Liquid Crystal Display (LCD) or Light-Emitting Diode display (LED) [77]. The HUD requires a special windscreen to visualize a clear image. The combiner is the surface where the image is visualized. The surface should have a high transmissivity and high reflectance to provide the driver a clear image of the information and objects. The electronic circuit controls the projection and provides brightness [78].

3
Methods and tools

This chapter presents the methods and tools that were applied to gather data and perform analysis.

3.1 Data collection

Interviews were conducted virtually via Microsoft teams with the experts from Volvo Cars, Torslanda. The reasons behind conducting these interviews were to understand how the company perceives and works with modularisation, how the company deals with future technologies and the challenges that the company is facing. A questionnaire regarding modularisation, space reservation, production, the role of the geometry of the components, and the flexibility of the platforms was presented to the respondents, shown in Appendix A.

Respondents from different departments were sought to get an understanding from different perspectives. The supervisor at Volvo Cars recommended relevant employees, thus a total of 9 respondents were contacted. Further details about the respondents, including position and experience, are presented in Table 3.1. Each interview was recorded and later transcribed using Microsoft Word. The transcription was used later to conduct in-depth qualitative thematic analysis.

Table 3.1: Details about the respondents

Interview ID	Position (P), Department (D)	Previous poisitions/departments	Experience
R1	(P) Product owner (D) Electrical Infrastructure	Similar position	+10 years
R2	(P) Architecture design leader (D) Base Product Development	1. Package engineering 2. Team leader for an integration unit	+10 years
R3	(P) Product Owner, Displays	Lead engineer for Head Up Display (HUD)	+5 years
R4	(P) Blockleader Cockpit (D) Interior Room Integration	Not mentioned	+20 years
R5	(P) Modular Product Architecture Strategist (D) Mechanical Integration	1. Working with modules past 5 years 2. Director for vehicle engineering department 3. Leading technical development in programs	+20 years
R6	(P) Technical expert (D) Electrical Infrastructure	1. Electrical designer schematics for complete vehicle 2. System designer for harnesses	+20 years
R7	(P) Sr. Manager (D) Mechanical Integration	1. Integration engineer, 2. Block leader 3. Manager 4. Section manager	+20 years
R8	(P) Architecture Manager (D) Mechanical Integration	Concept engineer for the body and trim department	+5 years
R9	(P) Technical expert (D) Mechanical Integration	1. Wokring within mechanical enginnering within different areas 2. Team leader	+20 years

3.2 Data analysis

This section provides steps followed in detail to conduct a proper thematic analysis. The analysis was performed on the interviews working at Volvo cars who undertake different positions at the company. The six phases of the thematic analysis are described to provide the reader with the problems being experienced at the company. Thematic analysis is a subjective but flexible approach to qualitative analysis.

3.2.1 Defining thematic analysis

Thematic analysis is a method that is used to code the data into relevant themes and sub-themes by getting to familiarize oneself with data [79] and exploring the meaning of emerging concepts from the interviews conducted [80]. All the gathered data for the scope of the study should be classified into different data sets; transcriptions of the conducted interviews, study objectives and study questions, and all other relevant material that could be used for the analysis could be included. For familiarizing with all the collated data, a re-reading is required to see the patterns and salient features of the data.

3.2.2 The phases of thematic analysis

A total of six phases are involved in the thematic analysis as seen in Figure 3.1 . Each phase would be described in detail with given examples from the interview's experience. For illustration of how the Nvivo software was used for different phases could be seen in the Appendix E.

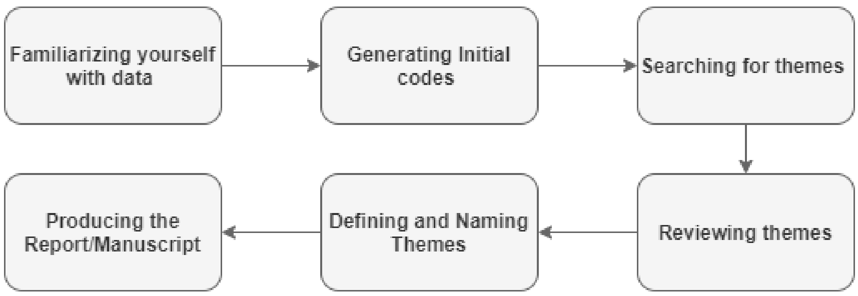

Figure 3.1: Thematic analysis

3.2.3 Phase 1: Familiarizing with collected data

All the interviews were conducted on Microsoft Teams and the video was recorded. Later the video recording was transcribed followed by an initial reading of the transcribed text to get the context of the data. The text is thoroughly read and analytically to understand the problems and issues faced by each employee.

Several techniques could be used to structure the given data. It is worth noting that qualitative data software like NVivo provides methods for easier structuring of the given data by coding it into nodes that are grouped into desired themes.

3.2.4 Phase 2: Generating initial codes

In this phase, all the relevant information identified by the reader from the interviews in phase one is used to produce the initial codes. The data is ordered and compiled relative to the perceived patterns and similarities.

A code is a type of data extracted from interviews. This could be either a word, a phrase or a pattern. Three types of codes are identified by Miles and Huberman [81]. A descriptive one which doesn't where interpretation is required to a small extent. An interpretive code, which includes data and requires interpretation to fully grasp it. The last type is inferential codes, which is related to data presenting explicative and indicate causal relationships.For systematic classification of the information, the codes should be classified with relation to defined study objectives.

3.2.5 Phase 3: Searching for themes

In qualitative research, a theme is a word or a sequence of words representing the interviewee's experience, situation, work, problems, etc. [82]. The coded data that is grouped into a theme according to the similarities and patterns. The creation of themes relies mainly on the reader's experience and is linked to a subjective approach that has no right or wrong, and it is dependent on how thorough one has been in the first phases of the analysis.

The themes would depend on the systematic and thorough way of working in the initial phases of the analysis. The process involves recognizing the patterns, differentiating the data, recombining, or grouping of data. Some themes would distinctively emerge from the given data, while for others the distinctive themes identified would merge to form a new theme. The process of linking different themes sometimes gives an insight into the forming of new themes, it gives a picture of a broader scope and constitutes the basis of the thematic analysis [83].

3.2.6 Phase 4: Reviewing themes

This stage involves systematic review and refinement of themes, some themes are fragmented into smaller themes and others are fused into a new theme. A deeper examination is done to avoid missing relevant data points from the previous phase of the analysis.

A few questions are asked to review the process.

- Do themes cover the research questions that are asked?
- Are the themes too generic?
- Are any themes overlapping?
- Is something important missing?
- Does each theme accurately describe the data?
- Are sub-themes in proper hierarchical relation?
- Is everything coded correctly?

- Does each theme give a proper representation of the code?

Following the systematic way of questioning, as shown above, gives the researcher the ability to compare and validate the data, which entails a successful and accurate analysis.

3.2.7 Phase 5: Defining and naming themes

In those stages, the themes and subthemes go through one final revision before proceeding to the last stage. Thus, the previous phases are analysed once again to see if the hierarchical relations are accurate to the coded data. The names of the themes must be iterated throughout the process to remove any ambiguity or misunderstanding for the readers. The name should be precise, concise and should immediately give the reader an idea of the theme before reading it. This phase ends when identifies and defines the themes.

A thematic diagram could give the readers an easier understanding of the hierarchical structure of themes and sub-themes.

3.2.8 Phase 6: Presenting and discussing results

This phase concludes the thematic analysis. The results are discussed which are found to be in data gathered by the interviewees. The analysis should be written in a concise, logical, and non-repetitive way. To further support claims in each theme, citations of the interviewees are given.

3.3 Component Tree

A component tree was created to further facilitate the understanding of the product structure and interaction between components. The component tree includes the different components and the connection between them through arrows. In addition, it includes the types of interfaces used to connect the different components.

3.4 Team Center for Visualization (TCVis)

Volvo Cars uses Software from Siemens Digital Industries called Team Center for product lifecycle management. All models of the vehicles are stored in the Volvo Cars database that could be visualised using Team Center. The software contributed to a better understanding of the current product architecture across different models. Team Center was further thoroughly used when performing the case study, explained in chapter 5.

4

Results from interviews and thematic analysis

This chapter presents the results from interviews and thematic analysis. A codebook describing the identified themes is presented in Appendix B.

4.1 Modularisation

This section itself is a theme with several sub-themes related to it as shown in the Figure 4.1.

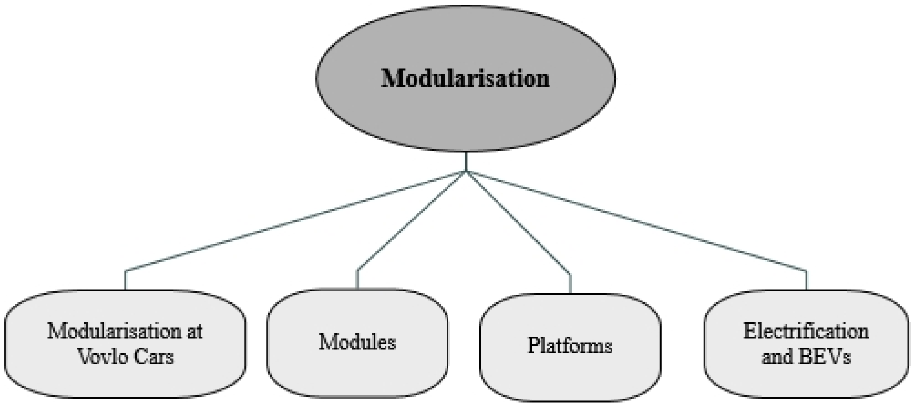

Figure 4.1: Modularisation sub-themes

4.1.1 Modularisation at Volvo Cars

The respondents had different perceptions and work experiences with modularisation. The respondents working in different departments is one of the reasons that different answers were given, as each respondent related the concept of modularisation with their department. Volvo Cars have been using modules as part of their architecture for a while, but a new definition was introduced during the development of their Scalable Platform Architecture (SPA) in 2015. Some of the respondents have been working using modules recently in their departments while others have not worked with them yet.

Furthermore, the respondents did not share the same definition of how modularisation is defined within the company. The respondents from the electrical department were not aware of the definition of modularisation, as it was not a part of their daily work. According to respondent **R9** modularisation is defined as:

"Distributing the responsibility of the different modules and structuring the modules." (**R9**)

Meanwhile, **R6** had a different view of modularisation but also mentioned that the definition varies.

"Modularisation is defined as one part that could be developed separately." (**R6**)

The modularisation strategy is well defined in the mechanical department and is involved in the workflow regularly, in comparison with the software and electrical department. **R8** explains that the concept of modularisation needs to improve in the software field.

"On the hardware side, we have always had an idea what a module is to an extent, but it hasn't existed on the software side." (**R8**)

4.1.2 Modules

The respondents had a similar perception of the definition modules used at Volvo Cars. For most respondents, the definition of modules is something along the lines of a unit with defined interfaces. The respondents from the electrical department related the concept of modules with the reusing of parts, but they could not relate to the modularisation process as the strategy is not implemented in their department. All answers from the respondents regarding the definition of modules are presented in Table 4.1.

Table 4.1: Definition of modules among respondents

Respondent	**Definition of module**
R2	*"Interchangeable parts with defined interfaces and could also be developed within their own boundaries"*
R3	*"Building block with defined interfaces"*
R5	*"Building block for a product, containing a certain capability and it fits the define interfaces to surroundings"*
R7	*"Defined by the module owners and its interfaces should not have a negative impact on the neighbouring module"*
R9	*"A unit that is fixed into the architecture by its common interfaces"*

The reasons why a modular strategy is followed by Volvo Cars are related to cost, performance, and bandwidth according to the respondents. For example, the respondents stated that modules are implemented to:

"Build a wider scope in terms of performance." (**R2**)

"Offer specific modules with different performance" (**R3**),

"Try to reuse everything expensive to develop." (**R5**), and

"Create a bandwidth of high and low specification cars." (**R9**).

R3 stresses that when developing modules with different performance levels, the company defines and follows the targeted bandwidth. Additionally, **R3** explained what the definition of the bandwidth is based on.

"The bandwidth is defined based on:
Stakeholder needs,
Different type of requirements,
Customer needs,
For display, it is the experience and the feel,
Sustainability, weight, etc requirements, and
Size, quality, and enough space." (**R3**)

R7 mentioned that costs and sizes are relevant factors when defining the bandwidth of modules. When defining the bandwidth, inputs from various sources are received to ensure success from the business perspective. According to **R5**, the modules are developed in dialog with strategy and business offices and an upgrade or downgrade of a module should have cost benefits.

"We don't only make a part better; it must be much better to have a different price. The step must be big enough and sometimes we also downgrade a module. The cost must be much lower to ensure it is a good business. We try to focus on how to make good business on the modules and based on that a definition of high-end and low-end performance can be made." (**R5**)

R8 explained that from the mechanical integration perspective, in collaboration with another department, boundaries for the modules are created and the development should be within or as close as possible to the boundaries.

"In collaboration with the arts we need to understand if those boundaries are sufficient to design different levels of performance. Or if we need different interfaces for another set of performance." (**R8**)

R3 mentioned that fewer variants are desired to decrease the complexity, but in some cases, there is a need for many variants. The respondent also pointed that the modules in their department are designed in collaboration with suppliers.

"We define the basic design and requirements to the suppliers, and they try to deliver the requirements." (**R3**)

The majority of respondents claimed that the development process of high-end and low-end modules are similar. According to **R9**, the development process is not affected by the performance level.

"There is not a big difference as the modules are developed concurrently." (**R9**)

R3 explained that they are developed similarly but the requirements are different. **R2** expressed that the low-end modules are cost-driven while the high-end modules are attribute-driven. Meanwhile, **R5** explained the impact of high-end and low-end from a business perspective.

"It is easier to improve the performance, but it is harder to decrease and make it cheaper. It is harder to downgrade a module than upgrade it." (**R5**)

R6 argued that the development process of high-end modules and low-end are similar even though the modules are cost-related.

"Of course, the modules are cost-related, but the features are added on to the complete product in the end and all modules are handled equally. If perhaps you are talking about the low-end modules, it could be a base module that is presented in all vehicles. High-end modules on the other hand are more feature based." (**R6**)

4.1.3 Platforms

Regarding the similarity between modules in SPA and CMA, various responses were gathered. From the electrical perspective, the parts in SPA and CMA are similar. From the mechanical perspective, the modules are defined differently between SPA and CMA. According to **R7**, the platforms are not similar due to:

"SPA being developed in-house while CMA is developed in collaboration with CEVT, the modules are not identical." (**R7**)

R5 explained that there are not many common modules between SPA and CMA, apart from the engine. **R9** also agreed that few parts are being shared but gave few other examples of interchangeable modules between the platforms.

"There are not many common modules between the platforms. Some drivelines are common, similar engines are being used, also some gearboxes and top head parts are shared between the modules but there are not many overall." (**R9**)

The product architecture is defined differently in SPA and CMA. SPA has higher scalability as its wheelbase can be extended more than in CMA. The modularity level of both platforms has not reached the desired level, and the modules are not interchangeable between the platforms according to the majority of respondents. The following reason was explained by **R5**.

"We don't use them as modules, we use them as part building platform." (**R5**)

Many respondents mentioned that changing modules between the different platforms indicates a high modularity level. The following statements were gathered from the interviews:

"From the mechanical perspective, the modules are not interchangeable, a module from CMA cannot be placed in SPA." (**R9**)

"SPA and CMA are not intermodular as the modules cannot be exchanged between the platforms." (**R8**)

"Modular is for example to take an electrical component from SPA and implement it to CMA without changing the surroundings." (**R4**)

R5 further elaborated on this matter and mentioned that there are common parts between the platforms, but the interfaces are different.

"When using modules, the interface should be identical, but the modules should have different performance levels, which is not utilised in SPA and CMA." (**R5**)

R9 also gave his thought on this matter and explained that even though the parts are common, they cannot be implemented in another platform.

"The common parts and systems do not have the same interface and cannot be used in another architecture or platform." (**R9**)

Additionally, CMA supports low specification vehicle bandwidth in comparison with SPA. **R9** explained that SPA produces vehicles targeting the premium segments, while CMA on the other hand procures vehicles with lower performance levels. Hence the modules cannot be exchanged between the platforms.

"When SPA was developed, it did not have the bandwidth to cover the lower specification vehicles, hence we were not able to share the modules with CMA." (**R9**)

Only **R7** argued that SPA is a modular platform due to having different bandwidths of parts. **R3** did not express whether the platforms were modular enough or not but stated that SPA is more modular than CMA.

"In SPA, we have managed to put on top heads with different bandwidth, diesel petrol plugin BEV. I would say it is flexible." (**R7**)

"SPA is more modular than CMA as CMA is more cost-driven. In the architecture of electric vehicles, the modularity can increase." (**R3**)

4.1.4 Electrification and BEVs

The product architecture of the new platforms under development has changed to a great extend after introducing the need to support Battery Electric Vehicle (BEV) models. There are additional systems and parts required in the platform to support the production of BEVs. The reduced impact of the internal combustion engine in the powertrain system has resulted in more freedom when defining the architecture. **R5** said the following about the changes in the product architecture after the introduction of BEV:

"I would say it has changed even though we have kept the basic conceptual design of the vehicle." (**R5**)

Newly added parts such as electrical motors and batteries have caused changes in the weight distribution of the vehicles. **R3** further explained how the weight distribution affects the architecture.

"The product architecture has changed with the introduction of BEV; it is a completely different prerequisite when developing the architecture. For example, changing the weight distribution of the vehicle, when it comes to battery setup and thermal situation." (**R3**)

R5 also addressed the impact of the weight distribution and stated that many areas had to be reinforced. He mentioned that a battery box was implemented and replaced the mid-floor.

"The battery box needs to do the same job, and more than the floor did before in the crash situation for instance, but at the same time you could increase the global stiffness of the body when you add a battery box, like a sandwich design battery box and when you increase that performance you actually can increase the handling, steering feeling, and other attribute parameters". (**R5**)

R8 shared his thought on this matter and mentioned that the proportion of the vehicle and space allocation of components have been affected by the introduction of BEV.

"The proportion of the vehicle, allocation of components in the geometric space of the architecture has also to some degree changed due to energy efficiency targets." (**R8**)

From the electrical perspective, the development process has been similar even after the introduction of BEV. **R1** explained that the electrical parts are similar and have not affected by BEV.

"Either BEV or not BEV or PHEV. We still have the high voltage harnesses – connecting the battery the charging outlet DC converts, we still have in BEV and PHEVs high voltage harnesses." (**R1**)

Furthermore, **R2** mentioned that Volvo Cars started to build electric cars on CMA, but the produced vehicle was not optimized. SPA is currently not producing electric vehicles due to its large size which requires higher energy efficiency, in contrast to CMA according to **R5**.

"The first electric car was built on a CMA platform based on the combust engine platform architecture, it was far from optimized for an electric vehicle." (**R2**)

R7 explained that by implementing BEV on CMA, platform adjustments were required.

"Adjustments along the way are required to deal with consequences on the platform, in comparison with platforms that only produces battery electric vehicles where everything necessary is considered from the start which is a benefit." (**R7**)

Although adjustments must be made when upgrading or developing a platform, important modules and interfaces are being kept, so called carryovers. **R5** addressed this matter by the following statement.

"We identify the good parts, interfaces, and conceptual setups which we later decided to keep. When upgrading a platform, we keep and define the new modules which are the carryovers." (**R5**)

There are unique modules and interfaces developed specifically for BEVs, for example, the battery box. But as mentioned previously, carryover modules are also applied but needs adjustments in certain cases. **R5** explained that the same modules are used but configured to a different level of performance to support BEV.

"We have the same conceptual setup of the steering. As the BEV is heavier than fuel vehicles, the steering power must increase and thus the size of electric motors increases." (**R5**).

"All the good stuff we take from SPA and upgrade by making it more energy-efficient to support a BEV vehicle with a big size like an E size vehicle." (**R5**).

4.2 Space Reservation

This section itself is a theme with several sub-themes related to it as shown in Figure 4.2.

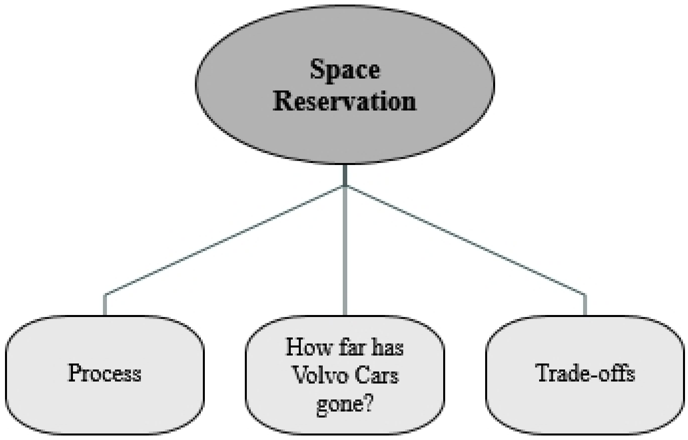

Figure 4.2: Space reservation sub-themes

4.2.1 Process involved for space reservation

Space reservation is a process of allocating a geometrically defined envelope for a part that might be needed in the future. All the respondents understood the term space reservation and were able to address the process involved in their relevant department. The methodology or practice followed at each department varied. The purpose of space reservation was explained by **R2** as adding the possibility to accommodate future needs if the architecture is designed flexibly.

"Some vehicles can be optimized, and a description list of what parts can be changed to accommodate future technology by developing the architecture in a flexible way."(**R2**)

The process of making a space reservation is quite common among the respondents involved in mechanical integration activities. The process was generally described as creating a volume or an envelope. The constricted volume to work with was referred to as a 'black box' by **R4** and **R5** in particular. **R4** explained the concept of a black box as volume created with no content assumed inside it. The volume of the black box defines the parameters and interfaces to work with for the development of the parts around and in contact with it. Whereas he described a white box as a volume with known content inside it.

"Whitebox is a box with a content when you are aware of the content and how it could be designed." (**R4**)

To provide an example, **R4** illustrated the process this way:

"For example, If a black box is going to be designed for the keyboard, we go through what content it should contain, what it should do, which environment it should be in,

and how this affects the black box. Is it feasible to fulfill that inside the black box? Before that we do all assumptions with the stakeholders, methods such as benchmarking are used to understand how the box would look like" (**R4**).

R9 described the process as creating a placeholder for a part in a system. Respondent further explained that the reserved space is stored in the Vehicle Support Structure (VSS) in Team Center Visualization. The reserved space is secured by the mechanical integration team working on it.

"The reserved space is guarded by the mechanical integration team." (**R9**)

The process of modularisation is not well defined at the company. The integration team working on the space allocation of the specified part is responsible to understand the concept and apply relevant methods and tools. Due to no concrete method, the allocated space for the part might not be included in proper documentation. The company lacking a well-designed systematic methodology would result in over-complicated tasks done in an inefficient way consuming more time and resources.

"There are some risks when it is not available in the ordinary bill of material in the vehicle, that it might be overseen or forgotten about in some way."

According to **R3**, to constraint the envelope properly and efficiently an input is required from the suppliers. To check the total scope of modules and bandwidth they cover an "Architecture book" must be followed where the complete platform and the bandwidth of its components are defined. It is used as a prerequisite when allocating space. Space is allocated to define the module and interfaces in that black box.

"Allocation of space of the black box is followed by defining the modules inside it and the interfaces. Later scalability could be built in that black box." (**R3**)

In contrast, respondents involved in electrical modules have a different perspective regarding space allocation. During the Space reservation process, a fully specified vehicle is considered to avoid overlooking parts that are not included in the low specification car of the same model. A 30 % space margin is kept for accommodating the wire harnesses required in the future, both **R1** and **R6** explained.

*"We always start design for the biggest cross-section of the harness plus 30 % growth." (**R1**)*

"We have a general 30 % requirement which is not a good one, but we are trying to follow that anyway. Make sure that we have the packaging volume for wire bundles through a grommet, inline connector, and ICU connector." (**R6**)

4.2.2 Trade offs

Although the space reservation comes at a cost, it provides a restricted geometry that could accommodate the development of parts in a flexible that might be needed to satisfy future customer needs. A common trade-off among almost all of the respondents was not utilising the reserved space resulting in sub-optimized solutions affecting the geometry of surrounding components thus adding additional cost and time. As **R7** states:

"Reserving space just for sake of reserving would result in a sub-optimized solution. We do not have much free space in any of our cars. Worse case of reserving space would be a bad design and not knowing how to use it."(**R7**)

R4 thinks that the flexibility of the architecture would decrease as it would affect how parts surrounding the reserved space would interact.

"Space claiming will affect the interacting components and space allocation of certain components might be restricted thus decreasing the flexibility." (**R4**)

According to some respondents, space reservation would make the solution too complex, heavy and costly, if not done properly. The constrained space needs to be filled with part/material to add stiffness to the vehicles getting the same crash results.

"You add additional money if you have a big Blackbox filled with air. You will add cost for a bigger Blackbox which could have been used for something else." (**R5**)

"If not correctly done space reservation creates an over-complicated, expensive and heavy solution." (**R8**)

Although reserving space comes at a cost, it also gives an edge to the company as described by **R5**;

"Space reservation will give a possibility to upgrade the solution whenever wanted with a short lead time."(**R5**)

4.2.3 Effect on Geometry

All the respondents believe that the geometry of surrounding components would be affected by space reservations except **R7** who had a different view.

"Rarely I would say the geometry gets affected, space is something we lack, we have more conflict than free space." (**R7**)

The geometry could become too complex if space is not reserved properly and complex geometries, in general, make for expensive solutions.

"The downside is that sometimes reserve too little space is reserved and the geometry becomes too complex and would result in an expensive solution." (**R8**)

One of the respondents states that the geometry of the part required to utilise the reserved space would not be affected but the surrounding ones will get affected by the process.

"If you are reserving space the component that might be added would not be affected but the surrounding ones will. For example, if we are forced to space claim for the ICU, we need to push away one of the surrounding components from the claimed space." (**R5**)

4.2.4 How far has Volvo Cars gone with space reservation?

Space reservation in the electrical infrastructure is overlooked in contrast to mechanical infrastructure. According to **R1**, the space for the wires cannot be claimed beforehand as the mechanical infrastructure often defines the space for the wires as it is costly to change and/or iterate the mechanical design.

"Usually we are forced to redesign, put the wires somewhere else, divide it, or create plastic parts that are keeping the wires down in its position which is expensive but not as expensive as changing a big tool." (**R1**)

According to **R6** most of the space claiming has been done for wire harnessing and core electrical components in the next-generation platform. It is dependent on a lot of pre-assumptions as it is impossible to predict the complete mechanical infrastructure of the vehicle.

"The uncertainty is that we do not know the content of the vehicle from the electrical perspective this early. We are basing our space claim on heritage to a large extent and guesses." (**R6**)

In contrast, on the mechanical side, the mechanical architecture is defined at early stages to be able to cover the complete bandwidth of cars. Often reserved space is utilized to accommodate the customer needs in later models. The interfaces and envelopes for the reserved space are systematically documented according to **R5**.

"We have documented the envelopes for different kinds of technologies and the interfaces, so we have enough space to increase performance over time in absolutely all areas." (**R5**)

R4 argues that the current platform lacks space reservations, and an evaluation must be made before implementing the process.

4.3 Challenges

This section itself is a theme with several sub-themes related to it as shown in the Figure 4.3.

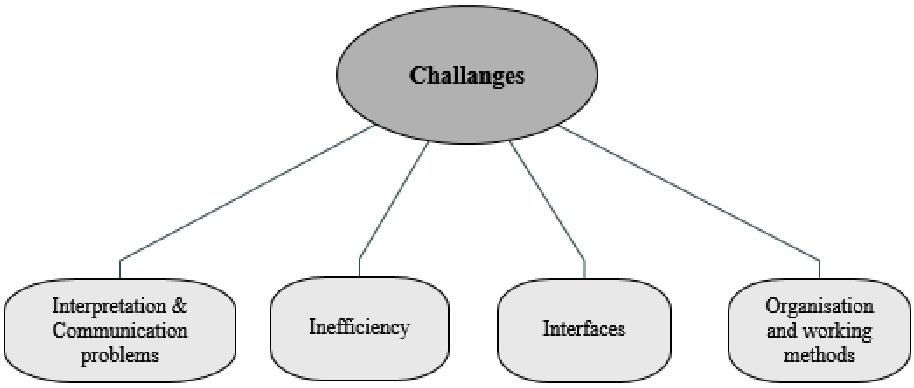

Figure 4.3: Challanges sub-themes

4.3.1 Interpretation & Communication problems

One of the main problems recognized by almost all the respondents is that there is not a common understanding and definition of modules among different departments. This results in communication and interpretation problems among them.

"We are not aligned what is a module." (**R5**)

"The definition of the module is different depending on person to person." (**R4**)

"A lot of communication problems is due to a lack of understanding to how to work with modules as the concept is relatively new." (**R3**)

The respondents working with Mechanical modules demonstrate a clear understanding of the modularisation aspects of the development process. In contrast to them, the respondents working with electrical modules do not have a clear set of guidelines to follow. In addition to that, the modularity benefits are not recognized at the same level as they are for the mechanical modularisation.

"The downside is that we don't have a common understanding of benefits." (**R6**)

4.3.2 Inefficiency

Modularisation poses many challenges at Volvo Cars. Such as defining the modules, interfaces and implementing the strategy efficiently and properly. All the respondents involved working with mechanical modules indicate that modularisation results in reduced flexibility and would hinder the innovation in the company as the organisation has to follow the strategy set in place.

"The drawbacks are you would reduce flexibility and think new." (**R4**)

"If you do not follow the rules. The module and interfaces would disappear. When following the rules, you follow the modularisation rules and instead of being innovative or new design every time." (**R4**)

Modularisation could result in sub-optimized car solutions where for example different segments share common modules.

"Between largest and smallest car, you won't get the most best solution for smaller cars if a module is designed for bigger one." (**R7**)

"Same rear axle is used for high performance and low-performance vehicle; in the low-performance level car the rear axle is too expensive and for a high-performance vehicle the rear axle has a low level of technology." (**R5**)

Furthermore, the people involved tend to be focused more on using common parts rather than common interfaces adding commonality in the variants producing similar products instead of differentiated products.

"And quite often people focus on common parts instead of common interfaces." (**R5**)

R9 believes, improving the modularity of parts and thus increasing the bandwidth in performance and reducing costs is a key to success in the emerging markets.

The respondents working with Mechanical modules demonstrate a clear understanding of the modularisation aspects of the development process. In contrast to them, the respondents working with electrical modules do not have a clear set of guidelines to follow. In addition to that, the modularity benefits are not recognized at the same level as they are for the mechanical modularisation.

"The downside is that we don't have a common understanding of benefits." (**R6**)

According to **R1** and **R6** the electrical infrastructure is not considered by the mechanical infrastructure team. Respondent describes it as:

"We are not considered at any stage; we are hit by each and every window change in the company." (**R1**)

"In electrical we do not cut cake in the same way mechanical; we are not following the technical needs in electrical modularisation." (**R6**)

Every variant of a car requires a different length of harnesses. For each variant, a new harness needs to be developed. Redesigning for every variant costs time and resources that could be utilized more productively.

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"Usually, 90 % of the time we are redesigning wire harnesses." (**R1**)

4.3.3 Interfaces

The interfaces are not well defined for electrical modules. The electrical parts are dependent on inputs from the mechanical department, and they are developed to fit those constraints.

"We are struggling with our module interfaces as we are part of everyone else's." (**R6**)

Each product owner defines their interfaces, and it increases the complexity for the wire harness to connect to the part via a connector (interface). **R6** and **R1** believe that the electrical modules have poorly defined interfaces and that this needs to be addressed and requires a systematic way of defining less complex interfaces. In comparison to mechanical interfaces, the software interfaces are not well defined, and work is needed to yield better integration.

"Software department needs to work on understanding the module and interfaces between them." (**R8**)

R5 stresses that a well-defined interface should be there as the software requires daily upgrades and maintenance. Suppliers often have predefined interfaces which determine the interaction of modules. Some respondents believe this affects the company adversely as they might contradict the standard interface rules defined at Volvo Cars, incurring additional cost and time. A good level of communication between the company and the supplier is required to reduce any misunderstanding.

"We must keep the interfaces and not let supplier chose the interfaces." (**R1**)

"The challenges would be the collaboration with for instance a supplier if they come up with an innovation. If they put that innovation into the system and want to further put it into the modularized architecture and it does not fit. Who decides what to keep?" (**R5**)

The respondents involved in electrical infrastructure had no input on the process involved for standardisation of the interfaces, as they currently lack well-defined interfaces. Apart from **R5** and **R3**, each of the remaining respondents interpreted the process differently. According to **R5** and **R4**, a software called Car Weaver™ is used to define the interfaces of the modular system in detail. The mechanical interfaces can be visualized using Siemens Teamcenter™. The mechanical integration team has a Microsoft Excel spreadsheet with the defined interfaces between the modules which are updated manually by the team.

"For CMA and SPA, a specified setup of CAD restriction geometries are used, might be the case for the future as well but it is a work in progress." (**R7**)

"A subjective assessment is used to standardize interfaces." (**R8**)

All the respondents involved in working with mechanical modules had a similar concept of how the interfaces evolve if a proposed change threatens the product architecture Limited documentation, methods, and tools are available to deal with the evolving product architecture. The team affected discusses first-hand among themselves, and then different proposals are presented and evaluated in cross-functional teams. A decision hierarchy is followed to decide a controlled and structured way.

4.3.4 Organisation and working methods

Volvo is focusing more on improving “Modularity in design” in contrast to “Modularity in Production”. The low number of plants adds flexibility when compared to other larger OEMs.

"We are a small car company, which means sometimes we don’t have 10 plants so we could somewhat be more flexible than other car brands, it might cost us more money." (**R7**)

It is challenging for automotive companies to predict the customer needs according to a few of the respondents. **R8** mentioned that what was deemed as important during the development of SPA, is completely different from what is deemed as important now.

"To give you an example, in SPA it was extremely important to have what was then perceived to be the premium look of a vehicle with a very long distance between the wheel center and the occupant, to have this appearance of being a rear-wheel driven saloon type of vehicle." (**R8**)

He further explained that the aesthetic and positioning of components had to be changed during the introduction of BEV. New regulations pushing for greener energy will affect the future developments of platforms. In addition, energy efficiency is required to succeed in emerging markets.

"Energy efficiency is highly important and changes how we setup the mechanical architecture." (**R8**)

According to **R8**, Volvo Cars are sometimes too overconfident in decision making related to the future resulting in poor forecasting and inefficiency. He also mentioned the negative impact that poor decisions can have.

"You lock the development, and you always look at those mechanical interfaces being set, you kind of limit the ability for the engineer to think freely and develop the system that is right for the next product." (**R8**)

Furthermore, **R8** expressed the importance of having all features on the first released vehicle and explained that the last vehicle will be the most outdated one.

"If you look at the previous architectures that we have done, the first product out is always the most relevant one. It has got all the bows and whistles. The last one out is always the outdated one because it is based on technology that was developed 10 or sometimes 15 years ago." (**R8**)

The concept of modularity is relatively new to the company. It is hard to define it and have the same understanding among different departments or people. Accepting the new way of thinking and the new strategy is a challenge for the older employees. The company would not be able to reap all the benefits unless people involved in the decision-making process are educated about the new concept of modularisation.

"It is hard to change the mindset of people who have experienced it for many years, people think that we are totally stupid because you have to think differently when focusing on modules."

5
Case Study

The case study was conducted to study the Head Up display and its surrounding components. How the geometry of the HUD affects the different parts was also investigated.

5.1 Case study of the HUD

During the background study, it was identified to be interesting to investigate a part that is innovative and affects users driving experience. When selecting the main components to investigate, one criterion was to find a component that contained electrical, mechanical, and software interfaces resulting in a multidisciplinary team coordinating together for creating solutions for the customers. It is part that needs to be assessed for future models and platforms.

The component that fulfills the required criterion, is the Head-Up Display (HUD). The HUD is a component that is outsourced to be procured from external suppliers. Volvo Cars does not have complete control over the component internal architecture. Therefore, it is a good representation of how the company can adapt to use modularisation and common interfaces between different models in the SPA platform. In addition to that, the components surrounding the HUD were also investigated to get a better understanding of how the configuration of different models or variants of the cars affects their geometry and interfaces.

The scope of the study was limited to left-hand drive Nordic models. To get a better understanding of the car structure, an in-depth study was conducted using TCVis (Team Center Visualization) to view, measure, and compare different car models. The cars produced by Volvo are categorized into different types, the models studied are shown in the Table 5.1.

Table 5.1: Models investigated for the research

Type	**SPA**	**CMA**
SUV	XC60, XC90	XC40
Estate	V60, V90	-
Sedan	S60, S90	-

The HUD is a unique component with several different types of interfaces. The HUD is not a standard part that comes with any standard vehicle, it is an add-on that is selected beforehand by the customers and that in the current cases cannot be upgraded to later.

TCVis was used to visualize the parts across different variants and models. Different tools in TCVis were used to filter out the parts required for investigation. A clearance filter of 30mm was applied to analyze the parts within 30mm of the HUD. To get a better understanding of the interaction of the components a DSM was constructed for three different vehicles as shown in the Appendix C to. The product architecture and modules were alike resulting in similar DSMs. Furthermore, component trees were used to facilitate the understanding of the DSMs as shown in Appendix D.

A car with HUD and without HUD for the same model was studied. The car with no HUD as an option had an empty space which is not being utilized. After questioning **R9** , there was no alternative to fill in space in a better way, although the emptied space would affect how the car would perform in crash tests, as the stresses across the structure would change. To balance the effect of having no HUD, the pedal column is designed in such a way as to accommodate the margin.

The parts selected for investigation were reduced to the HUD itself, the steering bracket, the pedal column frame (PCF), the cross car beam (CCB), and the dashboard. As shown in the Figure 2.9.

The interaction between examined parts is showed in the DSM, see Figure 5.1. To further simplify a component tree model is constructed to get a better understanding of how each of the components is connected, presented in Figure 5.2.

DSM		1	2	3	4	5	6
PEDAL COLUMN FRAME	1	■	x	x	x		
STEERING BRACKET	2	x	■		x		
HUD	3	x		■			
CROSS CAR BEAM	4	x	x		■		x
WINDSCREEN	5					■	x
DASHBOARD	6				x	x	■

Figure 5.1: DSM of the selected components

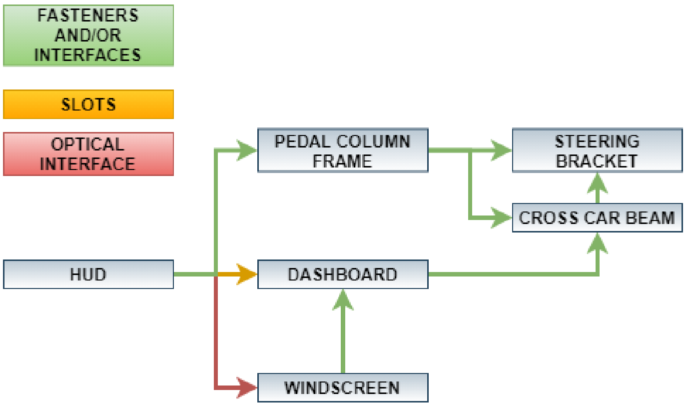


Figure 5.2: Component Tree of the selected components

After comparing the HUDs being used in different cars within Volvo's SPA platform. It was noted that the geometry varied between them. Although the interfaces connecting the HUD to the PCF were similar the location point for interface A was different across the HUDs as shown in the figure below, the red boxes indicate interface A and blue boxes show interface B as seen in Figure 5.3.

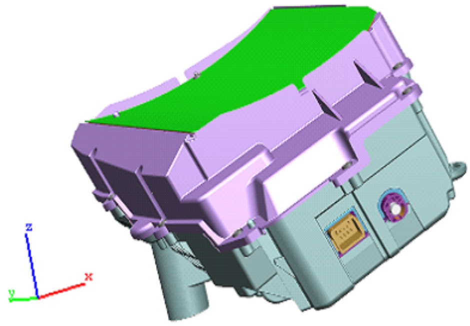
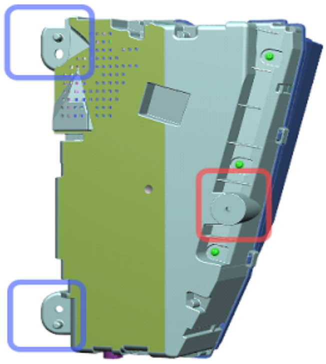
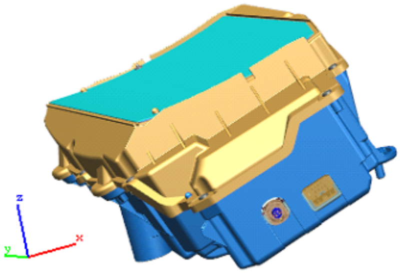
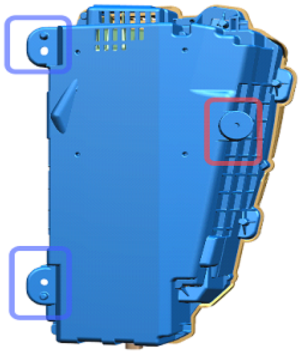
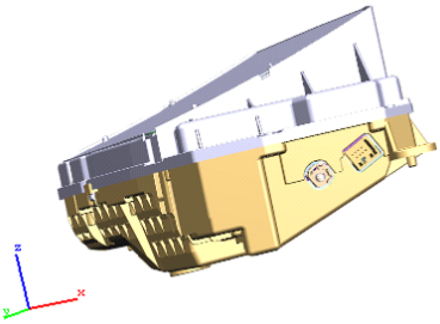
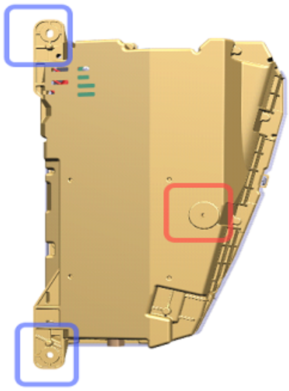
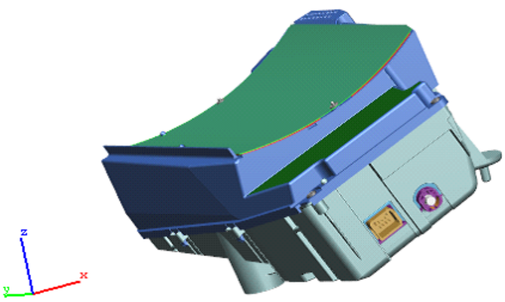
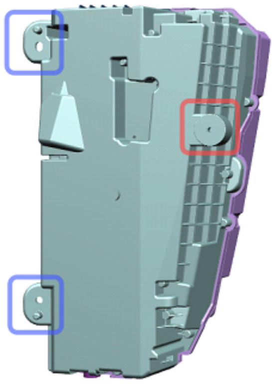
HUD	Isometric View	Bottom view
HUD A V90 S90		
HUD B V60 S60		
HUD C XC60		
HUD D XC90		

Figure 5.3: Different type of HUDs

TCVis was used to calculate the maximum dimensions of the HUD unit in each axis, Relative dimensions of different HUD models are calculated using HUD A as a reference as shown in Table 5.2 and Figure 5.4.

Table 5.2: Relative Dimensions of the HUDs

	With	**Length**	**Height**
A	1,000	1,000	1,000
B	1,044	1,026	0,992
C	1,041	0,922	1,046
D	1,044	1,094	0,979

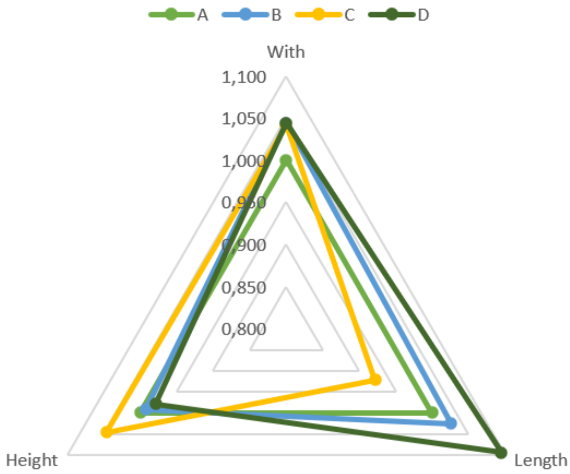


Figure 5.4: Visualization of relative dimensions

All the models analyzed produced on the SPA platform shared a common steering bracket part which is connected to PCF and CCB as shown in the Figure 5.5.

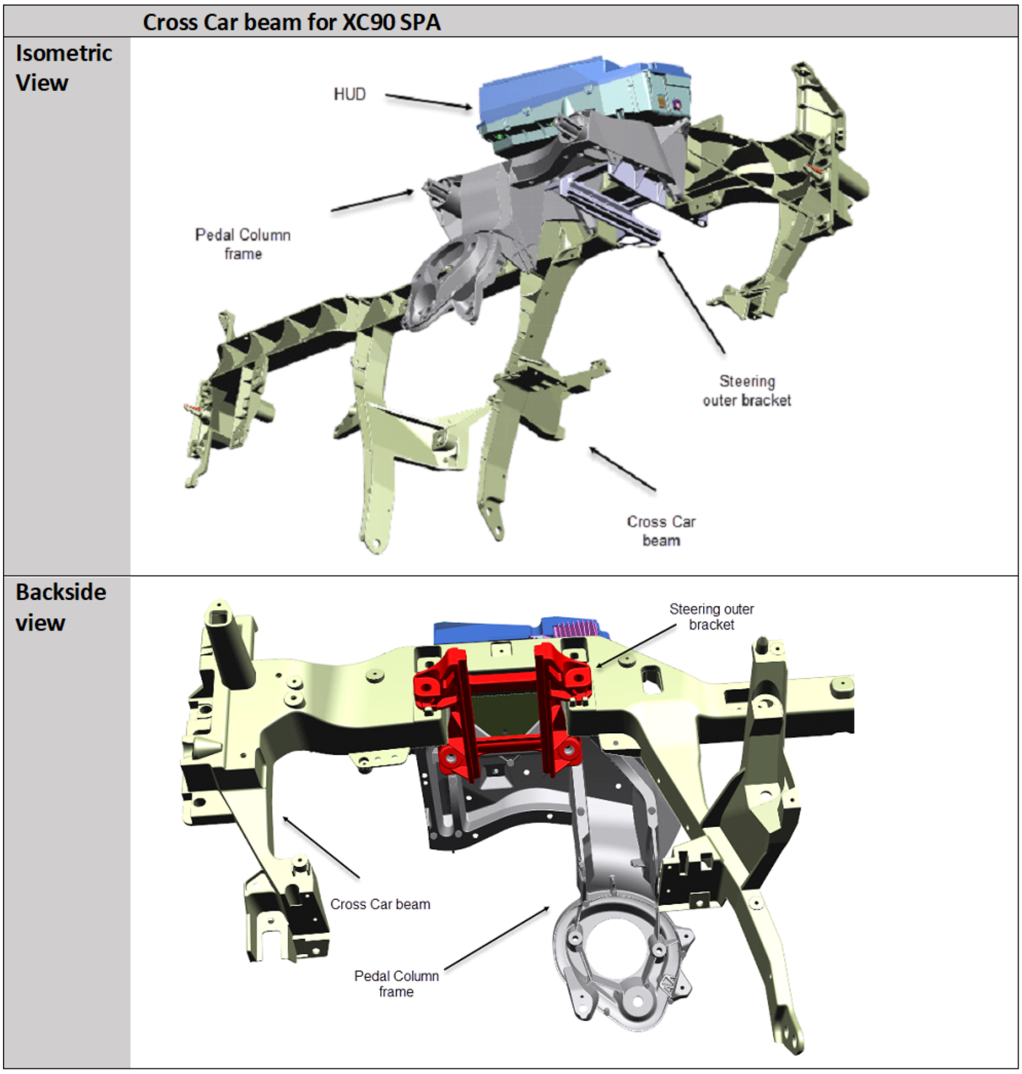


Figure 5.5: Steering bracket interactions with surrounding parts

The CCB of the studied sedan and estate cars are identical and also the PCF across them except the S90 which had different geometry. The SUVs both had non identical CCB and PCF.The images of both CCB and PCF are presented in Figure 5.6 & 5.7 for visualisation and better understanding.

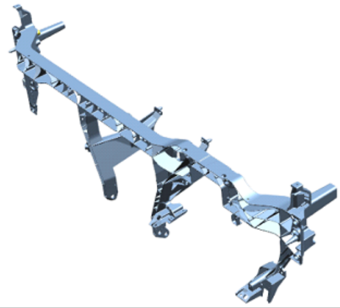
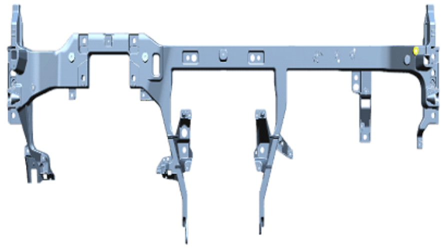
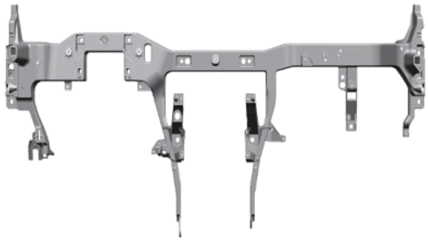
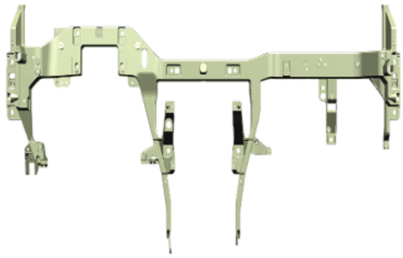
CCB	Isometric View	Backside View
A V60 V90 S60 S90		
B XC60		
C XC90		

Figure 5.6: CCB of different type of cars produced on SPA

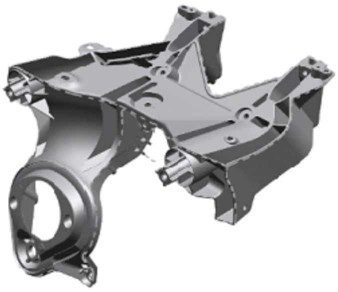
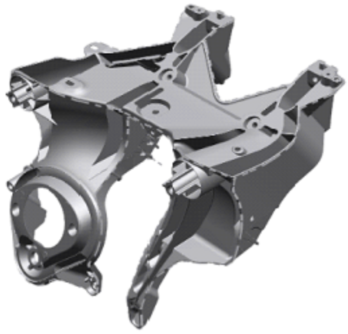
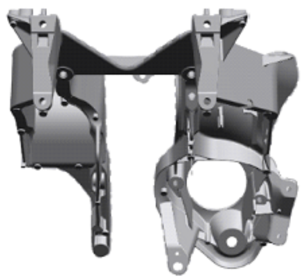
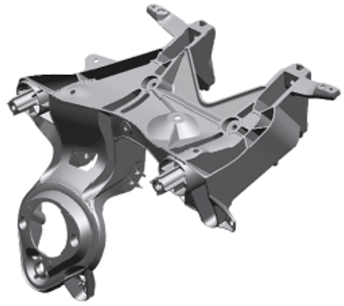
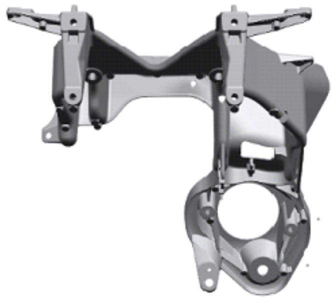
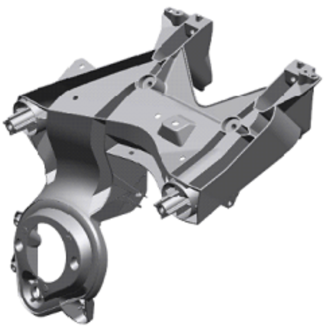
PCF	Isometric view	Back side view
A V90 S60 V60		
B S90		
C XC60		
D XC90		

Figure 5.7: PCF for different Vehicles

By investigating the selected models, it could be said that a car with common HUD would also have identical dashboard and windscreen as seen in the Table 5.3. According to a respondent the windscreen needs to be different as the angle the windscreen is fixed on, and the position of the driver determines the quality of the projected image. A special surface is required on the windscreen for the image projection, hence car variants with no HUD have different windscreens. It is to be noted that the aforementioned cars have common HUDs, windscreens, and dashboards. Furthermore, the variants with no HUD had different windscreens and dashboards as they are not required to support the HUD structure. If the HUD were to be added later by the user, a new dashboard and windscreen would be required resulting in complex disassembly, adding cost and time. Table 5.3 shows similar parts in different vehicles across the platform.

Table 5.3: Similar parts across different models

	Vehicles					
Parts	**V60**	**V90**	**S60**	**S90**	**XC60**	**XC90**
PCF A	x	x	x			
PCF B				x		
PCF C					x	
PCF D						x
Steering Bracket	x	x	x	x	x	x
CCB A	x	x	x	x		
CCB B					x	
CCB C						x
HUD A		x		x		
HUD B	x		x			
HUD C					x	
HUD D						x
Windscreen A		x		x		
Windscreen B	x		x			
Windscreen C					x	
Windscreen D						x
Dashboard A		x		x		
Dashboard B	x		x			
Dashboard C					x	
Dashboard D						x

The XC40, a car built on the CMA platform, was also analyzed to compare with the ones produced in SPA, to see how it differentiates from it, and to investigate why is it not flexible enough to accommodate a HUD. After thorough analysis using TCvis, it showed that the CCB looked completely different and it is named as “Cross member” in TCVis as shown in Figure 5.8. Instead of PCF, it has a “bracket brake pedal” which is geometrically different with smaller dimensions. The Bracket brake pedal does not have any support structure to accommodate the HUD.

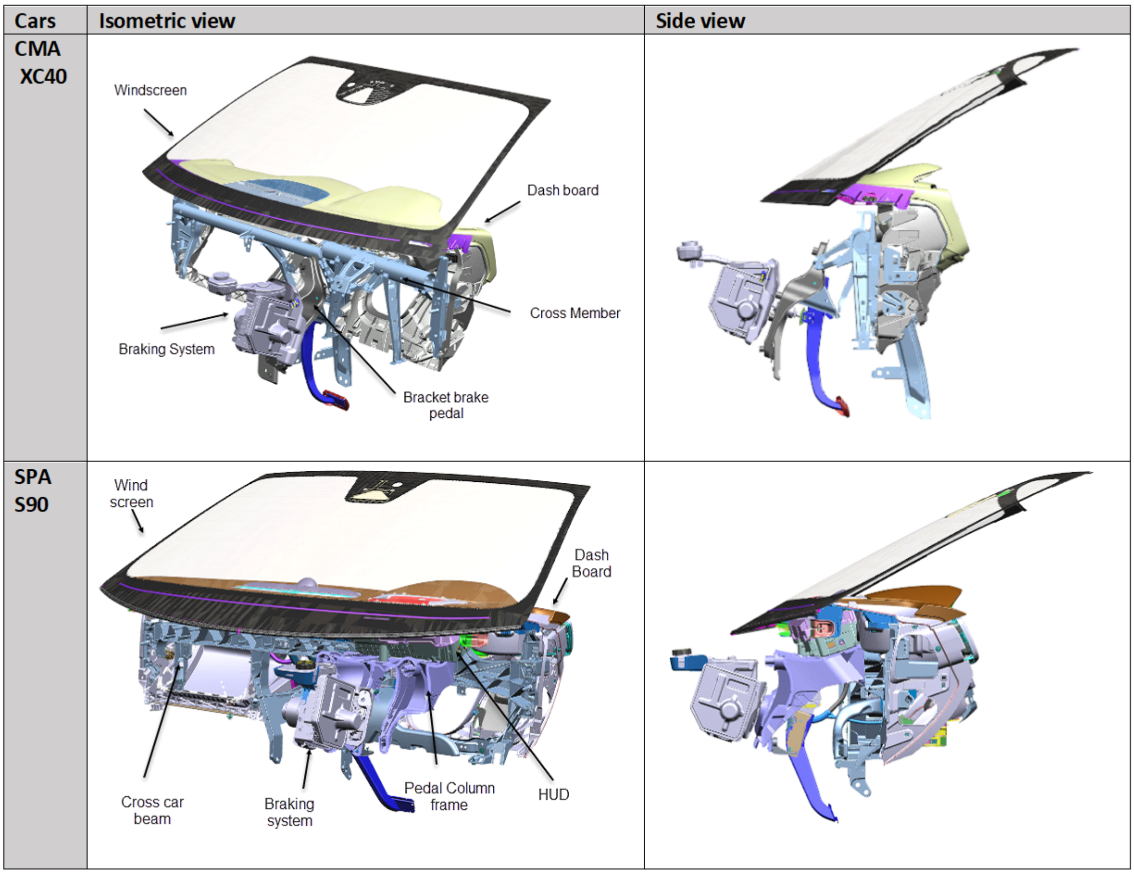


Figure 5.8: Comparison between car produced at different platforms

6
Discussion

The following chapter discusses the findings from the interviews and case study conducted.

6.1 Discussion of results

There is not a common understanding of the modularisation strategy among the employees at Volvo Cars. This could be due to the reason that the modularisation strategy has not reached all departments yet and that some are more experienced than others. Applying the modularisation strategy in the automotive industry is a complex task since there are many parts with different interfaces that needs to be considered. In the literature review, it was mentioned that it is important that the company is aligned with the process and expectations of the modularisation strategy to reap most benefits.

Moreover, having well-defined interfaces and taking trade-offs within the different function teams are factors contributing to a flexible product, highlighted in the literature section. The electrical department at Volvo Cars is not working with the modularisation strategy, the lack of well-defined interfaces and collaboration with other function teams was brought up in the interviews. In automotive industries, many parts are outsourced from suppliers making the company not having complete control over the design and interfaces of components as addressed in the literature. It was explained that the outsourced parts can threaten the modularised architecture if the communication between the company and suppliers is poor as mentioned by the respondents.

A modular platform is characterised by accommodating multiple variants from a single platform targeting a larger customer segment. From that perspective, it could be argued that Volvo Cars has succeeded in producing modular vehicles. SPA platform is modular enough covering a large bandwidth, producing cars in different segments, ranging from Estate, Sedan and SUV cars. As analysed in the Case Study, the cars produced on SPA share common parts such as CCB, PCF, HUD, dashboard to some degree. The case study and respondents suggested, the dimension of the HUD is determined by the packaging of the components surrounding it, due to this reason not all the models share similar parts. Only the steering column bracket is an identical part in all the models produced on SPA. Although the identified parts are not common among all the vehicles produced on SPA, they have similar standardised interfaces with identical geometry. Volvo has made the parts more modular by following the strategy which would help to keep the cost low but might make the product less appealing by have commonality between them.

The concept of modular platforms is relatively new at Volvo Cars and has not reached all departments yet. The journey started with the development of SPA in 2015 and has continued throughout the years by introducing and developing new platforms to target larger market segments. Producing vehicles targeting a large customer segment from a single platform is challenging. The automotive industries must prioritise and trade certain dimensions over others. In the case of Volvo Cars, the company derived premium looking vehicles with a long distance between the occupant and wheel center from SPA, which was trending during that time. However, the demand for energy-efficient vehicles has increased in recent times and the concept of Battery Electrical Vehicles has become the new trend.

The introduction of Battery Electrical Vehicles at Volvo Cars has led to many changes from an organisational and a technical perspective. BEV vehicles require different prerequisites to what has been defined during the development of SPA. Vehicles produced from SPA are large and require higher energy efficiency. Thus, BEV is not produced on SPA and a new platform (CMA) producing smaller vehicles supporting the concept of electrification was developed.

Volvo Cars collaborated with CEVT during the development of the CMA platform, unlike SPA which was developed only by Volvo Cars. CMA produces vehicles for both Geely and Volvo Cars, which could be another indication of the differences between the platforms. More actors were involved in the development process of CMA leading to different opinions and design ideas. However, a collaboration between companies is an excellent way to gain more knowledge and ideas, particularly for a broad concept such as Battery Electric Vehicles.

According to an interviewee CMA was developed for the production of combustion engine vehicles but later altered to support BEV. The product architecture is defined differently as the combustion engine is replaced by electric motors and batteries to power it. The weight distribution across the cars changes due to that and the new product architecture should fulfill the stress requirements for the safety of the passenger. The modules between both CMA and SPA platforms are not interchangeable as the product architecture defined looks completely different. Furthermore, the case study identified that the geometry and interfaces of the parts look completely different e.g. the PCF does not exist in CMA and would not support the HUD.

The process for space reservation is not well defined at the company. No clear set of guidelines or documentation are provided to follow up on the process. The team responsible needs to address the problem and proceed accordingly. The firm lacks proper documentation or methodology to be followed resulting in an inefficient way of working adding more time to tackle the issue. The supplier is also to be kept in check as products procured from them might have different geometry resulting in sub-optimized solutions. The interfaces are to be defined beforehand the actual part is installed in the reserve space. The mechanical integration teams had a way of proceeding with the problem, whereas the people involved in electrical infrastructure follow a rule of thumb of having a 30 % space margin in the vehicle to accommodate the future changes in the structure, as described by the interviews that they are overlooked, the mechanical infrastructure often defines how the product architecture should look like.

The space reservation would affect the geometry and packaging of the components surrounding it. If the process is not done properly, it would result in sub-optimized complex solutions adding additional cost and time to the company. In some cases, it might affect the flexibility of the surrounding parts as well because their design changes and positioning are further constrained but on other hand, it would let the company upgrade the vehicle with parts in the future. The PCF in the HUD and no HUD variant is similar. It adds the support structure for the HUD. In the HUD variants, a different dashboard and windscreen are required for the projection of the data. If needs be the customer could upgrade the car with the HUD but would have to deal with complex disassembly to deal with and would result in a costly and time consuming upgrade.

A key challenge of implementing the modularisation strategy described by respondents was having noticeable similarities among the products and working towards modularisation could hinder new innovative product ideas that might not come in production as it won't align with the strategy set in place, hence the platform would not support it. In the case study, it could be noted that different models in the platform share similar parts e.g. HUD, windscreen, dashboard adding commonality to the cars. The commonality of parts could result in sub-optimized solutions where a high-performance vehicle would be using a common module used in all the vehicles. Work needs to be done at Volvo cars to develop common interfaces instead of common parts while keeping the costs low, and developing differentiating products. The electrical infrastructure is struggling with modularity. The harnesses are not similar across different models or variants.

Moving towards much greener sources of energy for sustainability, the regulations set in place, the new emerging markets and change in product architecture, and new energy efficiency targets has resulted in a new way of thinking in terms of modularisation. Fully electric vehicles are going to be supported in the next generation platform. The modules in the current platforms are either not modular or optimized enough to support fully electrical vehicles. There are parts and systems required in the platforms to support BEV. The development of CMA is based on the combustion engine platform architecture and is hence not optimized for BEV and SPA does not support BEV as mentioned previously. By 2030 Volvo Cars goal is to switch to developing fully electric cars on their next-generation platform [13].

6.2 Limitations

This section discusses the limitations and credibility of this research. There is limited research with topics discussed in this report and the information gathered cannot be generalized. The study is directed to Volvo Cars and the result would look different at other companies. The methods followed affect the credibility and reliability of the results. Reflecting upon the methods used or how they could be done in a different way to increase credibility are discussed. The number of interviews conducted determines the accuracy of the results and the conclusion. To what degree they were performed tells the quality of the data gathered. A higher number of interviews and to what extent they were performed would give a relatively better indication of the process, modularity, and decision being followed at Volvo Cars.

Before formulating the interview questions, early research on different platforms e.g CMA or SPA would have resulted in more accurate, related, and specific questions. A way to increase the credibility of the interviews could be to have multiple interviews from a respondent, as the respondent would have time to think on the subject for the successive interview. It was not possible to arrange multiple interviews or focus group interviews where discussion and argument would have been constructive in drawing a more accurate conclusion. One method could have been sending interview questions beforehand the actual interview, so the respondent is well versed with the questions.

The Covid-19 pandemic also limited personal contact, it was harder to arrange meetings virtually due to limited in-person contact. Internal documents were not provided, which further reduced the scope of the study. The space reservation or allocation had no previous work done in the literature in the automotive industry. The Volvo Cars way of working could not be compared to other OEM's.

7 Conclusion

An investigation of Volvo Cars current platforms and level of flexibility was conducted in this research. The perception of the modularisation strategy at Volvo Cars among the employees was studied. In addition, the flexibility of the current platforms at Volvo Cars (SPA and CMA) were analysed. Lastly, the challenges with the current platforms and trade-offs of reaching high flexibility were identified. This thesis mostly tackles the research questions from a mechanical perspective, but electrical and software issues were also considered to an extent. Both qualitative and quantitative research methods were applied in this study to make a fair judgment of the results. A case study of a unit (HUD) was performed to further get an understanding of the space allocation and flexibility level of the current platforms. A systematic literature review, interviews with employees and a case study was performed and yielded some interesting findings concerning the research questions.

RQ1. How flexible are the current platforms at Volvo Cars?
The current Platform is flexible enough to accommodate different vehicle segments. Although the smallest SUV, XC40, is not supported or produced on the SPA platform as it does not support that bandwidth. The current platform SPA does not support BEV vehicles, whereas CMA is flexible enough for the development of BEV vehicles along with combustion engine vehicles. The modules across different platforms are not interchangeable. It could be said that Volvo Cars has reached some level of modularity, but the current platforms are outdated to cover the complete bandwidth of cars, thus a next-generation platform is required for the development of BEV and covering all the segments in a single platform.

The current platforms meet the stakeholder needs by producing different models of cars targeting specific customer segments by providing variants to choose from. The customer could order the car with specified add-ons if wanted. For example, Volvo Cars provides cars with HUD and without HUD. It provides the customer with the flexibility to choose different variants across models produced at Volvo Cars.

RQ2. What are the challenges to achieve a highly flexible platform?
A highly flexible product platform would support a car with a larger bandwidth. The initial cost of setting up the platform would be high. Models produced on a flexible platform often share common modules with a defined bandwidth. The use of common parts sometimes results in trade-offs. Sharing a module in a sedan designed for an SUV would incur additional cost and weight and produce sub-optimized solutions.

The space allocation process at Volvo Cars is not well defined, no proper documentation or set of guidelines are provided. The team involved decides how to proceed with the process. The trade-offs are measured, and the matter is brought up, approval at different hierarchical levels at Volvo where pros and cons are weighed and finally a decision is made. The reserved space needs to be protected by the team involved in the process.

The flexibility could be increased by having better communication and interactions with the supplier, to get better updates on the design and development procedure resulting in better control over the interfaces and design. The interfaces define the interaction points between different modules. Hence, a well-designed standard interface would not affect the product architecture and would be easier to integrate modules.

8
Future Work

The previous limitations discussed previously affected the results of this research. The trustworthiness of the report would increase by interviewing more people. It would be interesting to interview several people from similar departments to make a fair judgment. Furthermore, it is also beneficial to interview people from production to make a comparison with the product development perspective and identify trade-offs. Most of the interviewed employees have worked for Volvo Cars for many years. Involving employees with short experience would provide another view of how they have been introduced to the concept of modularisation.

Exploring more components provides beneficial insights and enables a comparison of modularity level and interfaces between the different components. Conducting interviews with suppliers would also be interesting to further understand how interfaces are defined.

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A

Appendix A

Interview

Initial questions

1. What department do you work in and what are your main tasks?
2. How How long have you been working for Volvo?
3. Did you have other positions at Volvo? If yes, what position did you have?

General definition of modules

4. For how long has Volvo been working with modules and what are the reasons behind their implementation?
5. How do you define modules?
6. Are the modules defined differently in Volvo's platform (SPA vs CMA)? If yes, how?
7. Is the product architecture defined differently in Volvo's platforms (SPA and CMA)?
8. Has the Product Architecture changed with the production of BEV?
9. Are modules defined differently after the introduction of BEV?
10. How modular is the product architecture in Volvo's platforms (SPA and CMA)? What parts are modular/what are not? Why?
11. Does every department have the same definition of modules and have you had communication problems due to different interpretations?
12. How are the interfaces defined and standardized at Volvo?
13. a) What happens if a proposed change threatens the standardized interfaces of the modular architecture? b) How does architecture evolve? c) How are exceptions handled?

Modularity

14. Is modularisation part of your day to day work and how?
15. What drawbacks are there with modularisation?
16. Is it harder to modularise products containing more software/electronics?
17. Which departments are working more towards modularisation and why?
18. Do you prioritise the modularity in design or the modularity in production?
19. When modularizing a product, do you consult the production beforehand or after?

20. How do you develop different versions of modules with different levels of performance?
21. Is there a difference between the development of high-end modules vs low-end modules?

Geometry

22. How do you reserve space for parts that might be needed in the future before designing the platform?
23. What measures are taken into account when allocating space for different components, and how does it affect the product architecture/platform?
24. What are trade offs encountered when reserving space for a part that might be included in the future?
25. Does reserving space for a specified part makes the product architecture more/-less flexible?
26. Is the geometry of the component affected by space reservation?
27. In the current product architecture/platform is how far have you gone with the space reservation,what are the uncertainties, and pros and cons?

Wrap up

28. How does the future look for Volvo in regards to modularisation?
29. What challenges do you expect?

B

Appendix B

Modularisation	The implementation of modularisation strategy at Volvo Cars	Citations
Modularisation at Volvo Cars	Interpretation of modularisation at Volvo Cars	"Distributing the responsibility of the different modules and structuring the modules" (R9)
Modules	Volvo's definition and work with modules	"Building block with defined interfaces" (R3) "Modules are implemented to create a bandwidth of high and low specification cars" (R9)
Platforms	The product architecture of the current platforms e.g SPA vs CMA	Q)Is the product architecture defined differently in Volvo's platforms (SPA and CMA)? "Yes, it is because SPA 1 is more has higher scalability that you could stretch the wheelbase more .You could have differnce in performance in a bigger scope .CMA I would not say one size fits all but it's a little bit, the scalability is really low, Only 'C' size vehicles are built on CMA'' (R5)
Electrification and BEVs	Effect of Battery Electrical Vechicles on Product Architrecure	Q)Has the Product Architecture changed with the production of BEV? ''Most of the tehcnology was robust, but when needed BEV Quickly understood need to develop architecture leading to SPA 2.Where we did big changes on the architecture enabling BEV .When big enough need you could redesign the architecture . But it needs to be done in a controlled way'' (R7)
Space Reservation	**Reserving a space for a part**	
Process	The procedure involved in space allocation	'The architecture team will create a volume or model that describe the bandwidth'' (R7)
Trade-offs	The tradeoffs for reserving a space that might not be needed in a future	"Reserving space just for sake of reserving would result in a sub-optimized solution. We do not have much free space in any of our cars. Worse case of reserving space would be a bad design and not knowing how to use it" (R7)
Effect on Geometry	How does space reservation effects the geometry of the components surrounding it	"The downside is that sometimes reserve too little space is reserved and the geometry becomes too complex and would result in an expensive solution" (R8)
Challanges	**The challenges Volvo is facing with regards to modularisation**	
Interpretation & Communication problems	The communication and intrepreation problem between the people and the departments	"A lot of communication problems is due to a lack of understanding to how to work with modules as the concept is relatively new" (R3)
Inefficiency	Inefficiencies that can be caused by an improper implementation of the modularisation strategy	"If you do not follow the rules. The module and interfaces would disappear. When following the rules, you follow the modularisation rules and instead of being innovative or new design every time" (R4)
Interfaces	Struggles of defining and standardizing interfaces at Vovo Cars	"We are struggling with our module interfaces as we are part of everyone else's" (R6)
Organisation and working methods	Decisions and working methods that can have a negative impact on the modularisation strategy	"You lock the development, and you always look at those mechanical interfaces being set, you kind of limit the ability for the engineer to think freely and develop the system that is right for the next product" (R8)

Figure B.1: Codebook for the themes

C

Appendix C

V60		HUD	PEDAL COLUMN FRAME	ROUND/POWER CABLE	SOUND ABSORBENT UPPER PCF	SQUARE/DISPLAY CAABLE	CROSS CAR BEAM LOW V54 X LHD	STNG SA OUTER BRACKET 4BOLT	SOUND ABSORBENT UPPER PCF	IP CABLE DUCT CENTRE	SOUND INS BETA DAMP 60X70	CABLE HARNESS COCKPIT	GHUD COVER	GHUD COVER SPOLIER	SKIN TOP MILLED	CARRIER MILLED	DEFROSTER CHANNEL	DIM COOLING ADAPTOR	HOSE DIM COOLING	AIR DUCT DRIVER	DEFROSTER OUTLET FRONT	DEFROSTER CHANNEL
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
HUD	1		x	x	x	x																
PEDAL COLUMN FRAME	2	x					x	x	x	x	x	x										
ROUND/POWER CABLE	3	x																				
SOUND ABSORBENT UPPER PCF	4	x																				
SQUARE/DISPLAY CAABLE	5	x																				
CROSS CAR BEAM LOW V54 X LHD	6		x					x								x		x				x
STNG SA OUTER BRACKET 4BOLT	7		x				x															
SOUND ABSORBENT UPPER PCF	8		x																			
IP CABLE DUCT CENTRE	9		x																			
SOUND INS BETA DAMP 60X70	10		x																			
CABLE HARNESS COCKPIT	11		x																			
GHUD COVER	12													x	x							
GHUD COVER SPOLIER	13												x									
SKIN TOP MILLED	14												x									
CARRIER MILLED	15						x										x					
DEFROSTER CHANNEL	16															x						
DIM COOLING ADAPTOR	17						x												x			
HOSE DIM COOLING	18																	x				
AIR DUCT DRIVER	19																					x
DEFROSTER OUTLET FRONT	20																					x
DEFROSTER CHANNEL	21						x													x	x	

Figure C.1: DSM of V60

V90		AIR DUCT DRIVER	CABLE HARNESS COCKPIT	CARRIER MILLED	CROSS CAR BEAM	DEFROSTER DUCT	DEFROSTER FRONT	DIM COOLING ADAPTER	DISPLAY CABLE	GHUD	GHUD COVER	HOUSE DIM COOLING	IP CABLE AIR DUCT	LEATHER DASHBOARD	PEDAL COLUMN FRAME	POWER CABLE	SKIN MILLED	SOUND ABSORBER	SOUND INS BETA DAMP 60X70	STNG COL SA OUTER BRACKET	TAPE MASTER	WINDOW SEALING	WINDSCREEN
Nr	COMPONENT NAME	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	AIR DUCT DRIVER	■				x																	
2	CABLE HARNESS COCKPIT		■						x						x	x							
3	CARRIER MILLED			■	x	x								x			x						
4	CROSS CAR BEAM			x	■			x							x					x			
5	DEFROSTER DUCT	x		X		■	x															x	
6	DEFROSTER FRONT					x	■							x									
7	DIM COOLING ADAPTER				x			■				x						x					
8	DISPLAY CABLE		x						■	x													
9	GHUD								x	■					x	x		x					
10	GHUD COVER										■			X			X				X		
11	HOUSE DIM COOLING							x				■											
12	IP CABLE AIR DUCT												■		X								
13	LEATHER DASHBOARD			x			x				X			■									
14	PEDAL COLUMN FRAME		x		x					x			x		■			x	x	x			
15	POWER CABLE		x							x						■							
16	SKIN MILLED			x							x						■						
17	SOUND ABSORBER							x		x					x			■					
18	SOUND INS BETA DAMP 60X70														x				■				
19	STNG COL SA OUTER BRACKET				x										x					■			
20	TAPE MASTER										X										■		
21	WINDOW SEALING					x																■	x
22	WINDSCREEN																					x	■

Figure C.2: DSM of V90

XC90		HUD	PEDAL COLUMN FRAME	ROUND/POWER CABLE	SOUND ABSORBENT UPPER PCF	SQUARE/DISPLAY CAABLE	CROSS CAR BEAM LOW V54 X LHD	STNG SA OUTER BRACKET 4BOLT	SOUND ABSORBENT UPPER PCF	SOUND INS BETA DAMP 60X70	CABLE HARNESS COCKPIT	GHUD COVER	IP TAILORED GHUD	CRASHPAD TAILORED GHUD	DEFROSTER DUCT	DIM COOLING ADAPTOR	HOSE DIM COOLING	AIR DUCT DRIVER	DEFROSTER OUTLET FRONT	DEFROSTER CHANNEL
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
HUD	1		x	x	x	x														
PEDAL COLUMN FRAME	2	x					x	x	x	x	x									
ROUND/POWER CABLE	3	x																		
SOUND ABSORBENT UPPER PCF	4	x																		
SQUARE/DISPLAY CAABLE	5	x																		
CROSS CAR BEAM LOW V54 X LHD	6		x					x						x		x				x
STNG SA OUTER BRACKET 4BOLT	7		x				x													
SOUND ABSORBENT UPPER PCF	8		x																	
SOUND INS BETA DAMP 60X70	9		x																	
CABLE HARNESS COCKPIT	10		x																	
GHUD COVER	11												x							
IP TAILORED GHUD	12											x								
CRASHPAD TAILORED GHUD	13						x								x					
DEFROSTER DUCT	14													x						
DIM COOLING ADAPTOR	15						x										x			
HOSE DIM COOLING	16															x				
AIR DUCT DRIVER	17																			x
DEFROSTER OUTLET FRONT	18																			x
DEFROSTER CHANNEL	19						x											x	x	

Figure C.3: DSM of XC90

D

Appendix D

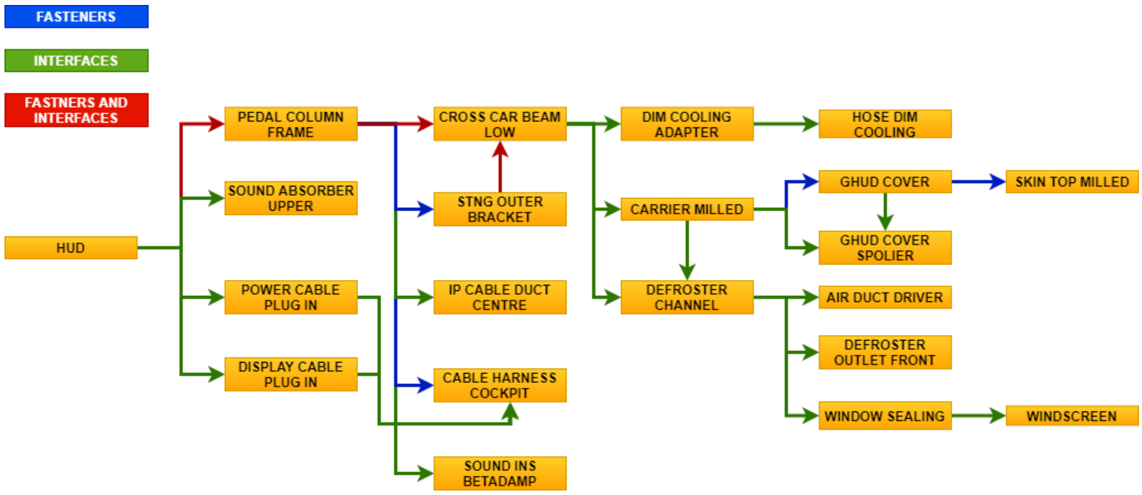


Figure D.1: Component Tree of V60

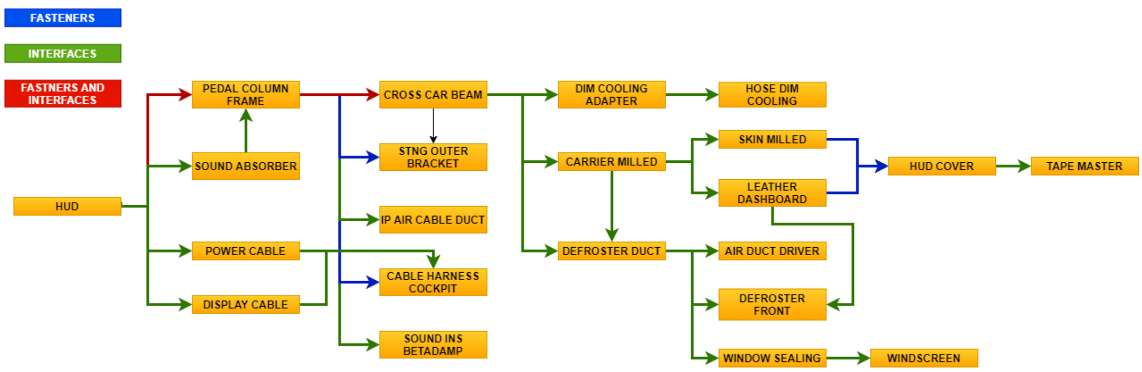


Figure D.2: Component Tree of V90

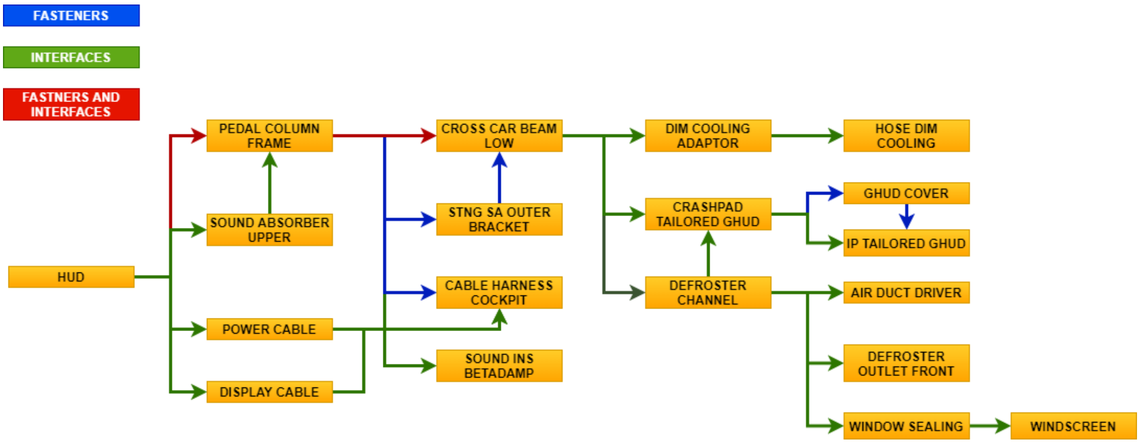


Figure D.3: Component Tree of XC90

E

Appendix E

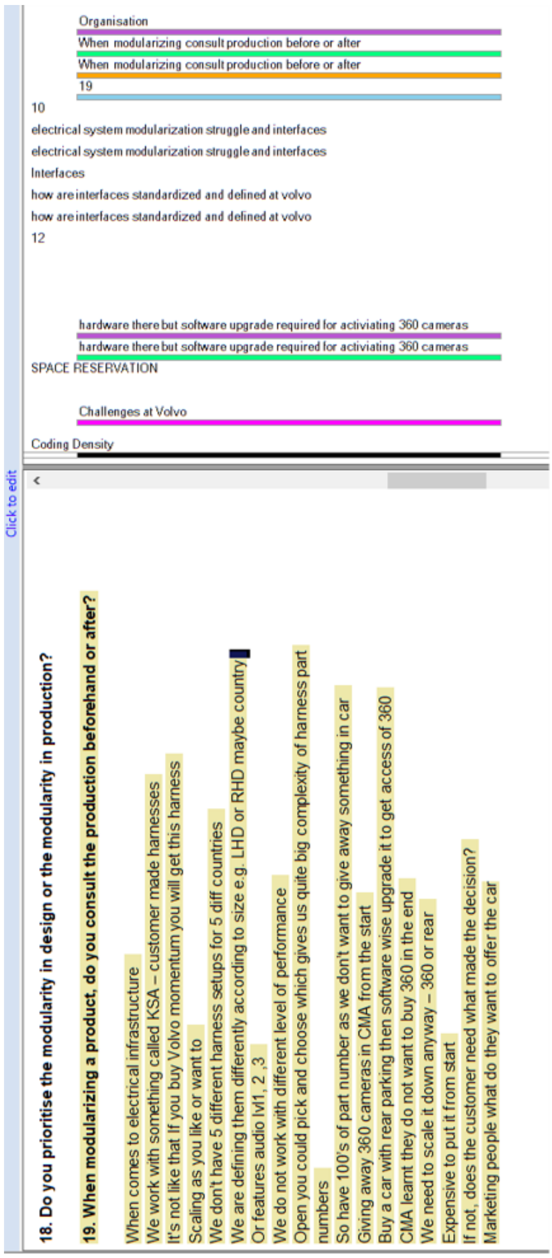


Figure E.1: Transcribed interview data coded into relevant nodes. Each color bar representing a different node, which are later used to define a theme.

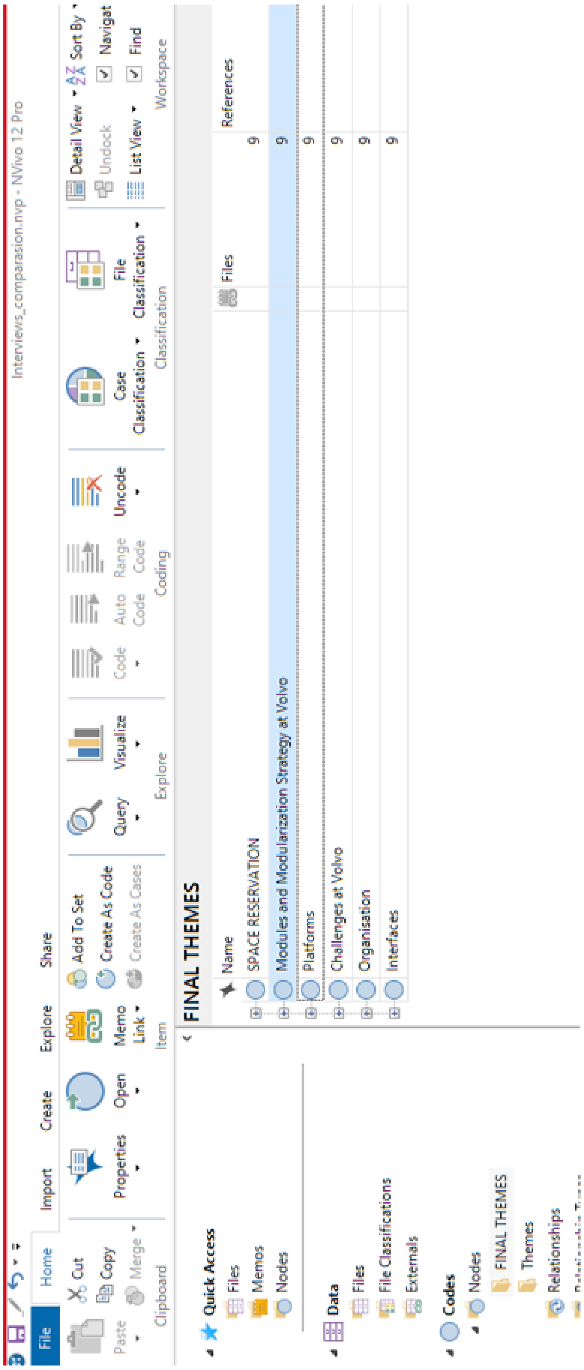
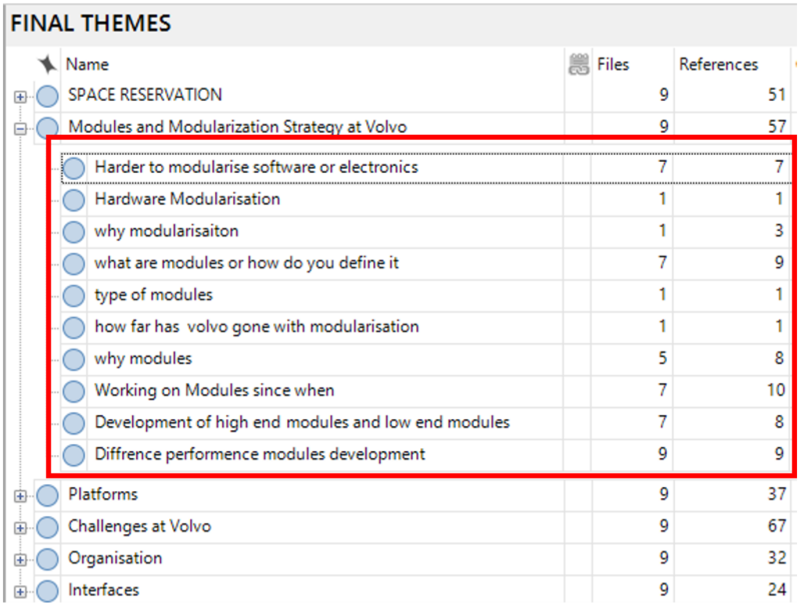


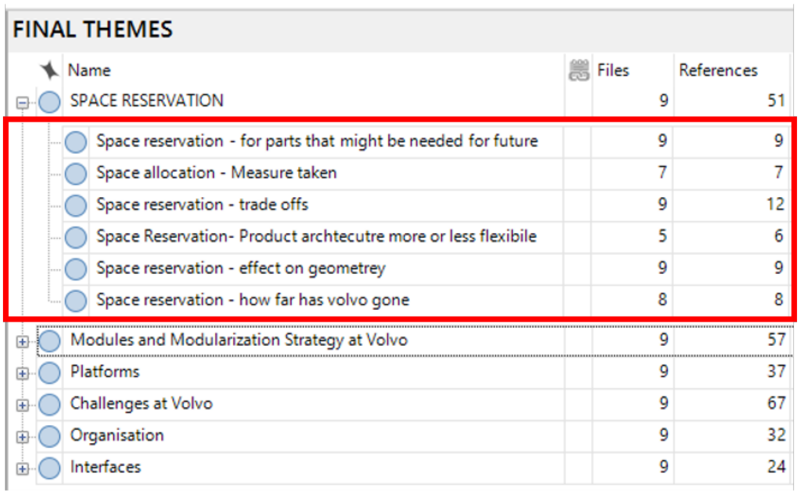
Figure E.2: Initial themes generated using Nvivo



FINAL THEMES

Name	Files	References
SPACE RESERVATION	9	51
Modules and Modularization Strategy at Volvo	9	57
Harder to modularise software or electronics	7	7
Hardware Modularisation	1	1
why modularisaiton	1	3
what are modules or how do you define it	7	9
type of modules	1	1
how far has volvo gone with modularisation	1	1
why modules	5	8
Working on Modules since when	7	10
Development of high end modules and low end modules	7	8
Diffrence performence modules development	9	9
Platforms	9	37
Challenges at Volvo	9	67
Organisation	9	32
Interfaces	9	24

Figure E.3: Expanded theme to visualise the nodes coded



FINAL THEMES

Name	Files	References
SPACE RESERVATION	9	51
Space reservation - for parts that might be needed for future	9	9
Space allocation - Measure taken	7	7
Space reservation - trade offs	9	12
Space Reservation- Product archtecutre more or less flexibile	5	6
Space reservation - effect on geometrey	9	9
Space reservation - how far has volvo gone	8	8
Modules and Modularization Strategy at Volvo	9	57
Platforms	9	37
Challenges at Volvo	9	67
Organisation	9	32
Interfaces	9	24

Figure E.4: Expanded theme to visualise the nodes coded

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