Modularization of Test Rigs

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KTH Industriell teknik och management	**Examensarbete MMK 2015:26 MKN 133** **Modularisering av provningsriggar** David Williamsson	
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Sammanfattning

Detta M.Sc. examensarbete innehåller resultatet av ett produktframtagningsprojekt som genomfördes i samarbete med *Scania CV AB* i Södertälje. Scania har en framgångsrik historia inom modularisering av fordon och var därför intresserade av att undersöka möjligheten att modularisera sina provningsriggar, för att uppnå olika typer av strategiska fördelar. Sektionen UTT (Laboratorieteknik) på Scania, där projektet genomfördes, hade dock lite erfarenhet av modularisering av produkter. Författaren av detta examensarbete identifierade därför en specifik provningsrigg och modulariserade den med hjälp av lämpliga metoder. Dessutom utvecklades en ny metod av författaren för att både kunna betrakta företagsstrategier och produktkomplexiteten under modulariseringen. Detta gjordes genom att anpassa en DSM (Design Structure Matrix) med strategier från en MIM (Module Indication Matrix), innan den klustrades med hjälp av algoritmen *IGTA++*. Resultatet av de olika modulariseringsmetoderna utvärderades och jämfördes slutligen innan den lämpligaste modulära provriggsarkitekturen valdes. Den valda arkitekturen analyserades sedan för att identifiera tänkbara strategiska fördelar som den skulle kunna möjliggöra.

Ett annat syfte med examensarbetet var att besvara forskningsfrågorna om möjligheten att kombinera en DSM och MIM, och om det i så fall skulle förbättra resultatet av modulariseringen. Målet med examensarbetet var också att förse sektionen UTT med en teoretisk bakgrund inom modularisering och systemkonstruktion.

Slutsatserna av examensarbetet är att den valda modulära produktarkitekturen har 41% lägre komplexitet (jämfört med den ursprungliga arkitekturen) och skulle dessutom potentiellt kunna öka flexibiliteten, minska risken för konstruktionsfel samt minska ledtiden (under utvecklingen) med upp till 70%. Det skulle också vara teoretiskt möjligt att återanvända upp till 57% av modulerna när den studerade provningsriggen behöver utvecklas i framtiden. Under examensarbetet identifierades också möjligheten att överföra information från en MIM till en DSM, vilket besvarade en av forskningsfrågorna. Det var dock inte möjligt att besvara frågan om det alltid förbättrar resultatet.

Nyckelord: *Modularisering, DSM klustring, Produktarkitektur, Systemkonstruktion, Gränssnitt.*

KTH Industrial Engineering and Management	**Master of Science Thesis MMK 2015:26 MKN 133** **Modularization of Test Rigs** David Williamsson

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Abstract

This Master of Science Thesis contains the result of a product development project, conducted in collaboration with *Scania CV AB* in Södertälje. Scania has a successful history in vehicle modularization and therefore wanted to investigate the possibility to modularize their test rigs as well, in order to gain various types of benefits. The section UTT (Laboratory Technology) at Scania, where the project was conducted, had however little experience in product modularization. The author of the thesis therefore identified a specific test rig and modularized it by using appropriate methods. Moreover, a new method was developed by the author, in order to modularize the test rig according to both product complexity and company strategies. This was done by adapting the DSM (Design Structure Matrix) with strategies from the MIM (Module Indication Matrix), before clustering it with the *IGTA++* clustering algorithm. The result of the different modularization methods was finally evaluated and compared, before choosing the most suitable modular test rig architecture. The chosen architecture was then analyzed, in order to determine potential benefits that it could offer.

Another purpose of the thesis was to answer the research questions about the possibility to combine a DSM and MIM, and if that would improve the result when modularizing a product. The thesis also aimed at providing the project owners with a theoretical background in the field of product modularization and System-Level design (embodiment design).

The conclusions of the thesis is that the chosen modular test rig architecture has 41% less complexity (compared with the original architecture) and could potentially increase the flexibility, reduce the risk of design mistakes and reduce the development time by up to 70%. It would also be theoretically possible to reuse up to 57% of the modules, when redesigning the test rig in the future. The thesis also identified that it is possible to transfer some information from a MIM and import it to a DSM, which answered one of the research questions, it was however not possible to claim that it will always improve the result.

Keywords: *Modularization, DSM clustering, Product architecture, System-Level design, Interface.*

FOREWORD

This chapter describes the context of the Master of Science Thesis and honors persons that has contributed with their time and knowledge during the project.

This Master of Science Thesis Project was the final stage before obtaining a M.Sc. degree in Engineering Design, at the Royal Institute of Technology (KTH) in Stockholm, Sweden. The project was performed in collaboration with Scania CV AB in Södertälje, during a 20 week period from January to June. Scania is one of the leading truck and bus manufacturers in the world and is today a part of the Volkswagen (VW) Group AG, which is one of the world's largest vehicle manufacturing groups.

I would like to thank my supervisor at KTH, Prof. Ulf Sellgren, for all valuable help and useful thoughts during the project. I would also like to thank my industrial supervisor Johan Sallnäs at Scania, for assisting the project within the company and explaining about the test rigs. I would finally like to thank the team of experienced senior engineers at Scania for providing useful feedback during the project.

David Williamsson

Stockholm, June 2015

NOMENCLATURE

In this chapter, the used nomenclature is defined.

Term	***Definition***
Component	Simple physical unit, e.g. a pump, which consists of several parts.
Interface	Surfaces or volumes creating a common boundary between two modules or parts, allowing exchange of signals, energy and material.
Modularization	Identifying the modules for a product, by decomposing it depending on company specific reasons.
Module	Physical and functional building block with standardized decoupled interfaces, which is chosen for company specific reasons.
Module variant	Alternative of a module with a certain performance or appearance.
Part	Physical unit that cannot be further decomposed, e.g. a screw.
Product family	Set of products based on the same product platform, which have specific features and functionality to satisfy different customer segments.
Product platform	Set of common components, modules, or parts from which different products can be efficiently developed and launched. Note that using common modules is not standardization.
Standardization	Reducing the number of different components, by identifying and using common components. Opposite to modularization, in terms of product variance.
Submodule	Lower level module, which could be used to build up a module/module variant.

Abbreviations

DFMA	Design for Manufacture and Assembly
DSM	Design Structure Matrix
IGTA++	Idicula-Gutierrez-Thebeau Algorithm, (clustering algorithm)
MATLAB	Matrix Laboratory, (computing software)
MFD	Modular Function Deployment
MIM	Module Indication Matrix
R&D	Research and Development

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1 INTRODUCTION

This chapter describes the background and problem description, the purpose and deliverables, the limitations and the methods used in the project.

1.1 Background and problem description

The section UTT – Laboratory Technology at Scania CV AB in Sweden, is responsible for the development of test rigs, see Figure 1, which are needed during the R&D (research and development) process at Scania. Scania is one of the leading truck and bus manufacturers in the world and is today a part of the Volkswagen (VW) Group AG, which is one of the world's largest vehicle manufacturing groups. Scania has a successful history in vehicle modularization and claims it is one of the most important reasons why they are a leading company today.

Figure 1. Example of a Scania truck and test rig

A test rig consists of several subsystems e.g. mechanical, electrical, control and measurement systems. All these systems are needed to run the test object under specified conditions and to measure desired properties. During the design of a test rig, five subsections at UTT are responsible of the development concerning their area of specialization. The subsections therefore have knowledge within mechanical design, control and measurement systems, automation and electronic systems, measurement technology and project management. The most common test rigs are the engine, transmission and strength test rigs. However, many other variants also occur.

When a new test rig is developed today, several technical solutions and subsystems are taken from similar older test rigs, in order to save material and time resources. This is however still time consuming and complicated, since the old subsystems and components normally need to be modified in order to fit the new application.

Since modularization is identified as one of the key factors to success at Scania, and is one of the cornerstones in the Scania R&D goals, the UTT section wants to investigate the possibility to modularize the test rigs as well, in order to save resources and to speed up the development time of new test rigs. The ultimate long term goal is therefore to create a modular test rig family. This could be seen as one of the next steps in the successful history of modularization at Scania.

1.2 Purpose and deliverables

The purpose of the Master of Science Thesis Project is to investigate the following bullets. Since the test rigs consist of several subsystems, covering different technical disciplines, a multidisciplinary approach is essential.

- Identify a specific test rig that is suitable for a modular product architecture, in order to save resources e.g. development time, if developing a new similar test rig in the future.
- Identify and implement suitable modularization methods for the purpose.
- Identify pros and cons if changing to a modular test rig architecture.
- Suggestion of a specific modular test rig architecture, including representation of the modules on system-level.
- Example of a module interface, including suggestion of an interface documentation.
- Evaluation of the suggested modular architecture, in terms of e.g. potential development time and cost savings, compared with the original product development methods and design.

The thesis also aims at answering the following research questions.

- Is it possible to combine a DSM (Design Structure Matrix) and a MIM (Module Indication Matrix) in order to improve the result during modularization?
- How can a DSM and MIM be combined?
- Is the provided requirement specification adequate to verify the final modular architecture?

Another purpose of the thesis is to make a clear definition of what a module is, different product architectures and how it is related to the test rigs at Scania. The result of the project, as well as the entire process, is documented in this thesis.

1.3 Delimitations

To fulfill the purpose of the project and to deliver the desired information, without overshooting any deadline, clear delimitations are crucial. Therefore the following delimitation were identified during the beginning of the project, which are consistent with the project owner demands.

Only one specific test rig will be modularized, the other test rigs will only be evaluated in terms of possible further improvements. A test rig is defined as the main systems around the test object, which means that the test cell itself, including all infrastructure systems and command room, is not a part of the test rig. The result of the thesis will therefore be a starting point in the ultimate goal of creating a modular test rig family.

Only physical components and interfaces will be used in the modularization process, therefore the different types of command and control interfaces will not be handled differently. This will only be suggested in the module interface documentation.

No redesigning, improvement or evaluation of the existing test rig design will be made, even if that might be needed to create a modular test rig. Neither will the final modular architecture be investigated in terms of system performance e.g. dynamical effects that might occur depending on module configuration.

The number of different components will not be reduced, this might however be possible in a future work.

1.4 Method description

In order to fulfil the purpose of the project, several scientific and industrial methods will be used. Some of the methods will be further explained in the Frame of Reference chapter.

To acquire the latest knowledge within the area of the project, an *information retrieval* will first be performed by using the internet, library and meetings with Scania engineers. Thereafter a *Gantt chart* will be created in order to manage the project, which follows the *Stage-gate process* that will be used as the overall project management tool. The *Gantt chart* will both be visualized in a spreadsheet and by *Visual planning* at Scania, which is a tool to visualize the planning by adding post-it notes in a timeline. The visual planning also includes *pulse meetings* to check the progress of the project and to identify problems.

A functional decomposition of a specific test rig will be made by using a function-means tree. This tool is used to understand the system (reverse engineering), in terms of function and technical solution, which is essential during modularization. By later using a *component structure diagram*, it will be possible to represent the interactions between the components, i.e. the base of the product architecture.

The modularization of the chosen test rig will be performed by using parts of the traditional *MFD* (Modular Function Deployment) method and by the *DSM* (Design Structure Matrix) method. The *DSM* method needs a clustering algorithm to calculate module candidates, therefore the *IGTA++* clustering algorithm will be used in this thesis. The clustering algorithm *IGTA++* was chosen due to its high computational speed, compared with other algorithms (Börjesson, 2012). When choosing the final modular test rig architecture, a *decision matrix* will be used in order to find the best alternative, by ranking the results of the different modularization methods according to identified criteria.

Finally, the proposed modular test rig architecture will be evaluated in terms of potential benefits e.g. development time and cost savings, compared with the original product development methods and design. This will be done primarily by calculating the *product complexity factor* of the system.

The methods presented in this section, are identified to be the most suitable for the purpose of the project. Several other options are also available, especially modularization methods. The *MFD* is a common method to modularize products, however it has a strong focus on finding modules according to company strategic reasons. Therefore a more technical approach is also needed, since the product complexity might increase otherwise. The *DSM* method offers that, and in combination with the *MFD* method, it will cover most of the different aspects during the modularization.

2 FRAME OF REFERENCE

This chapter presents the theoretical reference frame, which forms the basis of the performed Master of Science Thesis Project.

2.1 Test Rigs

Testing is normally a part during the verification stage, in a product development process. Similarly, experimenting is normally a part during research projects, the difference is the output of the test result i.e. predicting if something will break or why it is breaking.

Test rigs are used for all types of testing, for example to verify that exhaust emissions are fulfilled according to the Euro 6 standard. Therefore test rigs are widely used in the industry both during research and development.

For most products, but especially high performance one, it is crucial to predict the performance and reliability before the product is released to the market. Even if it is possible to calculate and simulate most of these aspects with mathematical models, it is still necessary to verify that the predictions correspond with reality or to get input data to the models.

Since one of the trends in product development is to shorten the time to market, it is important to shorten the testing part as well, without lowering the quality of the product. One of the most cost effective methods to perform a reliability test is with accelerated testing (Dieter & C, 2012). This type of testing involves test conditions that are severe compared with the predicted conditions, in order to acquire the test result faster.

There are many types of test rigs, which are normally custom made to test specific properties that needs to be investigated. It is therefore hard to state general things about them, however test rigs usually needs very high performance (e.g. stiffness) to measure the desired properties of the test object. They therefore tend to have an integral product architecture (not modular) and to be expensive.

2.2 Test Rigs at Scania

There are currently about 100 test rigs at Scania in Södertälje, most of them are engine, transmission and strength test rigs, however many other variants also occur. The engine test rigs are the most common type (49 rigs), followed by the strength and transmission rigs.

Engine Test Rigs

There are several types of engine test rigs e.g. functional full engine rigs, one cylinder rigs, acoustics rigs, lifetime full engine rigs and synchronization test rigs. Each of the test rigs are designed to fulfill a specific purpose during the R&D process.

An engine test rig consist of many systems, which primary purpose is to either prepare the engine for a test, simulate running conditions or to measure desired properties. The test rigs are located in test cells (rooms) that separates the test rigs and supplies needed infrastructure, see Figure 2.

When an engine (test object) is prepared for a test, it is first connected to an engine pallet outside the test cell, which later secures the engine to the floor in the test cell. A measuring box is also connected to the engine pallet, which makes it possible to connect all sensors from the engine. These steps are done before the engine enters the test cell, in order to minimize the set up time in the cell.

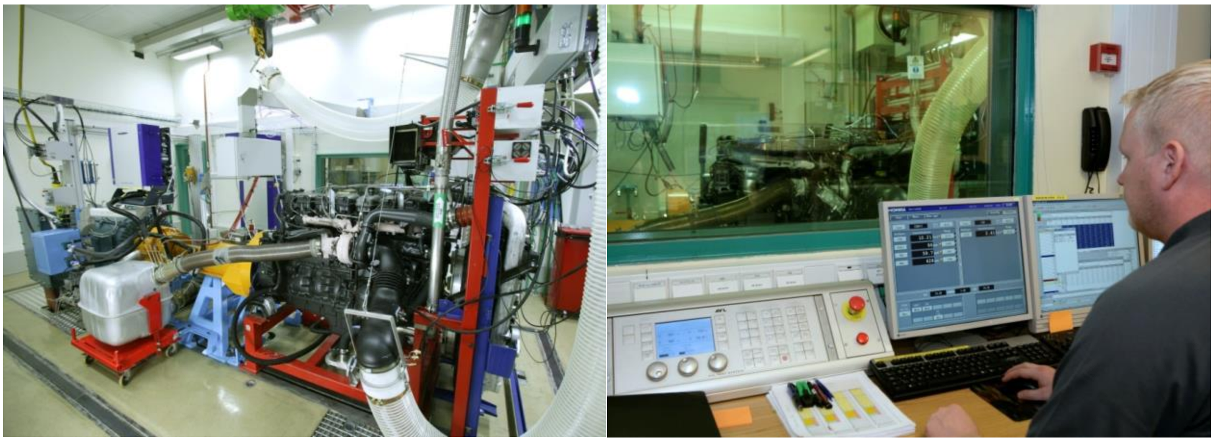


Figure 2. Engine test rig and test cell at Scania.

In a normal full engine test cell, the engine is connected to the combustion air system, fuel system, dynamometer system, cooling system, exhaust system, blow by system and the PUMA system. The PUMA system is one of the control and measurement systems that is used in the test cells.

After connecting all systems to the engine, the control system makes the final preparations for the test, with a simple command from the operator. This normally involves filling the primary circuits with coolant fluid, which is done automatically by the control system that opens and closes all valves and starts the needed pumps.

During the simulation stage, the control system is controlling e.g. all pumps, valves and fans to simulate a specific running condition. It is possible to simulate a great variety of running conditions e.g. changing the cooling effect, combustion air flow or engine torque resistance. The measurement system is at the same time recording and monitoring a great variety of measurements e.g. exhaust temperatures, combustion air humidity, exhaust particles, engine torque and fuel consumption.

The engine test rigs are used as much as possible, but at least during daytime (8 hour/day). The rigs are however designed to run nonstop.

When a new test rig is developed today, it is tailor made for the purpose, i.e. it does not have a modular product architecture. However some of the previous work (e.g. CAD models and solid mechanics calculations) and components are taken from similar older test rigs, in order to save resources. This is however still time consuming and complicated since the old systems and components normally need to be modified in order to fit the new application.

Some of the systems are currently purchased e.g. the blow by and fuel supply system. However, many of the systems or parts of them are developed in-house at Scania. The choice of developing a system in-house or purchasing it, is mainly determined by economic factors.

As an example of how much time and money that is needed to develop a new test rig, the new F16 engine test rig is here presented as an example. This test rig will mainly be used to test full engines with hybrid drive. The estimated total number of working hours that will be needed to develop this test rig is 15200 h, at an estimated salary cost of about 11 million SEK. This time and cost estimation does not include the cell building and infrastructure that is also needed. The investment cost of all material resources (e.g. pumps, valves and dynamometer system) is estimated to about 21 million SEK, including both bought and in-house developed systems.

Since the engines are constantly being developed, the demands of the test rigs are changing. Even if the basic needs are fairly constant, new systems sometimes needs to be added e.g. a hybrid transmission. One of the challenges is also that more electrical components are added, sometimes with high voltages that could interfere with the measurement equipment. This puts new demands on especially the flexibility of the new test rigs, as well as the measurement and control system.

Transmission and Strength Test Rigs

The transmission and strength test rigs are also widely used at Scania during research and development.

There are many types of transmission rigs, see Figure 3, which are used to test both single components and entire transmissions e.g. rear shaft test rig, retarder test rig, gearbox test rig, propeller shaft test rig, clutch test rig, synchronization rig. The testing normally involves life time and performance tests and therefore it is important to measure e.g. the oil temperatures, torques and sound levels.

One of the most common transmission test rigs is the gearbox test rig, which consist of an electric motor (simulating a truck engine) that is running the gearbox according to real running conditions. The gearbox output is then connected to a dynamometer (simulating the torque resistance from the wheels). The transmission test rigs also include systems that are similar to the engine test rigs systems, e.g. the cooling and control system. However some of these systems are bought, while they are designed in-house for the engine test rigs.

There are also many types of strength test rigs, see Figure 3, e.g. component shaking rig, suspension test rig, frame test rig, shaft test rig and various types of fatigue rigs.

The simulation and control part of the strength test rigs is significantly less complex compared with the engine test rigs.

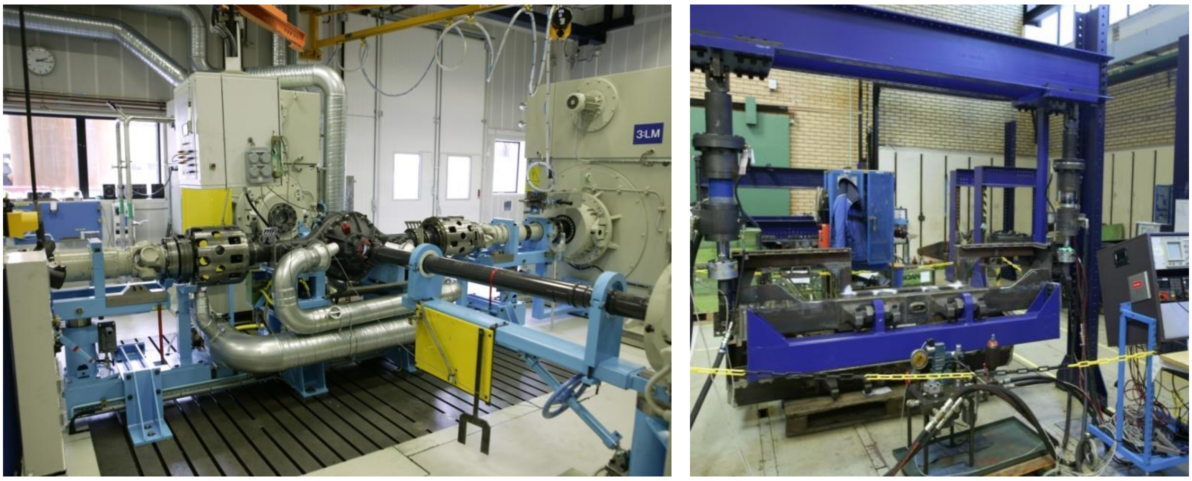


Figure 3. Transmission (left picture) and strength test rigs (right picture).

2.3 Product architectures

A product's architecture is usually defined during the *System-Level design* (embodiment design), when the functions are examined, arranged and divided into subsystems or modules.

Ulrich (1993) defined a product architecture as "the scheme by which the function of a product is allocated to physical components." Ulrich also defined it in a more formal way as: the arrangement of *functional elements*, the mapping from *functional elements* to *physical components* (also referred as technical solutions) and the specification of the *interfaces* among interacting physical components.

A functional element is one of the functions that the product should perform e.g. heat water or reduce drag. The arrangement of these functions and the interactions are normally presented in a function structure diagram, which could be a starting point when creating a product architecture (Dieter & C, 2012). The interactions (also referred as relations) are usually describe with simple terms e.g. transfer energy.

By mapping the functional elements to physical components, it is possible to see which component or components that are performing each function. If there is a direct dependency between the functional elements to physical components, the design is said to be *uncoupled*, meaning that only one component is performing each function, see Figure 4.

A practical example of an *uncoupled* design is a modern water tap with a thermostat and a flow control valve, which makes it possible to control the temperature and flow independently.

In a *coupled* design e.g. an old water tap with two control handles (hot and cold), it is not possible to change the temperature without changing the flow. This makes the controlling of the system unnecessarily complicated. Coupled designs also makes the design or redesign phase harder, e.g. it would be impossible to only redesign the cold water valve (on the old tap) without affecting the overall performance.

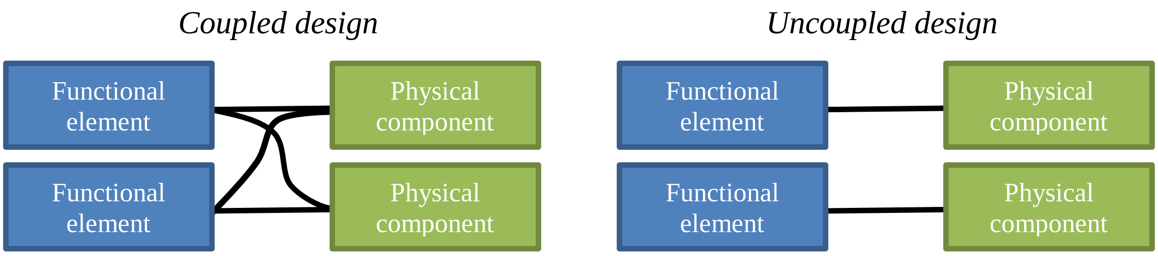


Figure 4. Coupled vs. uncoupled design.

According to the axiomatic design theory and the *independency axiom*, an uncoupled design is therefore always preferred (Silverstein, et al., 2009), mainly because it is easier to design and control.

There are two types of product architectures, integral or modular, see Figure 5. In reality there is also a possibility to have a hybrid between the two types. The product architectures will be further explained in the following sections.

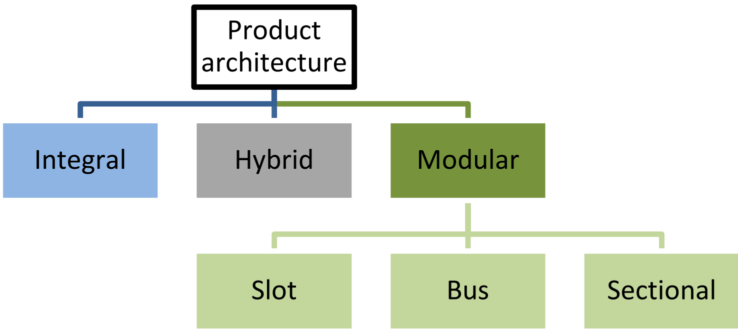


Figure 5. The different product architectures.

Modular product architecture

A modular product architecture must have an uncoupled design, otherwise the modules loses its purpose. It is therefore important to design the product according to the independency axiom.

In order to understand what a modular product architecture is, it is first necessary to define the word *module* (Close to Scania internal definition: komponentserie). The definition of a module is fairly consistent within the research area of modularization, however there is sometimes confusion in the industry, since it is loosely used in various types of everyday situations.

In this thesis a *module* is therefore defined as:

1. A physical and functional building block, performing one or several functions.
2. Has specified and standardized decoupled interfaces.
3. Is chosen for company specific reasons.

This definition is consistent with the MFD method and modular product platform definition (Erixon & Ericsson, 1999). Each module could also have different *module variants* (Scania internal definition: prestandasteg), i.e. alternatives of the module with different performance or appearance.

A module should have *decoupled interfaces*, meaning that it is possible to change between different module variants without affecting the other modules or the overall product performance (Ulrich, 1993). This is of course very complicated in practice since the interfaces will normally be coupled in some way, for example vibrations from one module will usually be transferred to the rest of the system. However, an interface is still said to be decoupled if the functionality is not affected more than acceptable.

The *interface* of a module is the surface or volume creating a common boundary between two modules, allowing exchange of signals, energy and material.

The interface documentation therefore needs to describe how the modules should interact, which normally is defined with spatial, attachment, command/control and transfer interfaces. It is of course necessary to standardize the interfaces if it should be possible to change between different module variants.

Types of modular product architectures

There are three different types of modular product architectures or types of modularity, which are based on the interfaces (Ulrich, 1993). Other definitions also occur, however this is one of the most common definitions in the field of Engineering Design.

The first type of modularity is the *slot* modular product architecture, see Figure 6. In a slot modular product architecture, the interfaces are different between the modules, i.e. interface A ≠ B. However the interface is of course still identical between the module variants within module A or B. This type of modularity can be found in a modular truck or in a car dashboard e.g. it is not possible to connect the car radio into the speedometer interface.

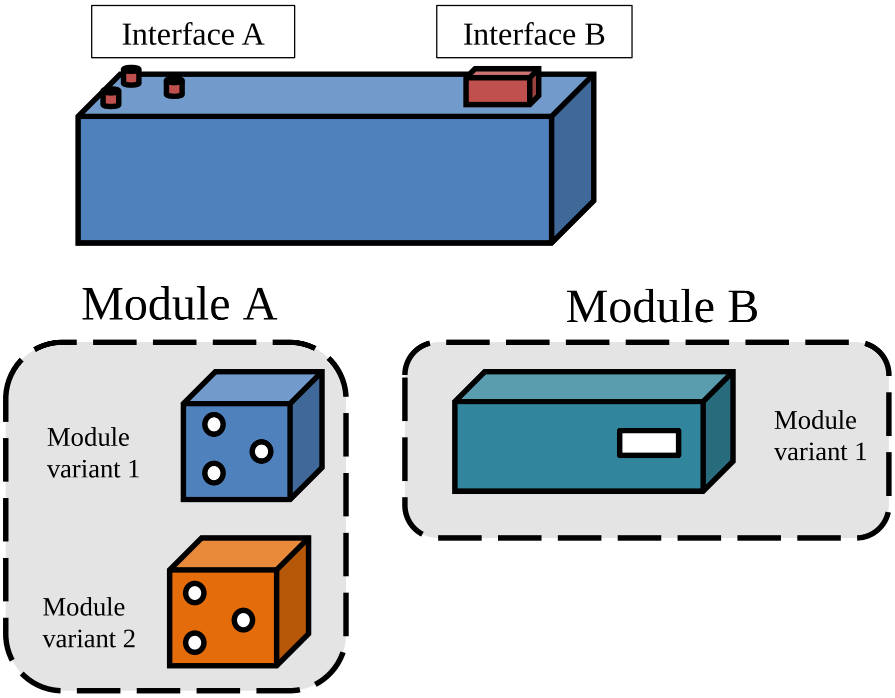


Figure 6. Slot modular product architecture.

The second type of modularity is the *sectional* modular product architecture, see Figure 7. In this type of modularity, all modules are connected via identical interfaces, and there is no common base module. An example of this type of modularity is a modular sofa, where different modules can be added to create the desired shape or dimension.

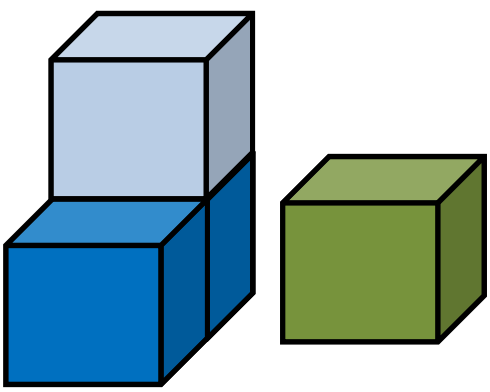


Figure 7. Sectional modular product architecture.

The third type of modularity is the *bus* modular product architecture, see Figure 8. In a bus modular architecture there is a common bus to which the other modules are connected via the same type of interface, i.e. interface A = B. This type of modularity is widely used in computers. As an example, in a USB port it is possible to connect printers and memory sticks etc. to the computer, even though they are performing totally different functions (different modules).

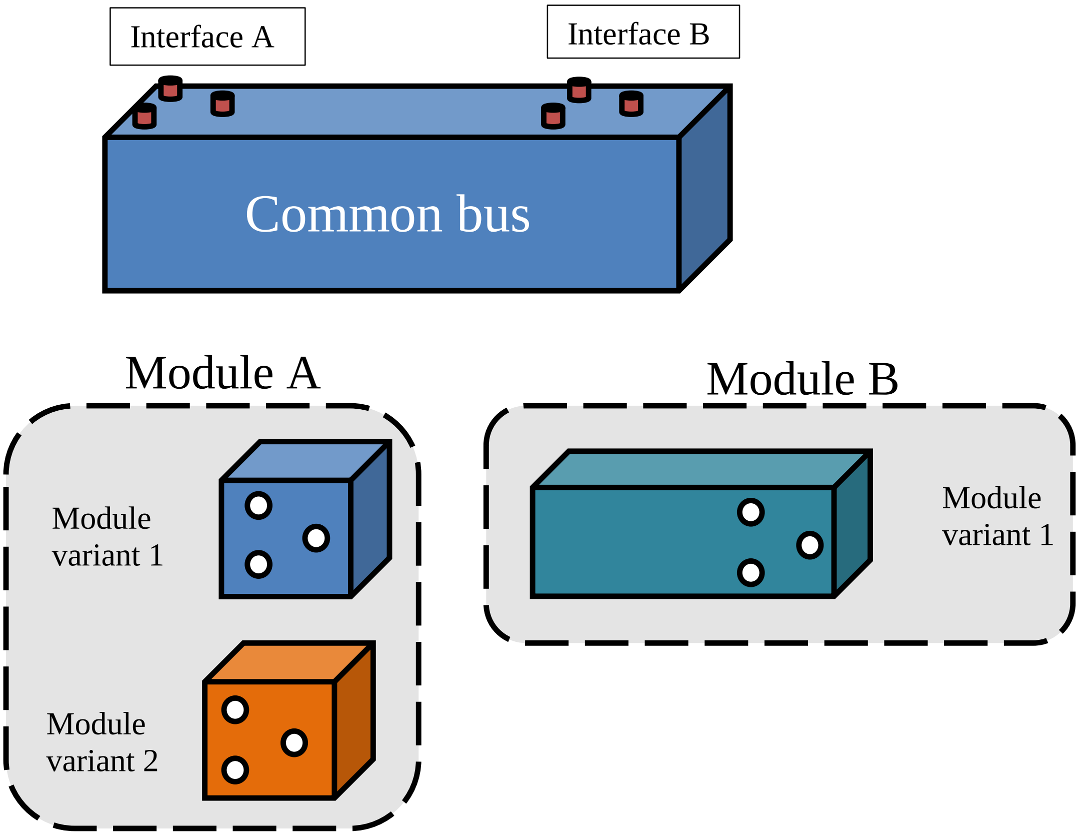


Figure 8. Bus modular product architecture.

Another example of a bus modular product architecture is the seats in an aircraft, the economy and business class seats (different modules) are attach to the same rails in the floor (common bus). This makes the aircraft highly flexible and allows the airline to change the cabin layout, in order to fit the right customer segments on a specific route.

Integral product architecture

Sometimes it is not possible to create an uncoupled or modular design, this normally occurs if the need for high performance is more important than all benefits that a modular architecture can offer.

An integral product architecture has a complex relation between physical components and functional elements, i.e. the design is coupled. This makes the design highly complex both when developing, manufacturing and assembling the product, since it is not possible to change one component without affecting the others.

An example of a product having an integral product architecture is a Formula one car. In this type of product, the performance is more important than everything else, which results in an extremely expensive and complex product, but with an impressive performance.

Product platform & family

A *product platform* is defined as a set of common components, modules or parts from which different products can be efficiently developed and launched (Simpson, et al., 2006). If a set of products are based on the same product platform, and at the same time have specific features and functionality to satisfy different customer segments, the products form a *product family*, see Figure 9.

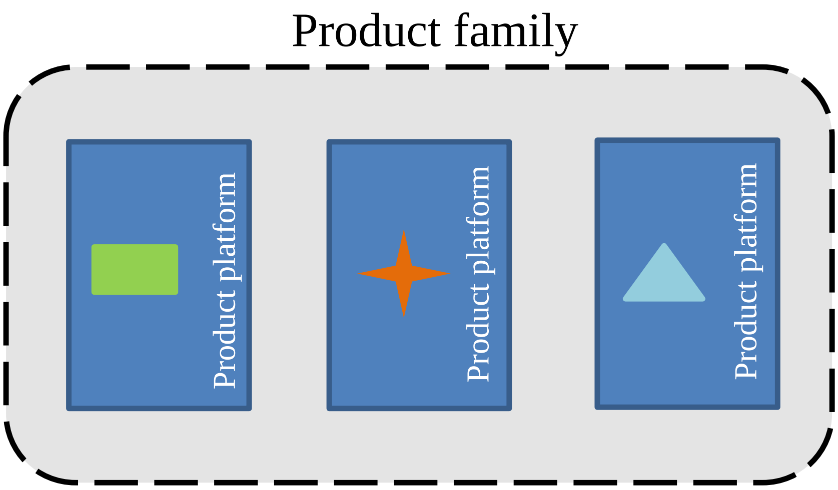


Figure 9. Example of product platform and product family.

An example of a product platform is the Volkswagen (VW) A-platform, which consists of floor/chassis modules, drivetrain, and internal cockpit modules. This product platform is shared among a wide variety of Volkswagen brands, e.g. VW, Audi, Seat, and Skoda. All cars containing the same platform forms a product family.

There are two kinds of product platforms which could be used to create a product family, see Figure 10.

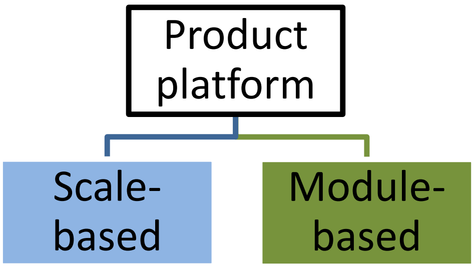


Figure 10. Scale-based and module-based product platforms.

In a *module-based* product platform, one or several modules are added or removed in order to create the desired product platform. It is then possible to add modules or components to the product platform, in order to create the end product. The final product architecture will be modular or a hybrid, depending on if other modules are added or not.

In many types of products, but especially in high performance one with an integral product architecture, *scale-based* product platforms are used.

Many aircraft manufacturers therefore use this type of product platform, e.g. Boeing, Airbus and Embraer (Simpson, et al., 2006). By scaling the fuselage and wings (scale-based product platform) of the aircraft, it is possible to create a few different alternatives to the customers, without adding too much development time or manufacturing cost, see Figure 11. An example is the Boeing 777 family, which comes in six variants (Boeing, 2015), with different flight range and seat/cargo capacity.

It is also possible to add modules to a scale based platform, the product architecture will then be a hybrid. This is done in many aircrafts as well, for example the doors and engines might be defined as modules, see Figure 11.

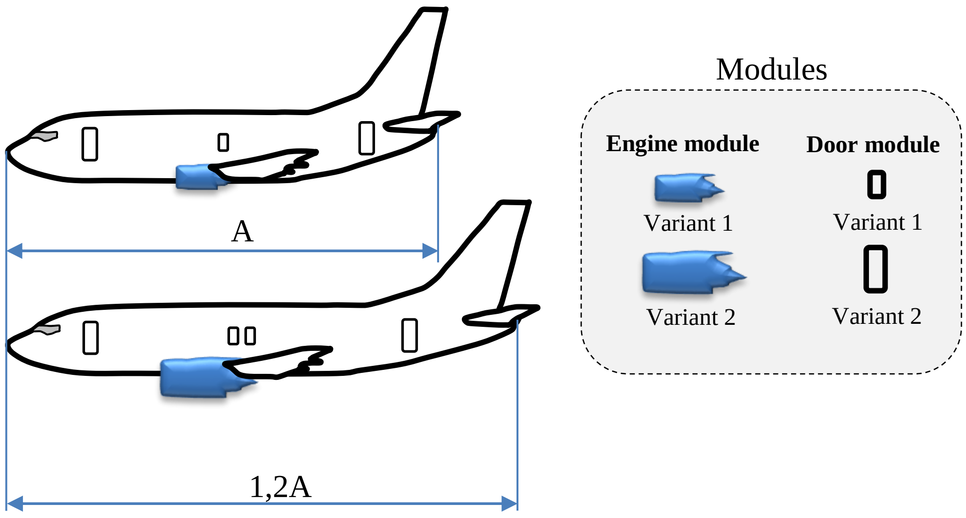


Figure 11. Scale-based product platform, with a hybrid product architecture.

Strategies with modular product architectures

During the 1920s, standardization and the Taylorism (Scientific Management) enabled an efficient production of the well-known T-ford. This resulted in a lower manufacturing cost compared with the old tailor-made cars. However the T-ford customers had no option to decide anything about the car appearance or performance, since everything was standardized, even the color.

Today the customers and market complexity is far more demanding and complex. At the same time the general product complexity has increased dramatically. The products also needs to be developed much faster in order to beat the competitors. To cope with all these problems, many of the world's most successful companies has modularized their products to some extent. Ford could therefore offer more then 3,8 million different car variants today, in order to fit a large part of the customer segments (Simpson, et al., 2006). At the same time, it does not cost a fortune to get a customized car. The cars are also developed in a much shorter time and with less work effort.

In order to mass produce a product efficiently, an internal communality of the products is required. However, an external variety is also needed to satisfy different customer segments. Modularization enables this through "mass-customization" i.e. mass production and customization at the same time (Kratochvíl & Carson, 2005).

When modularizing a product, the product complexity will also decrease, while the external variety increases. This will result in some of the benefits, but also drawbacks identified in Table 1.

Table 1. Pros and cons by using modularization, (Erixon & Ericsson, 1999).

Modular product architecture	
+ (Benefits)	**- (Drawbacks)**
High flexibility, easy to redesign some of the modules due to e.g. technology change.	***Reduced product performance***, all module variants will not be optimal in all configurations.
Reduced development time, possible to develop different modules in parallel.	***Brand "cannibalization"***, products starts to look too similar, which could damage the brand.
Reduced manufacturing time, possible to manufacture different modules in parallel.	***Easier to copy,*** a modular design makes it easier for competitors to copy the design.
Easier administration, efficient product development process.	
Mass-customization	

The main benefit with a modular product is usually mass-customization, but also the high flexibility, which allows the product to be redesign with minimal work effort. This is possible since the modules have standardized and decouple interfaces, allowing one module to be redesigned without affecting the others.

Another very important feature that modular product architectures offers is the possibility to develop the modules in parallel. This makes it possible to shorten the development time (lead time) dramatically, however it does not necessary mean that the amount of working hours will be reduced. To be able to work in parallel, when developing a complex product, an obvious prerequisite is to define the modules and interfaces. The design teams could then be grouped based on the identified modules, allowing minimal interaction between the teams, in order to develop the product as efficient as possible. As a result, the design teams may consist of people with skills in different technical fields e.g. mechanical and electrical.

Brand cannibalization is one of the drawbacks that might happen if a modular product shares to many modules within the product family. Customers then starts to see that they get the same product if they buy the basic product, instead of the high-end.

Even if designing of a product architecture is a very complex task, it is highly important since it will affect many aspects of the company and product life cycle. When modularizing a product, the modules therefore needs to be developed to fit the entire company needs and strategies. At the same time, only looking at the strategies when modularizing a product might create unnecessarily complex modules and interfaces.

Standardization vs. modularization

First of all, it is important to know that modularization is not standardization, it is in fact the opposite in terms of product variety and development process, see Figure 12.

Standardization of a product means that the number of different components are reduced, in order to gain various types of benefits e.g. reduced manufacturing or purchasing cost. However when reducing the number of components, the external variety will decrease to some extent. Standardization therefore aims at finding a product that fits all customer segments as good as possible.

Modularization of a product means that the product is divided into modules, which could be mass produced to reduce the manufacturing cost. The modules could, if they are well designed and strategically chosen, be added to create products that fits all customer segments very well (Simpson, et al., 2014). The customers could therefore be offered a product that fit their specific need, at a reasonable price.

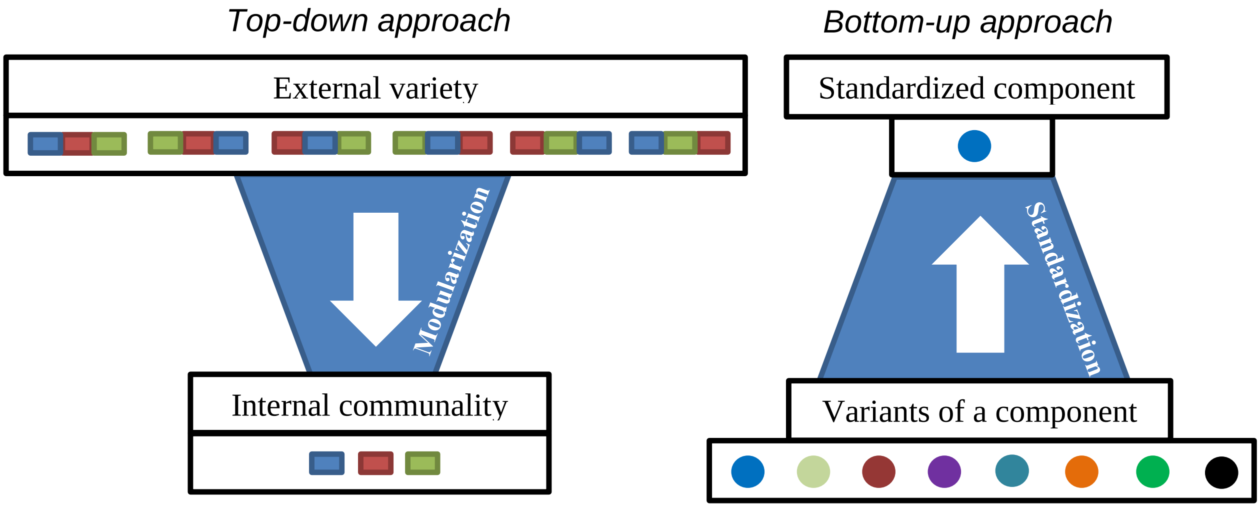


Figure 12. Modularization vs. Standardization.

Standardization is a *bottom-up* design approach (Simpson, et al., 2006), i.e. designing from the inside to the outside. This type of process is therefore used when redesigning a product by only looking at the component variety, in order to reduce it. As a result, there will be no strategic product plan.

The *Top-down* approach (designing from the outside to the inside) is preferably used during modularization. This process enables a new or existing product to be developed according to a product plan.

2.4 Modularization methods

When modularizing a product it is important to first identify a suitable method for the purpose, since there are many modularization methods available. For very simple products, it might be tempting to only reason about different alternatives in order to find a modular architecture, however this undefined process does not secure that all important aspects are taken care of.

For complex product with many types of systems (e.g. mechanical and electrical), it is simply impossible to find a low complexity, well-functioning, flexible and cost effective modular architecture without the right methods.

The overall aim for all types of modularization methods is to identify the modules, i.e. the physical and functional building blocks, with standardized decoupled interfaces, which are chosen for company specific reasons. A starting point of any modularization project will therefore be to have a great understanding of the product and the company strategies. It is important to understand that the modularization of a product will affect the entire company, including the product development process, i.e. not only the physical product.

Independently of if a new or existing product should be modularized, it is highly important to have a requirement specification. If a new modular product should be developed it is important to start thinking about modularity early in the product development process. This enables the design to be uncoupled, which is a good starting point when developing a modular product.

Function-means tree

A function-means tree is typically used during the conceptual design stage, to generate and model the mapping between functions and means i.e. technical solutions. A technical solution could both be a single component or a subsystem, while the function describes what the mean should perform, in its most general form e.g. heat water.

The decomposition of a product (Top-down approach) and its representation in a function-means tree, is usually a starting point when modularizing products. The function and means tree will have a hierarchical structure (Robotham, 2002), see Figure 13.

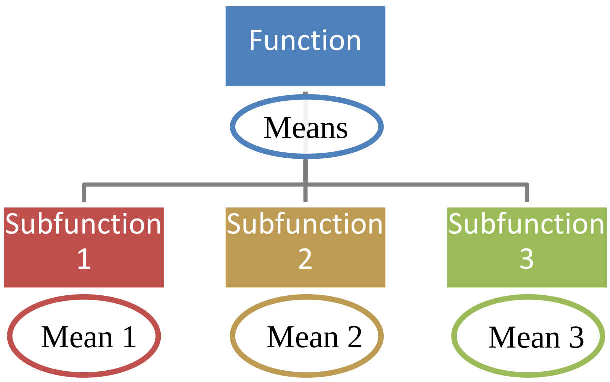


Figure 13. Function-means tree.

The level of decomposition is system dependent, meaning that there is no general way of knowing when to stop the decomposition. However, if the product is decomposed down to every screw and nut, the amount of data will probably be unmanageable and will usually not add any valuable information.

Subsystems that are bought e.g. an electric motor, is also an example when to stop the decomposition. It is of course possible to investigate all the component inside an electric motor, however the important thing when creating a product architecture is not to know the inside of the motor, the important thing is to know that an electric motor is needed to create a function. Bought components/subsystems could therefore be treated as black boxes that solves functions.

Modular Function Deployment

The MFD (Modular Function Deployment) method was originally developed by Dr. Erixon in his doctoral thesis at the Royal Institute of Technology, Stockholm, Sweden (Erixon & Ericsson, 1999). The method was created to take the company strategies and the entire product lifecycle into consideration when modularizing a product. This makes the method strongly market driven. However a functional analysis is also a part of the MFD, to evaluate and improve the design in terms of making it uncoupled.

The MFD method starts with a normal product development method, i.e. defining the customer requirements and transform them into requirement specifications via the technical solutions. The core of the MFD method is the MIM (Module Indication Matrix) which is used to identify why different technical solutions (components or subsystems) should become a module.

If using the entire MFD method, it consist of five steps, see Figure 14. The method could both be used to modularize a single product or an entire product family.

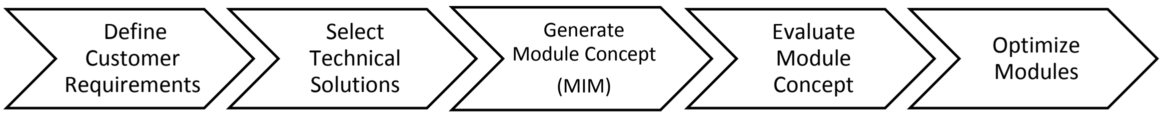


Figure 14. The Modular Function Deployment methodology.

In the MIM, each technical solution is evaluated against the *module drivers*, see Table 2. The evaluation consist of assigning numerical values, 1, 3 or 9, where 9 indicates a strong and 1 a weak driver for the technical solution.

After finishing the MIM, it is important to look for conflicts, i.e. module drivers that are contradicting each other. For example, a technical solution should not be a carryover and be planned for design changes at the same time.

When there are no conflicts in the MIM, it is possible to draw conclusions and find the module candidates by identifying the technical solutions having the highest score in the MIM. Research has shown that there is an optimal number of modules, in terms of assembly time, which occur when the number of modules is equal to the square root of the number of components (Erixon & Ericsson, 1999).

Finally, the rest of the lower weight technical solutions are grouped with the module candidates. There should be no conflicts within the module. If conflicts occur, they needs to be resolved by moving the conflicted technical solution to another module.

Table 2. The Module drivers.

Module drivers	Description
Carryover	It will be possible to reuse the component/subsystem in the next product generation. The component/subsystem is therefore not planned to be developed.
Technology evolution	The component/subsystem will likely be changed due to technology shift or new customer demands.
Planned product changes	The component/subsystem is planned to be changed due to a predefined product plan, e.g. launch of new product models.
Different specifications	It will not be possible to use the same component/subsystem to fulfill all customer demands, within the product family. Variants of the component/subsystem is therefore needed.
Styling	The component/subsystem will be important for the brand and/or will be influenced by trends and fashion.
Common unit	The component/subsystem can be used throughout the entire product family. A high common unit driver will therefore enable a large production volume.
Process/organization	Components/subsystems that will be manufactured with the same methods/process are suitable to form a module.
Separate testing	Components/subsystems that needs to be tested are suitable to form a module. This enables the entire module to be tested before the final assembling.
Supplier availability	The subsystem will be bought directly from a subcontractor, who develops and manufacture the entire module.
Service/maintenance	Component/subsystem that needs to be easily changed during maintenance or if damaged.
Upgrading	The component/subsystem will be upgraded by the customers in the future.
Recycling	Components/subsystems that are environmentally hostile are suitable to form a module. This enables an easier recycling of the product.

An example of a MIM can be seen in Figure 15. The example shows how four technical solutions has been assigned numerical values to each module driver. The pump and electric motor got the highest points after finishing the MIM, they therefore become module candidates. The module candidates has then been grouped with other technical solutions having a similar module driver pattern.

Category	Module drivers	Technical solutions: Pump	Valve	Electric motor	Sensor
Development and design	Carryover	**9**	**3**		
	Technology evolution			**9**	**3**
	Planned product changes				
	Different specifications		3	**9**	**3**
Variance	Styling				
	Common unit				
Manufacturing	Process/organization				
Quality	Separate testing	9			1
Purchase	Supplier availability				
	Service/maintenance	9		9	
After-sales	Upgrading				
	Recycling				
	Total:	**27**	6	**27**	7
		Module 1		Module 2	

Figure 15. An example of the MIM matrix.

One problem with the MFD method is that it does not form modules according to product complexity.

Design Structure Matrix

Pimmler & Eppinger (1994) introduced the DSM (Design Structure Matrix) to represent a product architecture, by inserting the relations between the technical solutions or functions (Blackenfelt, 2001) into a Product Architecture DSM. The DSM can also be used as a tool for organizing a company or processes. The product architecture DSM has been used by many successful companies e.g. when BMW in Germany developed a new concept for a hybrid vehicle architecture (Eppinger & Browning, 2012). The product architecture DSM will be referred as DSM in this thesis, since it is the only type used.

The relations in a DSM can be represented with four types; geometry, signal (information), energy and material, see Table 3.

Table 3. The relations in a DSM.

Type of relation	Two technical solution (or functions) needs to:
Geometry (g)	Be physically connection or orientation to each other.
Signal (s)	Exchange signals (all types) and data between each other.
Energy (e)	Transfer energy between each other.
Material (m)	Transfer material between each other.

By inserting the relations into a matrix, it is possible to represent complex systems in a clear and compact way. It also makes it possible to use clustering algorithms, like the *IGTA++* to calculate module candidates.

The aim is to create clusters (module candidates) that have as many relations as possible within the cluster and as few as possible between them. This allows the interfaces to be as simple as possible, for a given design. As a consequence, products with a coupled design will still have complex interfaces, even if the clustering algorithm finds the best modules for the given design.

As an example of the DSM methodology, the tangle of relations between the components (or functions) in Figure 16 needs a structured representation, therefore they are inserted into the matrix in Figure 17.

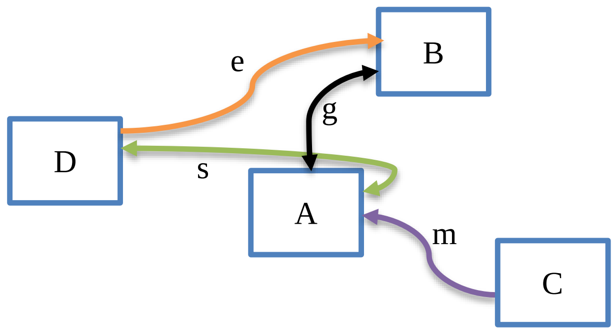


Figure 16. Example of relations between four components.

Please observe that the DSM is not symmetric ($A \neq A^T$), which makes it possible to represent each relation in one or two directions.

To \ From component	A	B	C	D
A		g	m	s
B	g			e
C				
D	s			

Figure 17. Example of a DSM, based on Figure 16.

Clustering the matrix in Figure 17 (by swapping the rows and columns by hand, or by using a clustering algorithm) yields the matrix in Figure 18.

	A	B	D	C
A		g	s	m
B	g		e	
D	s			
C				

Figure 18. Clustered DSM.

In this simple example, it is easy to see that if the components should be divided into modules, component "C" should be one of the modules since it only has one relation to the others, which makes the interface as simple as possible, see Figure 19. However in large systems with many relations, there is no obvious or easy solution, therefore clustering algorithms plays a crucial role if using a DSM to modularize a product.

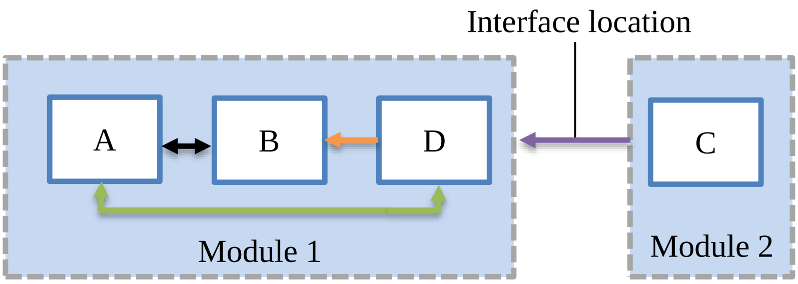


Figure 19. Representation of the modular design.

In this example all relations were equally important, it could however be argued that some relations are more important than others, e.g. a "material" relation could be three times as important as the other relations, since it might be harder to transfer material. Changing the importance of the relations will affect the result of the modularization and thereby the interface location.

The DSM method enables an objective approach to divide the product into modules. It also enables creativity and new thinking since the module proposals usually are "out of the box". It does however not take the company strategies into consideration, which the MFD method does.

2.5 Module interfaces

An *interface* is the surface or volume creating a common boundary between two modules, allowing exchange of information (usually signals), energy and material (Dieter & C, 2012).

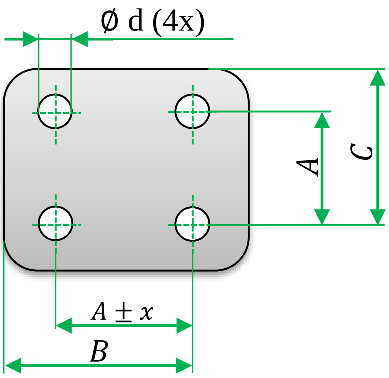
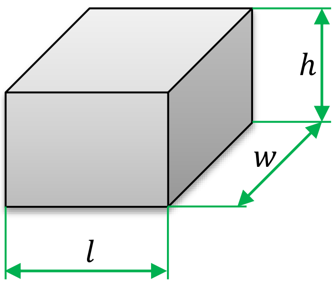
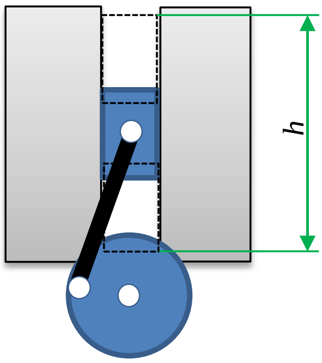
The interfaces should be designed to be as simple and robust as possible. However, if the modules are not carefully designed and chosen with suitable methods, the complexity at the interfaces will be unnecessary high, creating various types of problems and drawbacks. Earlier research has identified that there is a lack of methods to design simple and robust interfaces (Hölttä-Otto, 2005), it is however possible to use normal DFMA (Design for Manufacture and Assembly) knowledge in the design work.

When developing a complex product with many modules, the interfaces will create a communication point between the design teams. It is therefore highly important that the interfaces (and modules) are clearly defined and documented. Since the interfaces are the communication point, wrongly chosen modules will increase the amount of communication between the design teams, resulting in a less efficient product development process.

The interface documentation needs to describe how the modules should interact, which is defined according to the following points in this thesis (Simpson, et al., 2014). Examples of the interfaces can be seen in Table 4, Table 5 and Table 6.

- Attachment interface, is a fixed geometric interface between two modules.
- Spatial interface, is an interface concerning the space between two modules e.g. volumes or lengths describing the boundaries or movement.
- Command and control interface, allows transfer of information (normally signals).
- Transfer interface, allows transfer of material or energy.

Table 4. Attachment and spatial interfaces.

		
Attachment interface, with specified dimensions and tolerances.	**Spatial interface**, with specified dimensions.	**Spatial interface**, the moving piston has a spatial interface against the cylinder. (There is also a transfer interfaces transferring mechanical energy from the piston to the crankshaft via the connecting rod).

Some interfaces might follow a standard, e.g. a USB connector. The important thing is however that the interfaces are specified and remains constant over time.

Table 5. Command and control interface.

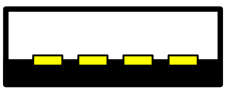
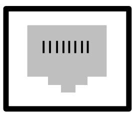
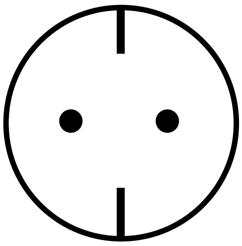
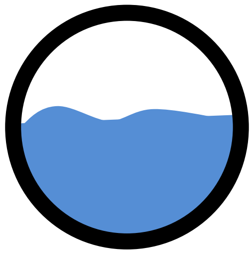
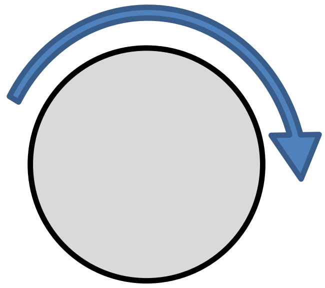
	
Command and control interface, information (signal) is transferred via a USB connector.	**Command and control interface,** information (signal) is transferred via an Ethernet connector RJ45.

Table 6. Transfer interface.

		
Transfer interface, energy (electricity) is transferred, e.g. socket CEE 7/4 AC power outlet (230 V).	**Transfer interface**, energy (heat) + material (water) is transferred, e.g. pipe ($\emptyset 40\ mm$) with a cooling water max flow of 200 l/min.	**Transfer interface**, energy (mechanical) is transferred, e.g. rotating shaft ($\emptyset 20\ mm$) with max torque 50 Nm.

The interface documentation is usually a part of the module documentation, which should contain more information i.e. the performance and strategies of the module.

The performance of the interface is also an important feature in the interface documentation. When deciding the interface performance, it is necessary to first know the performance of the entire product and then each module/module variant. It is also important to predict the performance needs for the future. Moreover the performance needs to be evaluated in terms of benefit and cost.

As an example, if a diesel engine and cooling system are identified as two modules, developed by two separate teams, the interface documentation will be the only thing that the two teams need to know about each other. The team developing the cooling system are not interested in all performance information about the engine, they only want to know which interfaces that are concerning them, and what the performance should be. From that information, the cooling system team will be able to design their system independently of the other team. Hence, the development will be effective and fast.

2.6 Evaluation methods of modular designs

It has been identified in earlier research (in the area of modularization) that there is a lack of evaluation tools for modular products (Blackenfelt, 2001). There are however methods that allows some aspects of modular designs to be evaluated. Many of them concerns development time reduction. It is also desirable to investigate other types of benefit that a modular design could offer, these benefits are highly company specific and might be hard to fully predict.

The *development time* or lead time in development, is the time interval from start to finish when developing a product. The development time could be reduced by working in parallel (independently), see Figure 20. There are many benefits by shortening the development time e.g. launching the product before the competitors.

If the design tasks are dependent, the outcome of e.g. task 1 needs to be done before task 2 could be performed, see Figure 20. However if all tasks are independent and uncoupled, there is no need to exchange information between the tasks, which is desirable.

Observe that the *design time* is not constant in Figure 20. The design time is the amount of working hours that is needed to finish a project, and is dependent of the product complexity and how the tasks are coupled.

To be able to work independently, without increasing the design time, the tasks needs to be as uncoupled as possible i.e. allowing the teams to work independent with minimal information transfer. Clear definitions and documentation of the modules and interfaces are of course also crucial to make the information transfer as efficient as possible.

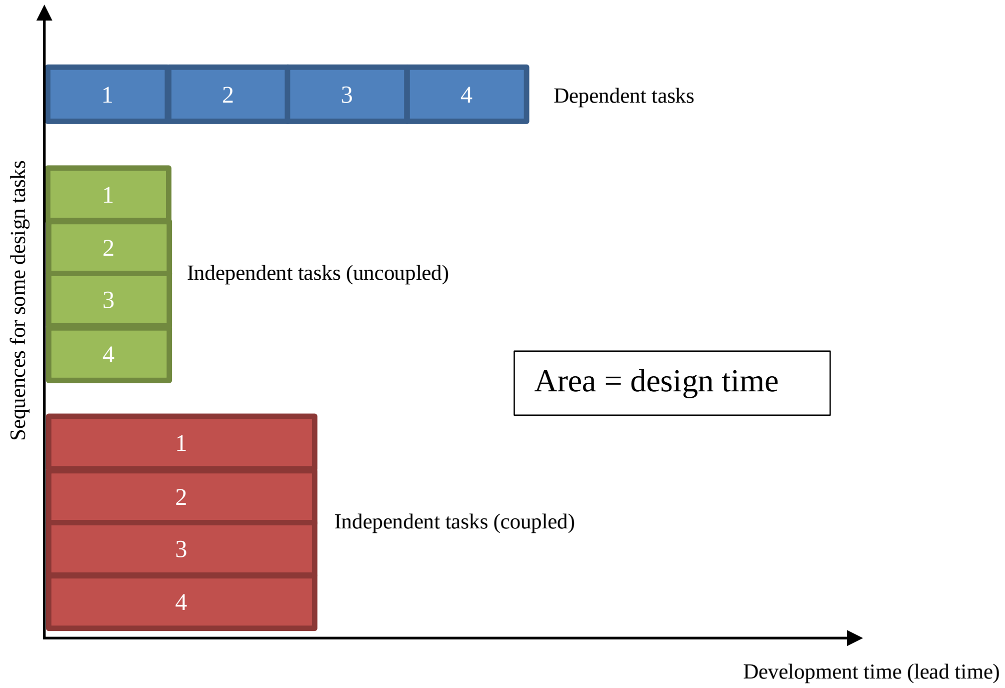


Figure 20. Product development time reduction.

If the design tasks and teams are formed according to the modules identified by the DSM method, the tasks will be as uncoupled as possible. A modular product architecture therefore enables both reduced product complexity, development time and design time. Case studies has shown that it is possible to reduce the development time by 30 - 60%, if changing from an integral to modular product architecture (Erixon & Ericsson, 1999).

The *product complexity factor* is a measure to determine how complex a product is, mainly based on the number of interfaces and modules, see equation (1). Since the interfaces are the communication point between the design teams, a low product complexity will result in a short design time, due to few and simple interfaces (Eppinger, et al., 1994). It will also reduce the risk of miscommunication, which otherwise may cause design problems.

In order to determine the product complexity, Pugh (1990) developed a measure for the product complexity factor, see equation (1).

$$\text{Product complexity} = \frac{K}{f} \cdot \sqrt[3]{N_p\ N_t\ \ N_i} \qquad (1)$$

Where K is a constant, f is the number of functions, N_p is the number of components or modules, N_t is the number of part types or module variants and N_i the number of interfaces. The number of functions will remain constant if a product is only modularized without making any design changes.

Another important feature that a modular product can offer is the possibility to reduce the *investment* and *development cost* when developing new products. The biggest measure to reduce the development cost is to use carryover modules, i.e. using an old module in a new product. In that way there is no need to spend money on salaries etc. when developing a new module.

The development cost could also be reduced by lowering the product complexity, since the product complexity affects the design time and thereby the salary cost.

The investment cost could be reduced by taking an old module and insert it into a new product. This form of cost saving might be appropriate for low quantity and expensive products that needs some development during its lifetime, e.g. a test rig.

3 IMPLEMENTATION

In this chapter the working process is described. The author has used the earlier defined methods, in order to fulfill the purpose of the project.

3.1 Identification of a Test Rig

The benefits of modularization is normally high for mass produced products, which needs to be customized. The test rigs at Scania are not mass produced, however they need to be customized and have a high flexibility. It was therefore interesting to study the benefits of a modular architecture for a specific test rig.

When choosing a test rig, it was identified during the background study to be especially interesting to investigate a test rig that covered different technical disciplines, and thereby having complex relations between the components. At the same time, it was identified that several of the systems should be developed in-house, meaning that there is a possibility to make larger changes. As explained in the Frame of Reference chapter, a product having many interfaces has a high complexity factor, meaning that there is a great possibility to reduce the complexity by modularizing the product.

The engine test rigs were identified to be the most complex test rigs, by both taking the number of components and the development time into consideration. This was also confirmed by Scania engineers.

The new F16 engine test rig is the latest test rig, and allows all types of Scania engines to be tested, but will mainly be used to test alternative fuel engines with hybrid drive. It has a clear need of flexibility and at the same time several systems are developed in-house. The F16 test rig was therefore chosen to be the studied product in this thesis.

Requirement specification

The chosen and studied test rig is a very complex system. It therefore has an extensive requirement specification created by experience Scania engineers, and contains all requirements for both the test rig and the cell. The entire requirement specification was therefore not presented in this thesis, however the most important requirements (in terms of verifying a product architecture) can be found in Table 7.

Table 7. Requirement specification of the F16 engine test rig.

Test object
Diesel engines up to 746 kW (1000 hp).
Alternative fuel engines up to 597 kW (800 hp).
A possibility to run engines with a variety of standard Scania gearboxes up to a maximum gearbox output torque of 5000 Nm.

The test rig shall be designed to run engines powered solely by electric battery or in combination with the following liquid and/or gaseous fuels: - Diesel - Gasoline - Ethanol (incl. Etamax) - Methanol - RME - Biogas	
Subsystems	
Dynamometer system	Communication between the main control system and drive equipment shall be via Profibus optical fiber.
Frequency converter	The frequency converter shall be water cooled.
	The cooling water shall be coupled in via a secondary loop which is shielded from the central water cooling system.
Engine pallet	A multi coupling between measurement box and fixture shall be used.
	The engines will be prepared as much as possible outside of the test cell, in a work shop. Cables are not allowed to lay on the floor.
Transmission	A shaft with support bearing shall be used for test objects without gearbox.
Media interfaces (interface between engine pallet and subsystems in the cell)	Transmission of media (e.g. cooling fluid) for the engine should be via an engine pallet. Plug in of media to the engine pallet shall be possible in less than 5 minutes.
	It shall be impossible to connect the wrong media for the engine pallet. Connections and tubing are not allowed to lay on the floor.
Exhaust system	An interface at 1450 mm away from the engine flywheel, located 300 mm above the floor is defined as the takeover point for exhaust from the test engine to the test cell.
Engine cooling system	The engine coolant system must be fully drainable for maintenance purpose.
Gearbox oil conditioning system	It shall be possible to connect the gearbox oil circuit or internal heat exchanger to an external conditioning device.
	Gearbox oil level shall be achieved by filling oil from a central distribution system, through the external oil conditioning device until oil flows out from gearbox level plug.
Hybrid inverter cooling system	It shall be possible to connect one or two separate electrical inverters to an external water cooling device.
Hybrid electric motor cooling system	It shall be possible to connect one or two electrical motors to one external water- cooling device.

3.2 Functional analysis

In order to understand the engine test rig (reverse engineering) and how the components were linked to the functions, a functional decomposition was performed by using a function-means tree, see Figure 21. The lowest part of the function-means tree was then used as the starting point when creating the *component structure diagram*.

As seen in Figure 21, the test rig was identified to have three overall functions; to measure the engine performance, simulate running conditions and prepare the engine for a test. The preparation function could also be used in reverse when ending the test. The white boxes under each function in Figure 21 represent the component/subsystem (mean) that solves the function.

When decomposing the sub functions one step further, several bought system were identified. These functions were marked with a green color in Figure 21, which means that they were not further decomposed.

The systems that were developed in-house were decomposed one step further, which revealed the components performing the functions. However, all specific components were not inserted into the function-means tree since it would create too much information. As a result, it was not possible to fully determine if the design was coupled or uncoupled. However, even if the design was coupled, it would not be possible to redesign it due to the boundaries of the project. The decision was therefore made to assume that the studied test rig was uncoupled.

During the decomposition, experienced Scania engineers played an important role when assisting and explaining about the different subsystems and their function. It was however still a complicated task since there was no overall system representation of the studied test rig. All specific components/subsystems were finally inserted in Table 8, and in the component structure diagram.

Function description of the chosen Test Rig

The measuring system function is to collect, transfer and process the data from the sensors or subsystems. This function is performed by the bought PUMA system and sensors that are connected via several signal boxes.

The simulation function is performed by different subsystems, which are both bought and developed in-house at Scania. The cooling system is especially interesting since it is developed in-house. The main cooling system cools the engine with a coolant fluid (water and glycol) and is controlled by the PUMA system via several valves and pumps. This enables various types of cooling conditions e.g. cooling the engine very fast or with normal cooling power. The coolant fluid is cooled via heat exchangers to the central cooling system in the building.

Other important simulation systems is the fuel, combustion air, exhaust and dynamometer system. These systems makes it possible to control and measure several of the most important properties of an engine e.g. the fuel consumption, exhaust emissions, engine efficiency and output power.

Before a test could be performed, the engine needs to be prepared for the test. This involves both manual work (e.g. installing sensors) and automated processes e.g. filling of coolant fluid and pressurizing the cooling system.

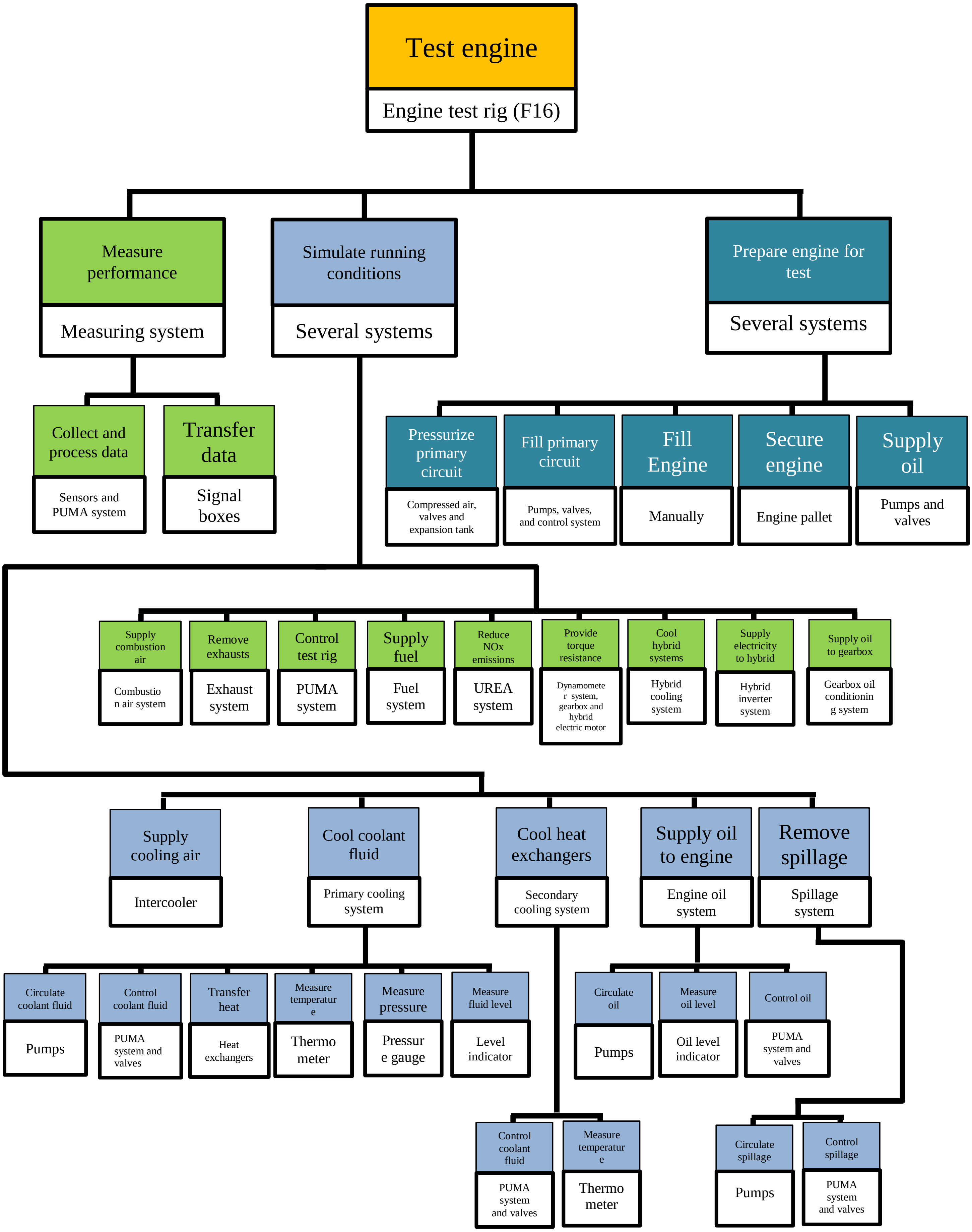


Figure 21. Function-means tree of the F16 engine test rig.

After performing the functional decomposition of the studied engine test rig, the specific components and subsystems were identified by looking at drawings and schematic diagrams of both the mechanical, electrical and control systems.

Table 8. Components/subsystems identified during the decomposition.

№	Component/subsystem name	№	Component/subsystem name	№	Component/subsystem name
1	Valve (KVMK9)	32	Valve (KVAV6)	63	Gearbox
2	Valve (KVAV3)	33	Valve (KVMKF)	64	Hybrid electric motor
3	Valve (KVIV4)	34	Valve (KVMKG)	65	Energy supply box
4	Valve (HKAVA)	35	Valve (KVMKH)	66	Signal box (A04)
5	Valve (HKAV9)	36	Valve (KVAV8)	67	Signal box (A17)
6	Valve (HKAV5)	37	Valve (KVSV3)	68	Energy supply box (A01)
7	Valve (HKAV4)	38	Valve (KVAV7)	69	Signal box + energy supply (A02)
8	Valve (HKAV6)	39	Valve (HKHV5)	70	Frequency converter
9	Valve (HKAV3)	40	Valve system 1	71	Engine (test object)
10	Valve (OLAV1)	41	Valve system 2	72	Engine pallet
11	Valve (OLAV5)	42	Valve system 3	73	ECU (engine control unit)
12	Valve (OLAV7)	43	Valve system 4	74	Intercooler
13	Valve (OLAV2)	44	Pump (OLPU1)	75	Measuring box
14	Valve (HKHV3)	45	Pump (KVPU2)	76	Hybrid inverter system
15	Valve (HKHV4)	46	Pump (KVPU3)	77	Spillage tank
16	Valve (HKIV5)	47	Sensor (KVGL1)	78	Sensor (OLGF1)
17	Valve (HKAV7)	48	Sensor (KVGL2)	79	Filter (OLFI1)
18	Valve (HKHV6)	49	Sensor (PW90)	80	Heat exchanger (KVVX1)
19	Valve (HKIV6)	50	Sensor (SSGP1)	81	Heat exchanger (KVVX2)
20	Valve (HKAV8)	51	Sensor (HKGT4)	82	Gearbox oil conditioning system
21	Valve (SYAV1)	52	Sensor (HKGT3)	83	Dynamometer system
22	Valve (SPAV3)	53	Sensor (HKGT2)	84	Dynamometer control system
23	Valve (KVIV5)	54	Sensor (HKGT1)	85	Combustion air system
24	Valve (KVIV1)	55	Sensor (OLGL2)	86	Fuel system
25	Valve (KVSV1)	56	Sensor (SPGL1)	87	Vent PLC
26	Valve (KVMKA)	57	Sensor (TW58)	88	Exhaust system
27	Valve (KVMKB)	58	Sensor (KVGL3)	89	Hybrid electric motor cooling system
28	Valve (KVMKC)	59	Pressure regulator	90	Hybrid inverter cooling system
29	Valve (KVMKD)	60	Directional valves	91	Blow by system
30	Valve (KVMKE)	61	Air Filter	92	UREA system
31	Valve (KVBV1)	62	Expansion tank	93	Measuring and control system (PUMA)

A component structure diagram, see Figure 22, was then created by investigating how the components/subsystems interacted with each other. The interactions was describe with the relations explained in the Frame of Reference chapter, i.e. geometry, signal, energy and material transfer.

The layout of the components/subsystems in the component structure diagram, is not representing the actual physical layout in reality, since the goal was to represent the relations. However, it gives a principle understanding of the test rig.

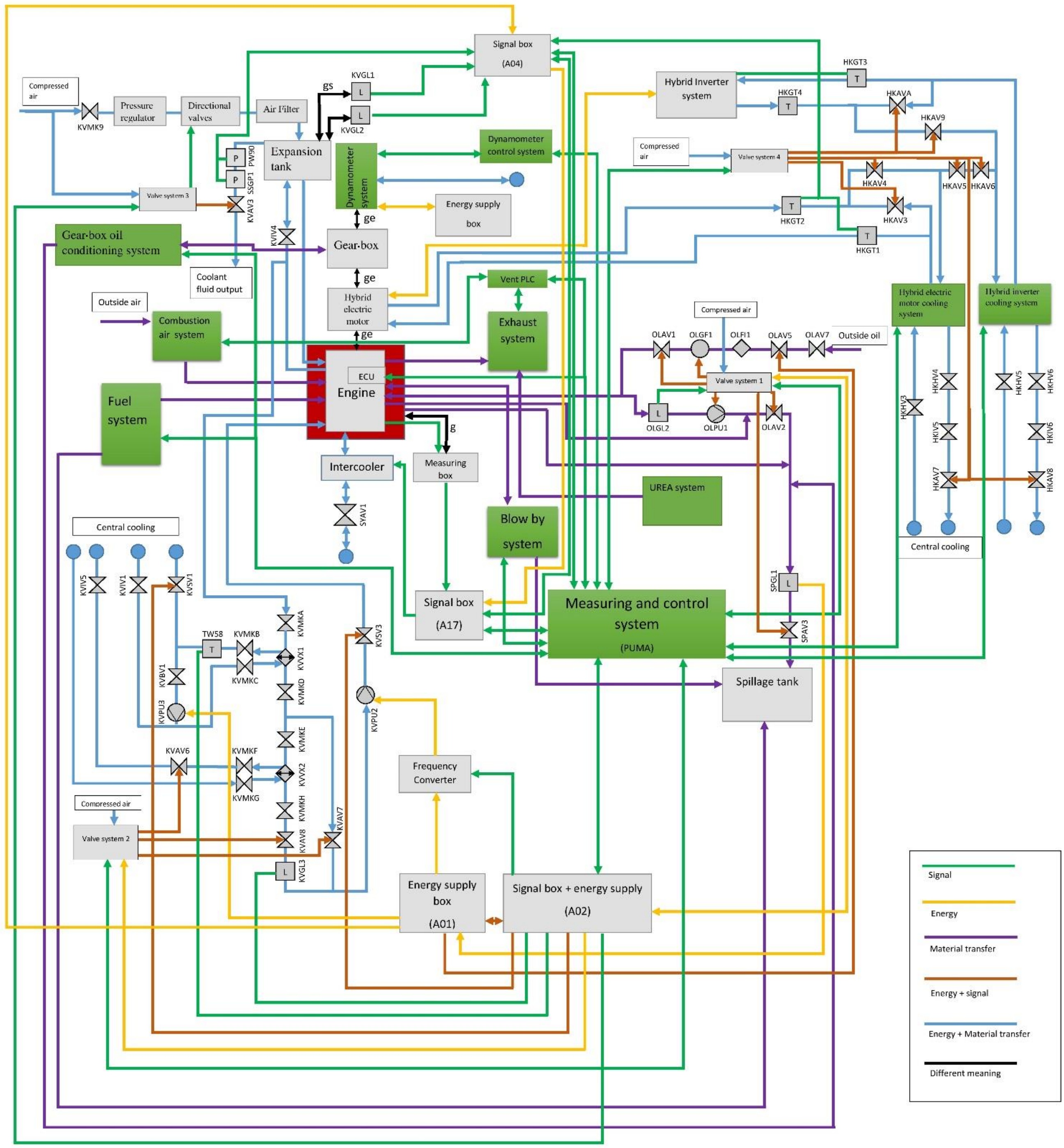


Figure 22. Component structure diagram of the F16 Engine test rig.

In Figure 22, the relation marked as “ge” means that there is both a geometry and an energy relation between the components/subsystems.

3.3 Modularization

Two independent methods were used in this thesis when modularizing the chosen test rig, in order to cover both the technical aspects and the company strategies. Previous research had identified that the combination of the MIM and DSM would be especially interesting to study further, since they complement each other (Börjesson, 2012). The decision was therefore made to create a new method that allowed some of the benefits from both methods.

The first steps in a normal product development process were not treated in this thesis, due to the boundaries of the project. Therefore the system-level design stage was of interest, since this is the stage when the product architecture is defined, see Figure 23.

It should be clarified that the chosen engine test rig was in the final stage of the development when the project started, the result of the modularization will therefore be used to identify possible improvements, if developing the chosen or a similar test rig in the future.

Figure 23. General product development process.

DSM creation

From the component structure diagram it was possible to create a DSM representing the chosen engine test rig, see Figure 24 and the Appendix chapter. After completing the matrix, it was carefully check before it was imported to MATLAB and the clustering algorithm IGTA++.

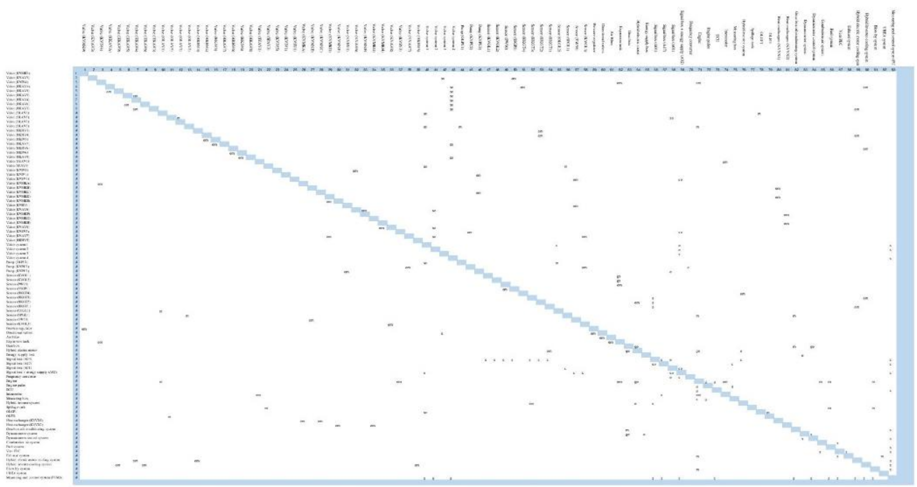


Figure 24. The DSM of the studied engine test rig.

DSM clustering

After importing the DSM matrix to the *IGTA++* clustering algorithm, two independent analyses were first performed. Each analysis had a certain relation weight (importance) of the relations, see Table 9 and Table 10.

Generally the signals and energy relations has a lower weight, since they are more portable than the material and geometry relations (Dieter & C, 2012). Therefore the weight of the signals and energy was lowered in the second analysis. After discussing the importance of the relations with Scania engineers, it was agreed to be appropriate for the studied test rig.

However it was still necessary to perform two independent analyses, in order to see how the result was affected when changing the relation weight.

Table 9. Relation weights in analysis 1.

Type of relation	Relation weight
Geometry(g)	1
Signal (s)	1
Energy (e)	1
Material (m)	1

Table 10. Relation weights in analysis 2.

Type of relation	Relation weight
Geometry (g)	2
Signal (s)	1
Energy (e)	1
Material (m)	2

Convergence was found at 600 iterations for the first clustering analysis and at 1000 iterations for the second one. The proposed modules (clusters) from the analyses, see Figure 25, were then imported to a component structure diagram (without the relations). This step was done in order to represent the proposed modules in an understandable way, see Figure 26 and Figure 27. The green modules indicates that the subsystem was bought while the red engine pallet indicates the “hart” of the test rig.

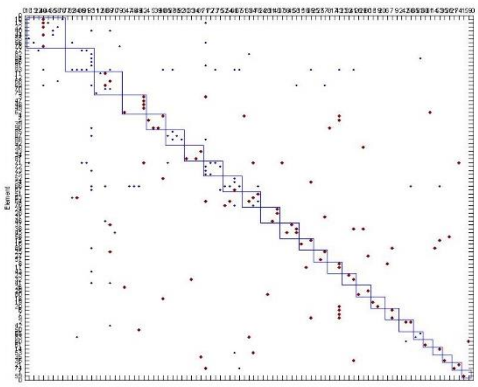
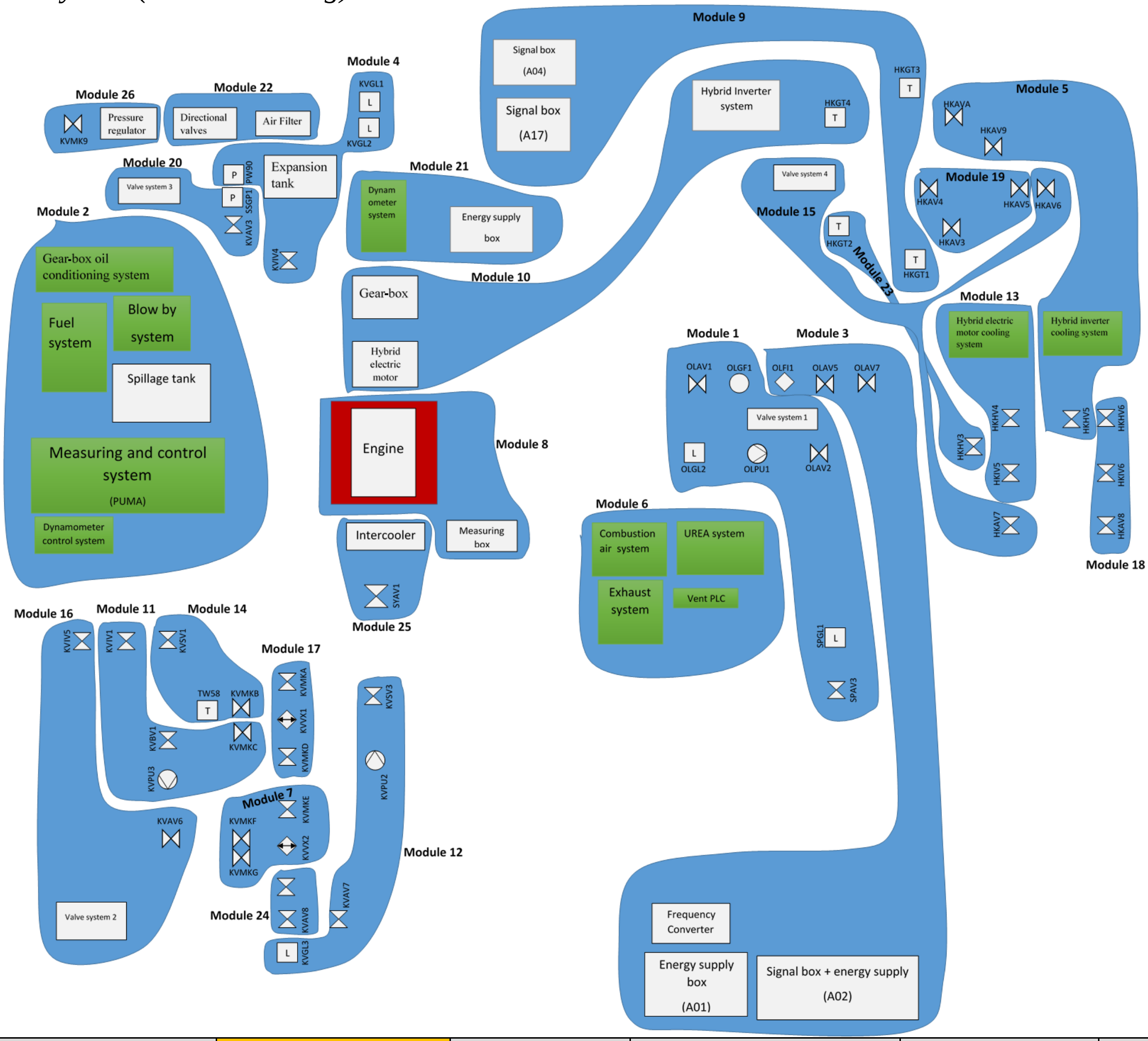


Figure 25. Result of the first clustering analysis.

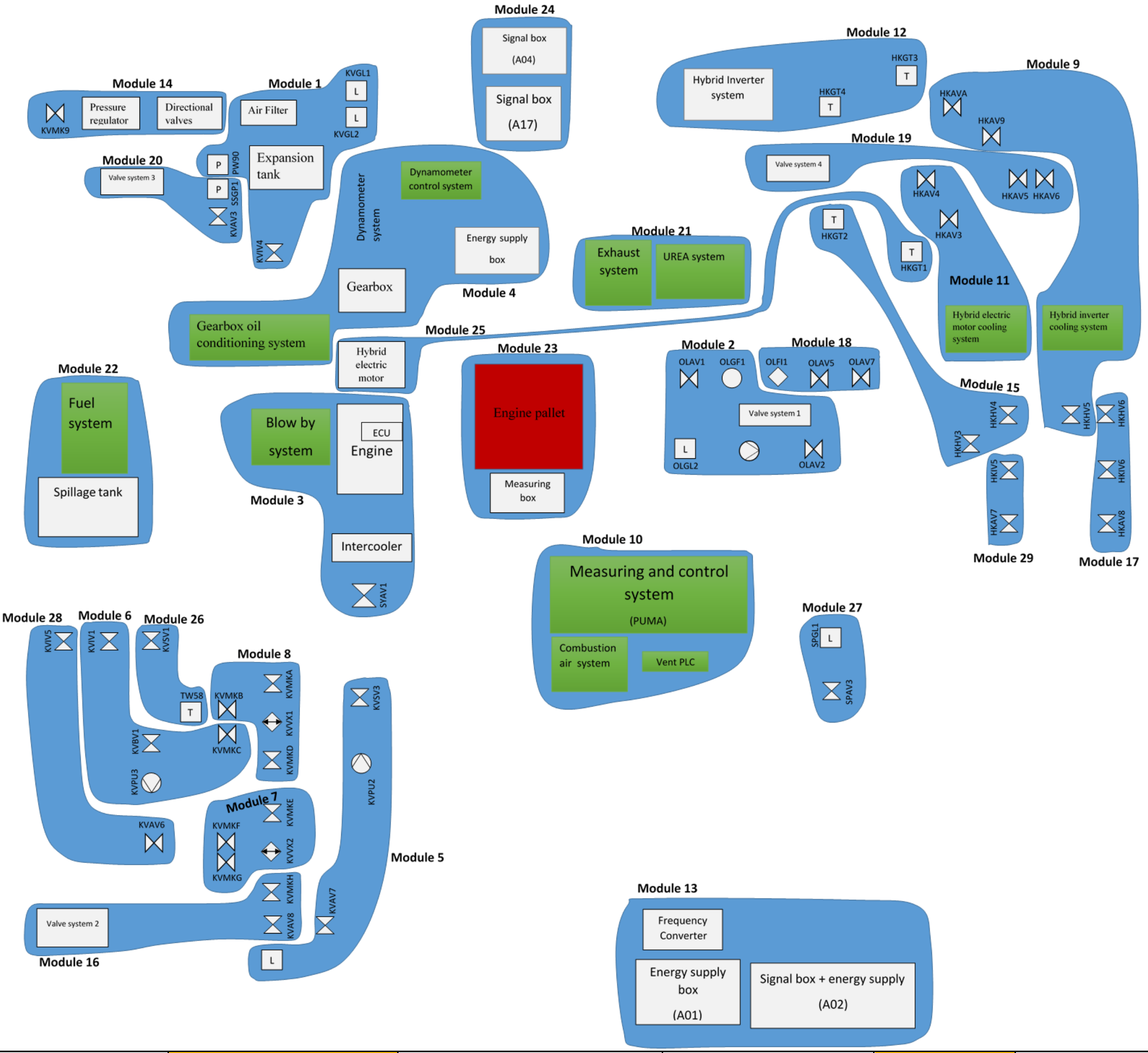
Analysis 1 (DSM clustering)



Module 1	Module 5	Module 9	Module 13	Module 17	Module 22
Valve (OLAV1) Valve (OLAV2) Valve (SPAV3) Valve system 1 Pump (OLPU1) Sensor (OLGL2) Sensor (SPGL1) Sensor (OLGF1)	Valve (HKAVA) Valve (HKAV9) Valve (HKHV5) Hybrid inverter cooling system	Sensor (HKGT3) Sensor (HKGT1) Signal box (A04) Signal box (A17)	Valve (HKHV4) Valve (HKIV5) Hybrid electric motor cooling system	Valve (KVMKA) Valve (KVMKD) Heat exchanger (KVVX1)	Directional valves Air filter
Module 2	**Module 6**	**Module 10**	**Module 14**	**Module 18**	**Module 23**
Spillage tank Gearbox oil conditioning system Dynamometer control system Fuel system Blow by system Measuring and control system (PUMA)	Combustion air system Vent PLC Exhaust system UREA system	Sensor (HKGT4) Gearbox Hybrid electric motor Hybrid inverter system	Valve (KVSV1) Valve (KVMKB) Sensor (TW58)	Valve (HKHV6) Valve (HKIV6) Valve (HKAV8)	Valve (HKHV3) Sensor (HKGT2)
Module 3	**Module 7**	**Module 11**	**Module 15**	**Module 19**	**Module 24**
Valve (OLAV5) Valve (OLAV7) Signal box (A01) Signal box + energy supply (A02) Frequency converter Filter (OLFI1)	Valve (KVMKE) Valve (KVMKF) Valve (KVMKG) Heat exchanger (KVVX2)	Valve (KVIV1) Valve (KVMKC) Valve (KVBV1) Pump (KVPU3)	Valve (HKAV6) Valve (HKAV7) Valve system 4	Valve (HKAV5) Valve (HKAV4) Valve (HKAV3)	Valve (KVMKH) Valve (KVAV8)
Module 4	**Module 8**	**Module 12**	**Module 16**	**Module 20**	**Module 25**
Valve (KVIV4) Sensor (KVGL1) Sensor (KVGL2) Sensor (PW90) Expansion tank	Engine Engine pallet ECU Measuring box	Valve (KVSV3) Valve (KVAV7) Pump (KVPU2) Sensor (KVGL3)	Valve (KVIV5) Valve (KVAV6) Valve system 2	Valve (KVAV3) Valve system 3 Sensor (SSGP1)	Valve (SYAV1) Intercooler
				Module 21	**Module 26**
				Energy supply box Dynamometer system	Valve (KVMK9) Pressure regulator

Figure 26. Result of the clustering analysis 1.

Analysis 2 (DSM clustering)



Module 1	Module 5	Module 10	Module 15	Module 20	Module 25
Valve (KVIV4) Sensor (KVGL1) Sensor (KVGL2) Sensor (PW90) Air Filter Expansion tank	Valve (KVSV3) Valve (KVAV7) Pump (KVPU2) Sensor (KVGL3)	Combustion air system Vent PLC Measuring and control system (PUMA)	Valve (HKHV3) Valve (HKHV4) Sensor (HKGT2)	Valve (KVAV3) Valve system 3 Sensor (SSGP1)	Sensor (HKGT1) Hybrid electric motor
Module 2	**Module 6**	**Module 11**	**Module 16**	**Module 21**	**Module 26**
Valve (OLAV1) Valve (OLAV2) Valve system 1 Pump (OLPU1) Sensor (OLGL2) Sensor (OLGF1)	Valve (KVIV1) Valve (KVMKC) Valve (KVBV1) Pump (KVPU3)	Valve (HKAV4) Valve (HKAV3) Hybrid electric motor cooling system	Valve (KVMKH) Valve (KVAV8) Valve system 2	Exhaust system UREA system	Valve (KVSV1) Sensor (TW58)
Module 3	**Module 7**	**Module 12**	**Module 17**	**Module 22**	**Module 27**
Valve (SYAV1) Engine ECU Intercooler Blow by system	Valve (KVMKE) Valve (KVMKF) Valve (KVMKG) Heat exchanger (KVVX2)	Sensor (HKGT4) Sensor (HKGT3) Hybrid inverter system	Valve (HKAV6) Valve (HKIV6) Valve (HKAV8)	Spillage tank Fuel system	Valve (SPAV3) Sensor (SPGL1)
Module 4	**Module 8**	**Module 13**	**Module 18**	**Module 23**	**Module 28**
Gearbox Energy supply box Gearbox oil conditioning system Dynamometer system Dynamometer control system	Valve (KVMKA) Valve (KVMKB) Valve (KVMKD) Heat exchanger (KVVX1)	Signal box (A01) Signal box + energy supply (A02) Frequency converter	Valve (OLAV5) Valve (OLAV7) Filter (OLFI1)	Engine pallet Measuring box	Valve (KVIV5) Valve (KVAV6)
	Module 9	**Module 14**	**Module 19**	**Module 24**	**Module 29**
	Valve (HKAVA) Valve (HKAV9) Valve (HKHV5) Hybrid inverter cooling system	Valve (KVMK9) Pressure regulator Directional valves	Valve (HKAV5) Valve (HKAV6) Valve system 4	Signal box (A04) Signal box (A17)	Valve (HKIV5) Valve (HKAV7)

Figure 27. Result of the clustering analysis 2.

As seen in Figure 26 and Figure 27, the result is relatively different. This was expected and shows the importance of having a cross disciplinary approach when modularizing a product.

Six of the modules were found in both analyses (marked orange), these are less sensitive to the change of relation weight and therefore has a stronger reason for being modules.

MIM Creation

In this thesis the MIM was the only part used from the MFD method, see Figure 28, since the other steps were beyond the scope of the project. However, if an entirely new test rig should be developed, the MFD method could be used from the beginning of the project, allowing the product architecture to be as uncoupled as possible.

The MIM and MFD method was first introduce to a team of experienced senior engineers at Scania. Each of the engineers then had the chance to think about the module drivers and how they could be applied to the components/subsystems, which were identified earlier during the functional decomposition, i.e. the same components as in analysis 1 and 2.

It was however hard to use this method for the studied test rig, due to the lack of strategies. The module drivers were therefore evaluated mostly based on earlier experience when developing test rigs. To really get use of this method, it is important to have clear strategies for the future, even if that is a challenging task.

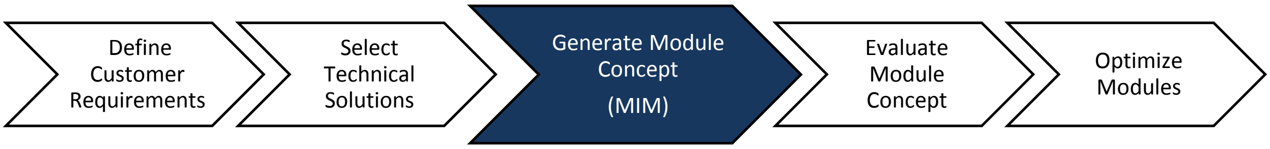
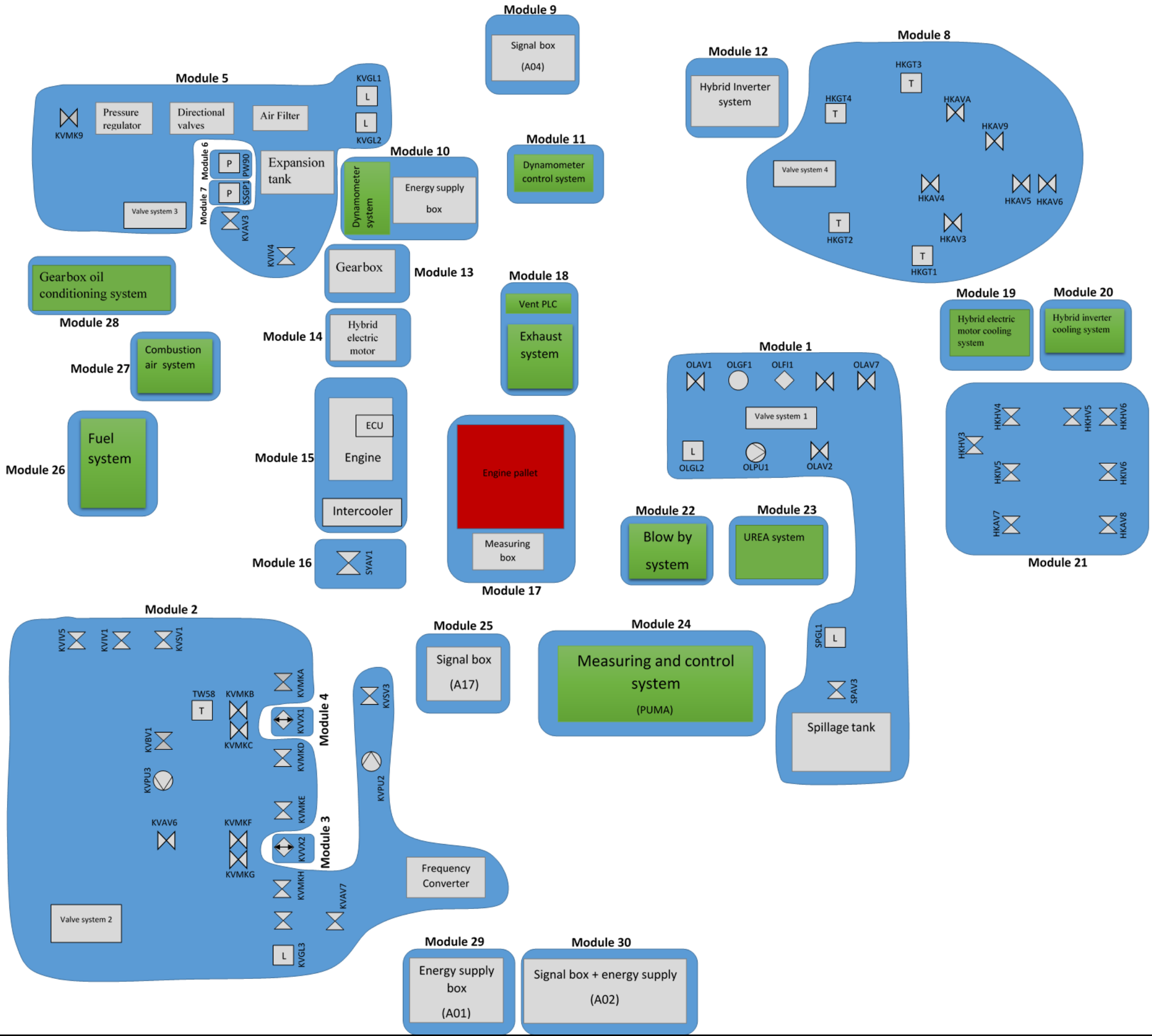


Figure 28. The main steps in the MFD method.

The final MIM was then evaluated to find module proposals, according to the methodology earlier described. The entire MIM can be found in the Appendix chapter, however the result is presented in Analysis 3, see Figure 29.

Components/subsystems that had the same module driver, were split at some places, since the modules would simply be too big otherwise. The common unit and different specification drivers were not used, since they are only used if modularizing a product family.

Analysis 3 (MIM)



Module 1	Module 3	Module 9	Module 16	Module 22
Valve system 1 Valve (OLAV1) Valve (OLAV5) Valve (OLAV7) Valve (OLAV2) Valve (SPAV3) Sensor (OLGF1) Sensor (OLGL2) Sensor (SPGL1) Filter (OLFI1) Pump (OLPU1) Spillage tank	Heat exchanger (KVVX2)	Signal box (A04)	Valve (SYAV1)	Blow by system
	Module 4	Module 10	Module 17	Module 23
	Heat exchanger (KVVX1)	Dynamometer system Energy supply box	Engine pallet Measuring box	UREA system
	Module 5	Module 11	Module 18	Module 24
	Valve (KVMK9) Sensor (KVGL1) Sensor (KVGL2) Pressure regulator Directional valves Air filter Valve system 3 Expansion tank	Dynamometer control system	Vent PLC Exhaust system	Measuring and control system (PUMA)
				Module 25
				Signal box (A17)
Module 2	Module 6	Module 12	Module 19	Module 26
Valve system 2 Valve (KVIV5) Valve (KVIV1) Valve (KVSV1) Valve (KVMKA) Valve (KVMKB) Valve (KVMKC) Valve (KVMKD) Valve (KVMKE) Valve (KVMKF) Valve (KVMKG) Valve (KVMKH) Valve (KVBV1) Valve (KVAV6) Valve (KVAV7) Valve (KVAV8) Valve (KVSV3) Sensor (KVGL3) Sensor (TW58) Pump (KVPU2) Pump (KVPU3) Frequency converter	Sensor (PW90)	Hybrid inverter system	Hybrid electric motor cooling system	Fuel system
	Module 7	Module 13	Module 20	Module 27
	Sensor (SSGP1)	Gearbox	Hybrid inverter cooling system	Combustion air system
	Module 8	Module 14	Module 21	Module 28
	Valve system 4 Sensor (HKGT1) Sensor (HKGT2) Sensor (HKGT3) Sensor (HKGT4) Valve (HKAVA) Valve (HKAV3) Valve (HKAV4) Valve (HKAV5) Valve (HKAV6) Valve (HKAV9)	Hybrid electric motor	Valve (HKHV3) Valve (HKHV4) Valve (HKHV5) Valve (HKHV6) Valve (HKIV5) Valve (HKIV6) Valve (HKAV7) Valve (HKAV8)	Gearbox oil conditioning system
		Module 15		Module 29
		Engine ECU Intercooler		Energy supply box (A01)
				Module 30
				Signal box + energy supply (A02)

Figure 29. Result of analysis 3.

The MIM was identified to be less suitable for this kind of industrial application, due to the lack of future strategies. Another problem was that the evaluation of the MIM became rather subjective, since there was not only one option that could be identified.

The result therefore became much more predictable (in a negative way) and did not support the work to find an optimal solution. Some information was however valuable from the MIM, especially the possibility to identify which technical solutions that should or should not be developed in the future.

Combining the DSM and MIM

Since there is no method of combining the two methods, a proposed methodology was developed by the author. Because the MIM and DSM contains different kind of information, they cannot be directly added. However, the proposed methodology suggests that it is possible to transform some of the information from the MIM to a "strategy transfer DSM" before adding it with the DSM, see Figure 31.

The module proposals identified in Analysis 1 and 2, had several conflicting technical solutions within the modules, based on the conflicting module drivers, see Table 11 and the Appendix chapter. To resolve the conflicts, all conflicting technical solutions were identified from the MIM and imported to the "strategy transfer DSM", see the Appendix chapter. Because the common unit driver was not used, there were only two conflicting options i.e. carryover or not carryover.

Table 11. Conflicting module drivers.

Conflicting module drivers	
Carryover	Technology evolution
	Planned product changes
	Styling
Common unit	Different specifications
	Styling

The example from the Frame of Reference chapter is presented in Figure 30 in order to explain the proposed methodology. As seen in Figure 30, the components have boundary conditions based on the module drivers, which prohibits conflicting components to have relations between each other.

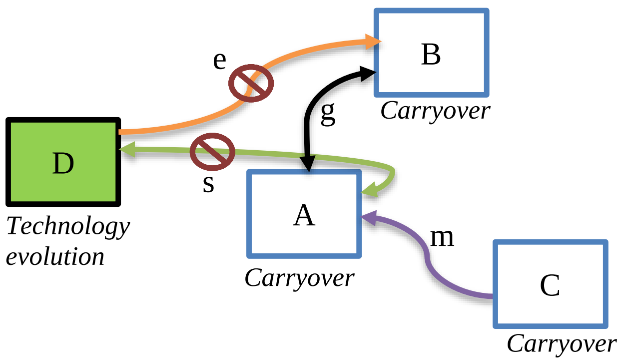


Figure 30. Example of components with relations and boundary conditions.

The “strategy transfer DSM” contains all possible conflicts between the technical solutions. All technical solutions overlapping with a negative element gets removed (during the clustering stage), after adding the DSM and the “strategy transfer DSM”, see Figure 31.

	A	B	C	D
A		g	m	s
B	g			e
C				
D	s			

DSM

+

	A	B	C	D
A				-
B				-
C				-
D	-	-	-	

Strategy transfer DSM

=

	A	B	C	D
A		g	m	
B	g			
C				
D				

Strategically adapted DSM

Figure 31. Matrix addition.

In the original clustering example (presented in the Frame of Reference chapter), component “D” was a part of module 1. As earlier described, it is not suitable to have components with different strategies in the same module, since it will result in more work when component “D” needs to be developed. However, when using the proposed methodology, component “D” was moved to module 2, after clustering the “strategically adapted DSM”, see Figure 32. The result therefore gets improved, but at the cost of increased product complexity.

	A	B	D	C
A		g	s	m
B	g		e	
D	s			
C				

Clustered strategically adapted DSM

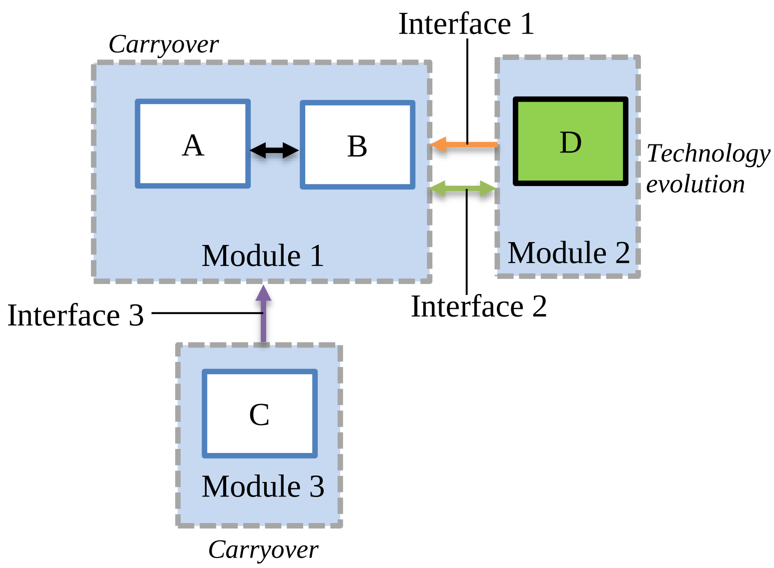
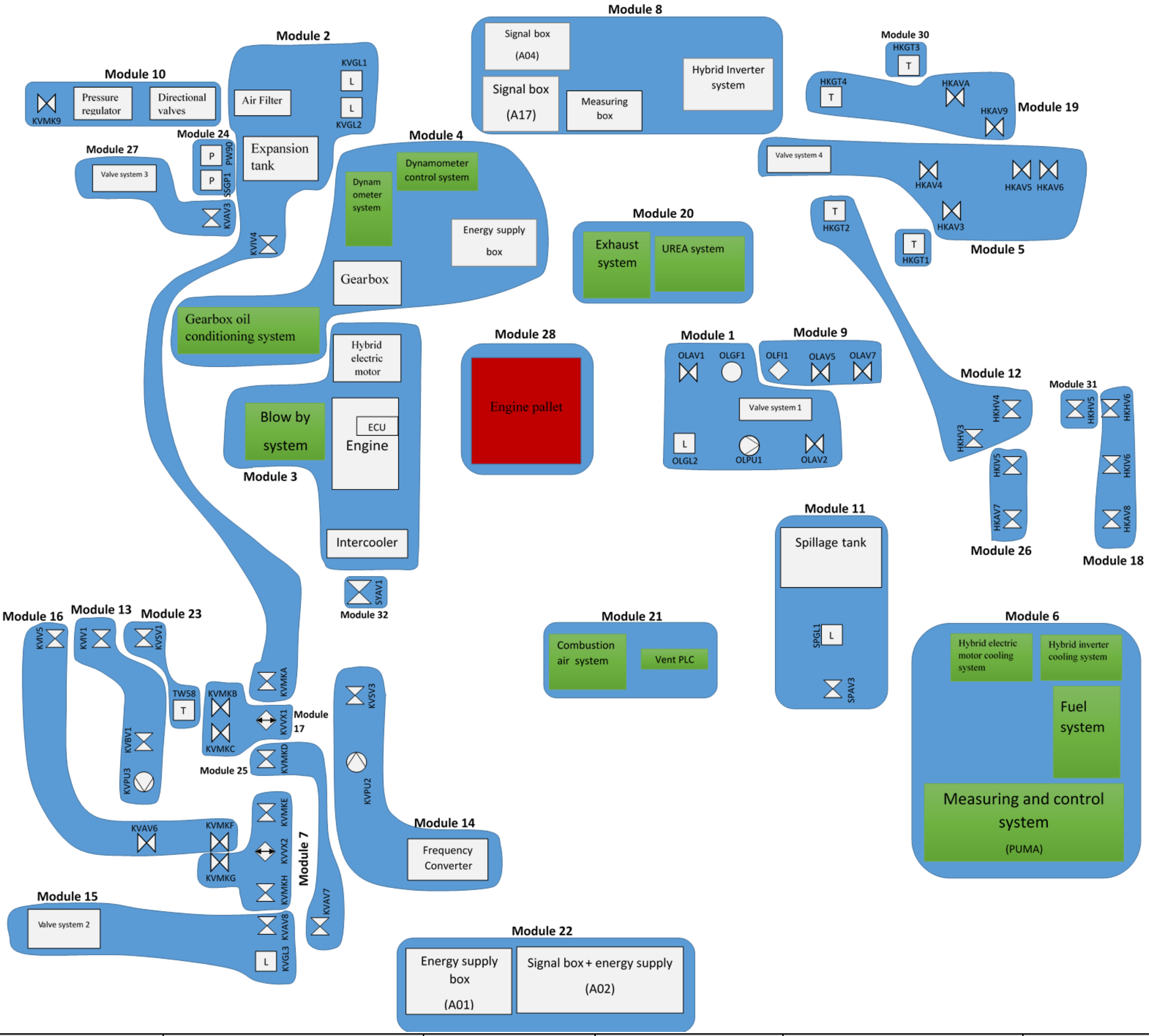


Figure 32. Module proposals from the proposed method.

In this example the product complexity increased by 108%, compared with the original example in the Frame of Reference chapter. The complexity is however still 28% less compared with if the product would have an integral architecture.

The same methodology was then performed for the studied test rig, see Figure 33. The relation weight was set to the same as in analysis 2, since it was assumed to be appropriate for the studied test rig. Convergence of the result was found at 1000 iterations i.e. the same as in analysis 2.

Analysis 4 (Strategically adapted DSM)

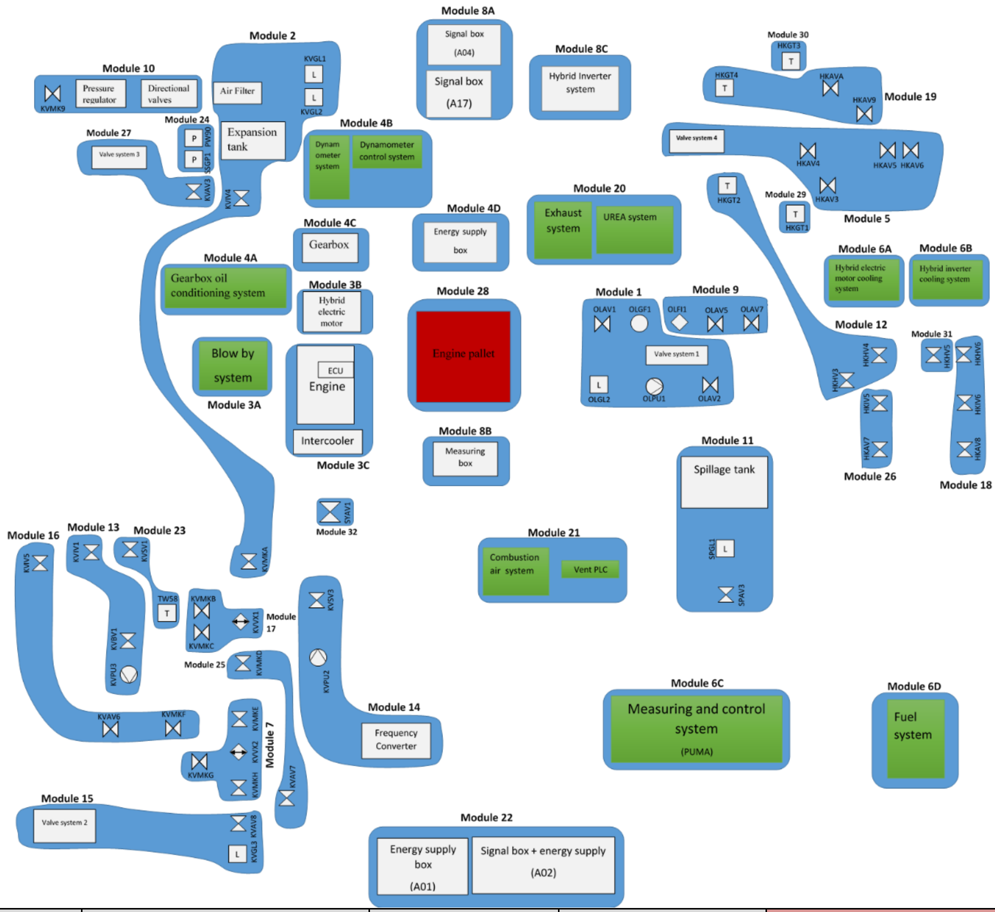


Module 1	Module 5	Module 10	Module 15	Module 20	Module 26
Valve (OLAV1) Valve (OLAV2) Valve system 1 Pump (OLPU1) Sensor (OLGL2) Sensor (OLGF1)	Valve (HKAV5) Valve (HKAV4) Valve (HKAV6) Valve (HKAV3) Valve system 4	Valve (KVMK9) Pressure regulator Directional valves	Valve (KVAV8) Valve system 2 Sensor (KVGL3)	Exhaust system UREA system	Valve (HKHV5) Valve (HKAV7)
Module 2	Module 6	Module 11	Module 16	Module 21	Module 27
Valve (KVIV4) Valve (KVMKA) Sensor (KVGL1) Sensor (KVGL2) Air filter Expansion tank	Fuel system Hybrid electric motor cooling system Hybrid inverter cooling system Measuring and control system (PUMA)	Valve (SPAV3) Sensor (SPGL1) Spillage tank	Valve (KVIV5) Valve (KVAV6) Valve (KVMKF)	Combustion air system Vent PLC	Valve (KVAV3) Valve system 3 Module 28 Engine pallet
Module 3	Module 7	Module 12	Module 17	Module 22	Module 29
Hybrid electric motor Engine ECU Intercooler Blow by system	Valve (KVMKE) Valve (KVMKG) Valve (KVMKH) Heat exchanger (KVVX2)	Valve (HKHV3) Valve (HKHV4) Sensor (HKGT2)	Valve (KVMKB) Valve (KVMKC) Heat exchanger (KVVX1)	Signal box (A01) Signal box + energy supply (A02)	Sensor (HKGT1)
Module 4	Module 8	Module 13	Module 18	Module 23	Module 30
Gearbox Energy supply box Gearbox oil conditioning system Dynamometer system Dynamometer control system	Signal box (A04) Signal box (A17) Measuring box Hybrid inverter system	Valve (KVIV1) Valve (KVBV1) Pump (KVPU3)	Valve (HKHV6) Valve (HKIV6) Valve (HKAV8)	Valve (KVSV1) Sensor (TW58)	Sensor (HKGT3)
	Module 9	Module 14	Module 19	Module 24	Module 31
	Valve (OLAV5) Valve (OLAV7) Filter (OLFI1)	Valve (KVSV3) Pump (KVPU2) Frequency converter	Valve (HKAVA) Valve (HKAV9) Sensor (HKGT4)	Sensor (PW90) Sensor (SSGP1)	Valve (HKHV5)
				Module 25	Module 32
				Valve (KVMKD) Valve (KVAV7)	Valve (SYAV1)

Figure 33. Result of the clustering analysis 4.

After analyzing the result of analysis 4, it was clear that some of the modules were very big and was not reasonable due to the testing procedures and manufacturing. The decision was therefore made to split module 3, 4, 6 and 8 into smaller individual modules. After performing the splitting, the following modular architecture was found, see Figure 34.

Analysis 5 (Strategically adapted DSM + splitting)



Module 1 Valve (OLAV1) Valve (OLAV2) Valve system 1 Pump (OLPU1) Sensor (OLGL2) Sensor (OLGF1)	Module 5 Valve (HKAV5) Valve (HKAV4) Valve (HKAV6) Valve (HKAV3) Valve system 4	Module 10 Valve (KVMK9) Pressure regulator Directional valves	Module 15 Valve (KVAV8) Valve system 2 Sensor (KVGL3)	Module 20 Exhaust system UREA system	Module 26 Valve (HKIV5) Valve (HKAV7)
Module 2 Valve (KVIV4) Valve (KVMKA) Sensor (KVGL1) Sensor (KVGL2) Air filter Expansion tank	Module 6A Hybrid electric motor cooling system Module 6B Hybrid inverter cooling system Module 6C Measuring and control system (PUMA) Module 6D Fuel system	Module 11 Valve (SPAV3) Sensor (SPGL1) Spillage tank	Module 16 Valve (KVIV5) Valve (KVAV6) Valve (KVMKF)	Module 21 Combustion air system Vent PLC	Module 27 Valve (KVAV3) Valve system 3 Module 28 Engine pallet
Module 3A Blow by system (A) Module 3B Hybrid electric motor	Module 7 Valve (KVMKE) Valve (KVMKG) Valve (KVMKH) Heat exchanger (KVVX2)	Module 12 Valve (HKHV3) Valve (HKHV4) Sensor (HKGT2)	Module 17 Valve (KVMKB) Valve (KVMKC) Heat exchanger (KVVX1)	Module 22 Signal box (A01) Signal box + energy supply (A02)	Module 29 Sensor (HKGT1)
Module 3C Engine ECU Intercooler	Module 8A Signal box (A04) Signal box (A17)	Module 13 Valve (KVIV1) Valve (KVBV1) Pump (KVPU3)	Module 18 Valve (HKHV6) Valve (HKIV6) Valve (HKAV8)	Module 23 Valve (KVSV1) Sensor (TW58)	Module 30 Sensor (HKGT3)
Module 4A Gearbox oil conditioning system Module 4B Dynamometer system Dynamometer control system Module 4C Gearbox Module 4D Energy supply box	Module 8B Measuring box Module 8C Hybrid inverter system Module 9 Valve (OLAV5) Valve (OLAV7) Filter (OLFI1)	Module 14 Valve (KVSV3) Pump (KVPU2) Frequency converter	Module 19 Valve (HKAVA) Valve (HKAV9) Sensor (HKGT4)	Module 24 Sensor (PW90) Sensor (SSGP1) Module 25 Valve (KVMKD) Valve (KVAV7)	Module 31 Valve (HKHV5) Module 32 Valve (SYAV1)

Figure 34. Result of analysis 5.

Module 3 was split into three modules, since the Blow by system (bought subsystem) and Hybrid electric motor (test object) naturally forms modules. The engine also needed to be prepared outside the test cell, which would be complicated without splitting module 3. Similarly, module 4 and 8 needed to be split due to testing procedures. Module 6 was also split into smaller modules, mainly because it consisted of bought subsystems.

After clustering the strategically adapted DSM, it was clear that all conflicting strategies which occurred in analysis 1 and 2, disappeared. The modules marked red in Figure 34 (table part) indicates that the module is planned to be developed in the near future i.e. not a carryover module. The rest of the modules are carryovers. It is therefore theoretically possible to reuse 57% of the modules, when developing the test rig in the future or a similar test rig.

Some of the modules in analysis 4 can be found in analysis 2 as well, e.g. module 4. These modules did not have any conflicting strategies within or close to the module, and was therefore not affected by the strategies. However most of the modules were affected and changed, even if the changes were relatively small.

3.4 Evaluation of the modularization

The different analyses were evaluated and compared with the original integral product architecture. It was assumed that the original test rig had a purely integral architecture, meaning that each component/subsystem generated interfaces, which resulted in a high product complexity.

All relations outside the clusters (in each analysis 1-5) was added together, according to the assumed relation weights in analysis 2, in order to determine the total number of interfaces, N_i, see Table 12. The relation weights in analysis 2 was chosen since it was assumed that geometric and material relations created more complex interfaces.

Table 12. Complexity factor inputs.

Analysis	N_p	N_t	N_i
Original design	93	55	399
Analysis 1 (DSM)	26	26	194
Analysis 2 (DSM)	29	29	190
Analysis 3 (MIM)	30	30	231
Analysis 4 (Strategically adapted DSM)	32	32	211
Analysis 5 (Strategically adapted DSM + splitting)	42	42	242

An interface having relations in both directions was also assumed to be twice as difficult as a single direction. The number of modules or components/subsystems, N_p and the number of part types or module variants, N_t was calculated by using Table 8 and the outcome of analysis 1-5.

Because the complexity factor helps to predict the change in development time, design time and the associated cost, it was calculated for each analysis, see Table 13. By comparing the complexity, it was clear that all analyses, independent of modularization method, had a much lower complexity compared with the original design.

Table 13. Calculated complexity factor for the different analyses.

Analysis	Complexity factor	Difference
Original design	127	Reference
Analysis 1 (DSM)	51	-60%
Analysis 2 (DSM)	54	-58%
Analysis 3 (MIM)	59	-54%
Analysis 4 (Strategically adapted DSM)	60	-53%
Analysis 5 (Strategically adapted DSM + splitting)	75	-41%

The complexity factor was then used as one of the criteria in the decision matrix, see Table 14. The decision matrix was used to determine which of the analyses that resulted in the overall best modular architecture. The result of the final evaluation can be found in the Results chapter.

Table 14. Decision matrix.

Criteria	Weight	Analysis 1	Analysis 2	Analysis 3	Analysis 4	Analysis 5
Few conflicting strategies	4	4	4	9	9	9
Low product complexity	5	9	9	8	8	6
Easy maintenance	3	5	5	4	6	9
Easy to move modules	2	5	5	4	6	9
Total:		86	86	96	106	111

As seen, analysis 5 scored the highest point in the decision matrix. The decision was therefore made to select it as the final modular architecture.

3.5 Identification of interfaces

In order to describe how an interface documentation might look like, module 14 and its interfaces was identified from the selected modular architecture. Module 14 was chosen since it contains both mechanical and electrical components, which makes the interfaces extra complex.

As earlier described, the interface documentation is only a part of the more extensive module documentation. The module documentation was not investigated in this thesis due to the chosen delimitations.

Module 14 has four relations to four other modules, see Figure 35. Each of these relations creates a need of an interface. The interfaces needs to be designed and standardized in order to create the final modules. The design of the interfaces of module 14 can be seen in the Results chapter. Observe that the frequency converter was a part of module 22 before the strategies were added, see analysis 1 and 5. As a consequence, some of the interfaces therefore became more complex. This indicates the importance of choosing suitable relation weights and strategies.

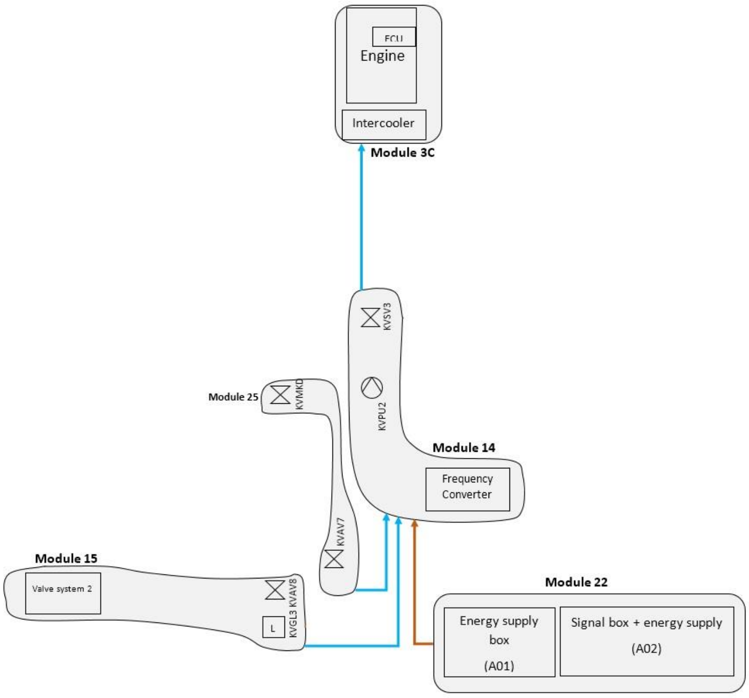


Figure 35. Interfaces to module 14.

4 RESULTS

In this chapter the results are collected, analyzed and compared with the existing knowledge presented in the Frame of Reference chapter.

4.1 The final modular architecture

The final modular test rig architecture can be found in Figure 36. In order to see how the modules interacted with each other, the relations were inserted in the same way as in the component structure diagram.

By investigating the "flow" of the relations, it is possible to see how the weight of the relations has influenced the final result. For example, there are few strong relations between the modules e.g. material + energy (marked blue) and many weak signal relations (marked green). This is reasonable and was preferred, since it is a lot easier to e.g. transfer signals than material.

It is also possible to see how the signals are transferred from the source to the target. For example, module 1 works as a router, forwarding the signals from module 22 to module 11.

The relations in Figure 36 also indicates where an interface is needed, which obviously is required before designing the modules and interfaces. Observe that the shape of the modules in Figure 36 does not show how the modules should look like in reality, since it is only a system representation.

As explained in the Frame of Reference chapter, there are three different types of modular product architectures. The chosen modular test rig architecture will have a slot modular architecture, since the interfaces will be different between the modules. However, it might be possible that some of the modules will have submodules, with a bus modular architecture. It is also possible that some of the modules will have an integral architecture. The overall product architecture will still be modular, independently of what architecture the modules have.

By investigating and comparing the modules identified in the final modular design, with another modularized test rigs, it might be possible to find a common set of modules. These modules may create a module-based product platform, which later could be used to form a modular test rig family. These steps were beyond the scope of the project, and is therefore a potential future work.

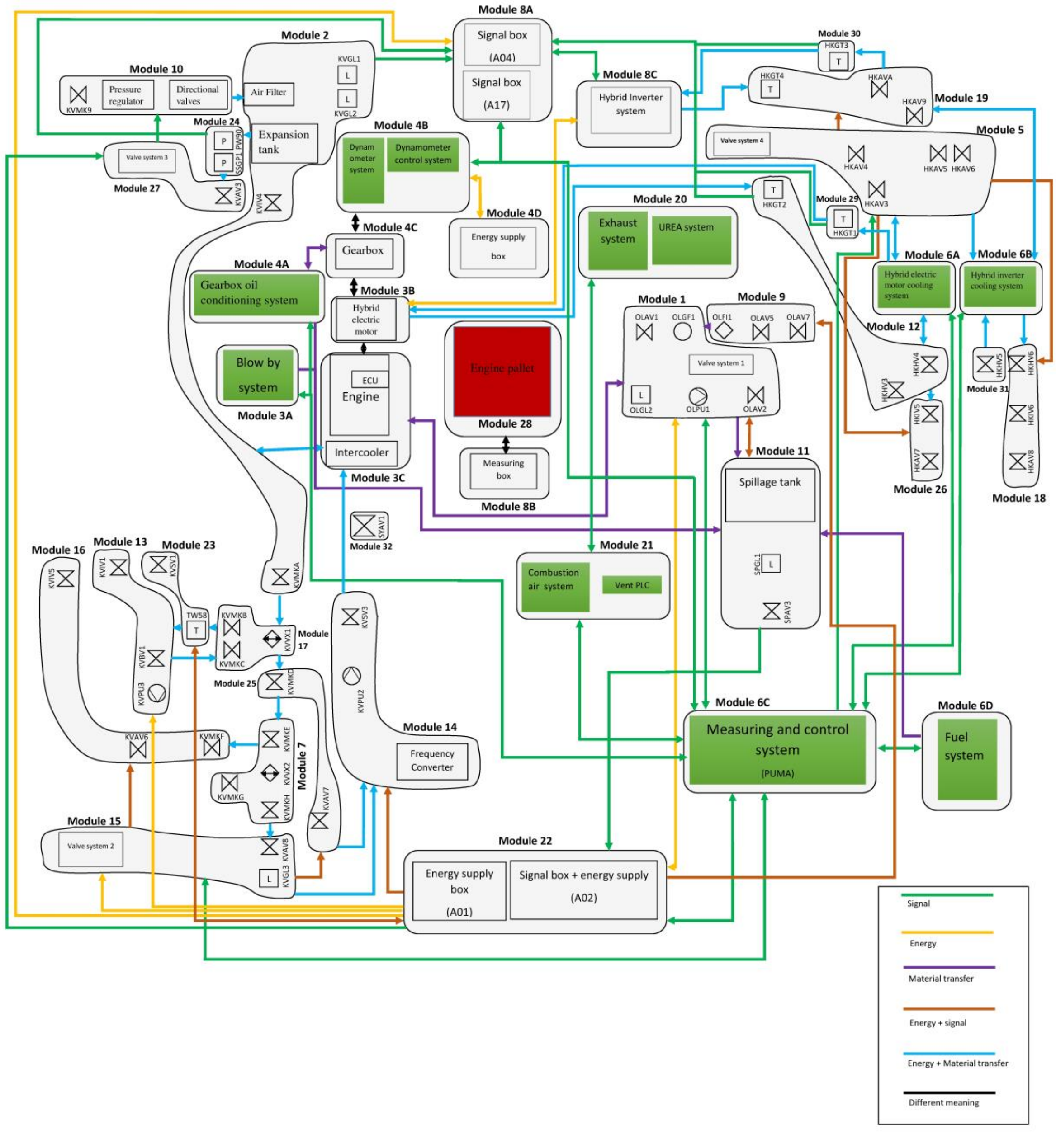


Figure 36. The final modular architecture.

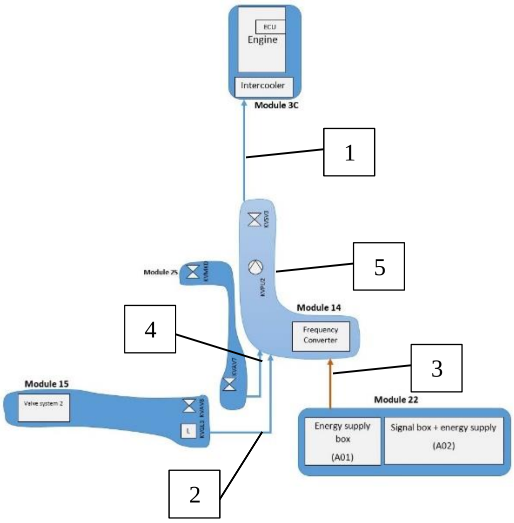
4.2 Interface documentation

A proposal of an interface documentation can be found in Figure 37. Notice that the appearance of the modules and specification of the interfaces, only is a suggestion, due to the boundaries of the project.

In reality the modules might have a totally different appearance depending of the shape and size of the components, as well as how they are arranged. Also observe that the internal interfaces in the modules does not need to be standardized, unless there is a reason to create submodules. As earlier explained, there are four types of interfaces, see the Frame of Reference chapter. The interface types are specified in the interface documentation, as well as other important information.

Interfaces to module: 14					
Interface No.	Interfacing with	Type of interface	Type of relation (DSM)	Transmitting	Responsible
1	Module 3C	Transfer	Energy + material	Coolant fluid	UTTD
2	Module 15	Transfer	Energy + material	Coolant fluid	UTTD
3	Module 22	Transfer + Command and control	Signals + energy	Signals+ High and low voltage electricity	UTTE
4	Module 25	Transfer	Energy + material	Coolant fluid	UTTD
5	Wall	Attachment	-	-	UTTD

Overview:



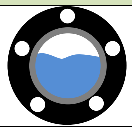
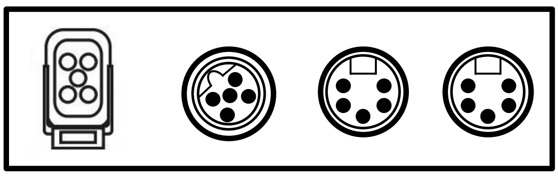
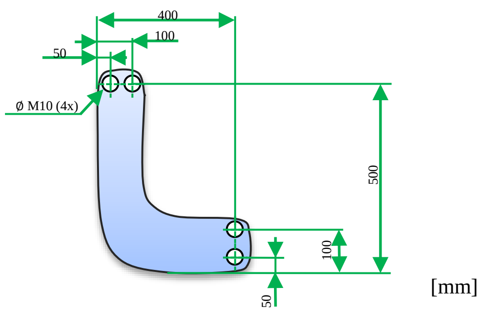
Interface No.	Appearance	Interface specification
1, 2 & 4		Flange coupling, $\emptyset 76\ mm$ fastened with 5 x M10 screws. Capable of handling coolant fluid.
3	 Line supply connection / PROFIBUS connection / DC24V / AC24V + signals	<u>Line supply connection</u> HAN Q4/2 socket (Female), 380 - 500 V 3 AC. <u>PROFIBUS connection</u> PROFIBUS M12 socket (Female), Max 12 Mbit/s. <u>DC24V</u> 5-pole 7/8" socket (Female), 24 V DC. <u>AC24V</u> 5-pole 7/8" socket (Female), 24 V AC + two-way analog control signals.
5		4 x M10 screws.

Figure 37. Proposal of an interface documentation.

4.3 Evaluation of the modular architecture

The chosen modular test rig architecture enables many types of benefits, see the following sections. As earlier explained, these benefits are highly company specific and therefore needs to fit the company strategies.

One of the potential drawbacks is the reduction in overall test rig performance, e.g. measurement accuracy and precision. Since the performance is the single most important objective, it needs to be evaluated before modularizing the test rig in practice. If the performance cannot be achieved by the modular architecture, the test rig will need to have an integral product architecture.

High flexibility

By modularizing the studied test rig according to the chosen architecture, it will be possible to redesign the technology evolution modules, without affecting the 57% of carryover modules, see Figure 34. Hence, the redesign can be performed with minimal work effort and in a short time, when the demand of the test rig is changing. Using carryover modules could therefore be an important measure to lower the development cost of future test rigs, as well as lowering the development time.

Reduced risk of design mistakes

Since the complexity of the chosen modular architecture is lower than in the original design, the risk of miscommunication between the design teams will be reduced, due to less communication points. By using a common interface documentation, the risk will also be reduced.

Easier administration

The interface documentation will make the handling of information between the design teams easier. By using a standard interface documentation and the nomenclature defined in this thesis, less time can be spent on communication problems.

Reduced development time

The product development time (lead time) for the studied test rig was estimated to about 24 month, see Figure 38. Since there were 14 employees, each capable of working 150 h/month, they spent in average 30% of their full-time employment on the project. It would however been desirable that everyone worked 100% during the entire project, in order to lower the development time.

If all employees would have worked 100%, i.e. only working with one project at a time, it would have been theoretical possible to lower the development time to 7,2 months, i.e. a 70% reduction. This estimation is based on the assumption that the same amount of design time is needed to finish the project and that everyone could work in parallel during the entire project. It would also mean that all employees could perform all tasks, which may not be the case in reality.

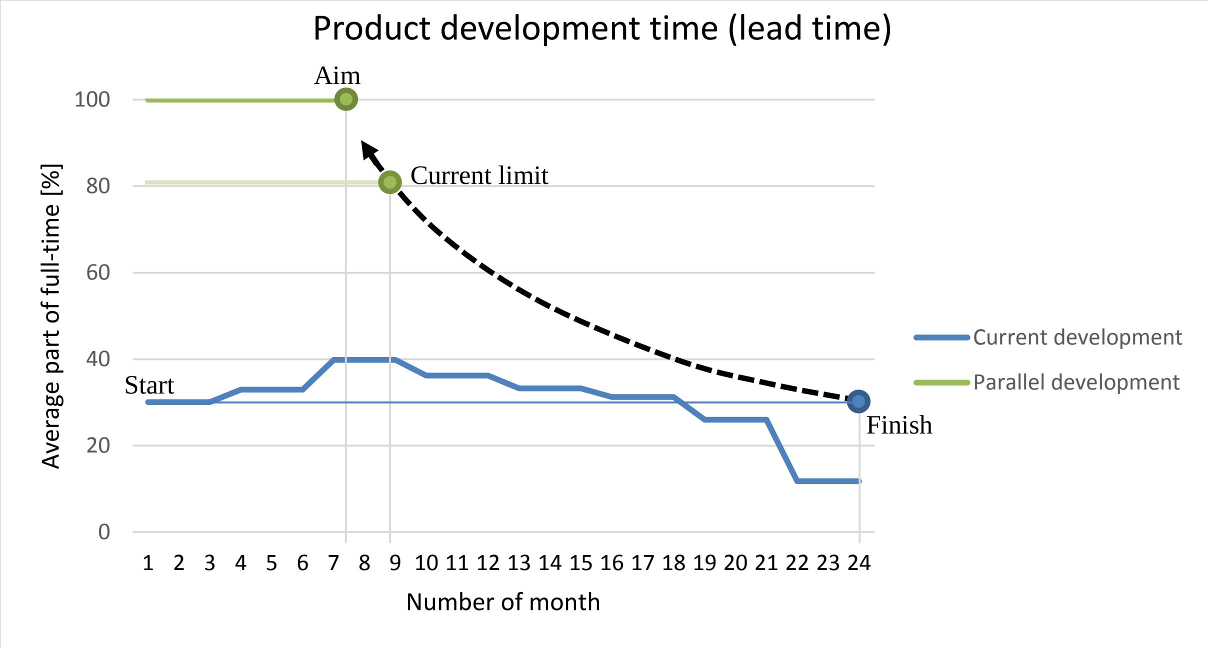


Figure 38. Product development time.

Hence there was a limiting factor, which was the UTTP section in this case at 37% (average part of full-time employment), see Table 15. This means that the UTTP section (closely followed by UTTD) will be limiting the minimum number of month to finish the project, if the exact same project would be performed again. Therefore the current theoretical limit is 8,9 month, if everyone at UTTP worked at 100%. The average part of full-time employment would then be 81%.

Table 15. Design time and work distribution.

Technical field	Subsection (at Scania)	Number of employees	Design time [h]	Average part of full-time [%]
Electrical	UTTE	2	1740	24
Computer	UTTI	3	1620	15
Mechanical	UTTD	5	6480	36
Project management	UTTP	4	5360	37
Total:		14	15200	

Observe that the values in Table 15 does not refer to the efficiency of the work or how well the project was managed. It only reflects the possibility to work in parallel, in order to minimize the product development time.

A modular product architecture, with clearly identified interfaces, allows some of the modules to be developed in parallel. To work in parallel, all modules and design tasks needs to be as uncoupled as possible, a prerequisite to lower the development time is therefore to plan the project according to how the modules and tasks are coupled.

As seen, it is potentially possible to reduce the development time substantially, which will have many positive effect e.g. possibility to act quickly when there is a need to develop a new test rig. In order to calculate the exact reduction, the entire project would need to be rescheduled, which was not possible due to the boundaries of the project.

Requirement specification

The chosen modular architecture was finally evaluated against the requirement specification, provided by the project owners, see Table 16.

Table 16. Requirement specification.

Requirement		**Status**
Test object		
Diesel engines up to 746 kW (1000 hp).		Unknown
Alternative fuel engines up to 597 kW (800 hp).		Unknown
A possibility to run engines with a variety of standard Scania gearboxes up to a maximum gearbox output torque of 5000 Nm.		Unknown
The test rig shall be designed to run engines powered solely by electric battery or in combination with the following liquid and/or gaseous fuels: - Diesel - Gasoline - Ethanol (incl. Etamax) - Methanol - RME - Biogas		Unknown
Subsystems		
Dynamometer system	Communication between the main control system and drive equipment shall be via Profibus optical fiber.	Satisfied
Frequency converter	The frequency converter shall be water cooled.	Satisfied
	The cooling water shall be coupled in via a secondary loop which is shielded from the central water cooling system.	Satisfied
Engine pallet	A multi coupling between measurement box and fixture shall be used.	Satisfied
	The engines will be prepared as much as possible outside of the test cell, in a work shop. Cables are not allowed to lay on the floor.	Unknown
Transmission	A shaft with support bearing shall be used for test objects without gearbox.	Unknown
Media interfaces (interface between engine pallet and subsystems in the cell)	Transmission of media (e.g. cooling fluid) for the engine should be via an engine pallet. Plug in of media to the engine pallet shall be possible in less than 5 minutes.	Not Satisfied
	It shall be impossible to connect the wrong media for the engine pallet. Connections and tubing are not allowed to lay on the floor.	Unknown
Exhaust system	An interface at 1450 mm away from the engine flywheel, located 300 mm above the floor is defined as the takeover point for exhaust from the test engine to the test cell.	Unknown

Engine cooling system	The engine coolant system must be fully drainable for maintenance purpose.	Satisfied
Gearbox oil conditioning system	It shall be possible to connect the gearbox oil circuit or internal heat exchanger to an external conditioning device.	Unknown
	Gearbox oil level shall be achieved by filling oil from a central distribution system, through the external oil conditioning device until oil flows out from gearbox level plug.	Unknown
Hybrid inverter cooling system	It shall be possible to connect one or two separate electrical inverters to an external water cooling device.	Unknown
Hybrid electric motor cooling system	It shall be possible to connect one or two electrical motors to one external water-cooling device.	Unknown

As seen in Table 16, many of the requirements could not be verified. A new requirement specification therefore needs to be done, before it is possible to fully verify the chosen modular test rig architecture.

5 DISCUSSION AND CONCLUSIONS

A discussion of the results, and the conclusions that the author have found during the Master of Science thesis are presented in this chapter.

5.1 Discussion

As seen in the Results chapter, it was not possible to verify some of the requirements, due to the fact that the requirement specification was not made for a modular product architecture. The requirement specification therefore needs to be modified before it is possible to state that the chosen architecture fulfills the requirements.

The chosen and studied test rig was assumed to have an uncoupled design, however this is not entirely the case, and therefore additional investigation of the design is needed. Since the PUMA system is connected directly or indirectly to almost all modules, the product architecture will be somewhat coupled. This will make the chosen modular architecture less optimal and will reduce some of the benefits e.g. lowering the development time. It is therefore interesting to investigate if some of the components in the PUMA system should be moved out to the modules, to make the design less coupled and to lower the complexity.

The author's proposed methodology of combining a DSM and MIM into a strategically adapted DSM, indicated reasonable results after performing the clustering analyses. However further research is still needed to fully understand the methods usage and limitations. If the method works as expected in other studies, it might be a useful tool, since the DSM and MIM both contains important information when modularizing products. It might also be possible to insert other types of boundary conditions to the strategically adapted DSM, e.g. a component might be sensitive to heat and should therefore not be located close to heat emitting components.

When splitting some of the modules in analysis 5, the complexity factor increased slightly, however many other aspects will probably become better, e.g. how many types of test that could be performed or minimizing the downtime when changing between test objects. Since the big module 4 only contained bought subsystems, it would not make sense to add the subsystems together, mainly because they natural forms into modules. Hence the only reason for adding them together would be to lower the product complexity. Module 3, 4 and 8 was also split, mainly due to practical testing procedures. For example, the gearbox and hybrid electric motor are modules in the truck, it is therefore necessary to keep them as modules in the test rig as well.

There are many types of modularization methods available, since there is not only one reason for modularizing products. The chosen methods in the thesis reflects two of the most common methods, however if choosing another method, the outcome of the analyses would probably not be the same.

The lack of strategic goals for the studied test rig made it hard to find a strategically adapted modular architecture. It is therefore important to have clear goals before modularizing a product. It is also important to identify measures to determine how much better the modular architecture becomes, compared with the original one.

The final modular architecture presented in the thesis is mostly based on the authors understanding of the test rig, with some help from Scania engineers. Since there was no clear strategies in the beginning of the project, it is most likely that the identified strategies will change, and thereby the result of the architecture. The modularization methodology is therefore one of the most important things to learn from the thesis, if a new test rig should be developed.

During the usage of the DSM method, the relation weights was chosen by the author. It would however been desirable to spend more time on investigating the different relation weights, in order to see how it affected the result. The performance of the test rig might also be affected by the choice of relation weight, it is therefore important to predict how the relation weight affects the test rig performance, mainly in terms of measurement precision and accuracy.

The final selection of the modular architecture was done with a decision matrix, as earlier described. When choosing the final modular architecture, many parameters needs to be considered. This step is rather subjective and to support the choice, a decision matrix is therefore recommended, as well as clear requirements.

The Scania engineers preferred the DSM method rather than the MFD. This was a bit unexpected since the MFD method is a more industrial method and has been used at many companies. However they found the DSM method to be complicated to use in practice, due to the knowledge and time that is needed. The author of the thesis agrees that the DSM method is complicated, and is therefore only useful if having substantial experience and knowledge in systems engineering.

It may be possible to modularize the test rig without using the methods presented in the thesis, which also appeals to the internal customers at Scania. However, finding the lowest product complexity and allowing for all benefits identified in the thesis, is a much more complicated task. The author therefore strongly recommends to use some of the methods explained in this thesis.

Since only one test rig was chosen and modularized, due to the time limitation of the project, the result of the thesis is a starting point in the ultimate goal of creating a modular test rig family. Before creating an entire test rig family, it is essential to evaluate that the modular test rig works as expected, otherwise there is no meaning of modularizing the other test rigs. The last step in the ultimate goal of creating a modular test rig family might be to standardize some of the components, in order to reduce the complexity and increase the volume of some of the parts.

The chosen modular test rig architecture could potentially offer many other types of benefits, in addition to the benefits earlier described in the Results chapter. The biggest benefit will probably be the reduction in design time and development cost. By reducing the complexity by 41%, it should be possible to reduce the design time and development cost substantially, if managed correctly. Since the estimated design time was 15200 h, at an estimated cost of about 11 million SEK, even a small change will result in a relatively large cost saving.

By using 57% carryover modules, it should also be possible to lower the development cost, when the studied test rig needs to be developed in the future or if a new test rig with similar functionality and performance is needed. The exact cost reduction was not possible to calculate, since the required design time of the different modules was not available.

It should be stated that if the test rig will be developed according to the chosen modular architecture, the investment cost will probably increase, mainly because the performance of some modules will be higher than currently needed, i.e. there is a price to pay for the benefits that the architecture allows. In the future this extra cost might on the other hand result in a saving, since the test rig lifetime might increase.

If modularizing the test rig, the maintenance should be easier and faster because of the standardized and specified interfaces. This should also reduce the downtime since it will be possible to have spare modules that could replace a broken one. The quality of the test rig may furthermore be increased, because of the possibility to test the modules separately, before adding them together.

5.2 Conclusions

The earlier stated purpose and deliverables of the Master of Science thesis was fulfilled, see the following bullets. The end result i.e. this thesis and a final presentation, was furthermore provided to the project owners according to the predefined schedule.

- It was not possible to fully answer the research question about the possibility to combine the DSM and MIM in order to improve the modularization result. Even if the result of the modularization indicated that it is likely, further research is needed to understand its usage and limitations.
- A suggestion of how a DSM and MIM can be combined was stated in the thesis. The suggestion implied that some information from the MIM could be transferred to a "strategy transfer DSM", which then could be added with the DSM. It was therefore possible to answer the research question about how a DSM and MIM can be combined.
- The provided requirement specification was not adequate in order to verify the final modular architecture, hence the final research question was answered. Another requirement specification (adapted for the modules) is therefore needed to fully verify the proposed modular architecture.
- The thesis consists of an extensive Frame of Reference chapter in order to make a clear definition of what a module is, different product architectures and how it is related to the test rigs at Scania.
- A specific test rig was identified and modularized with the DSM, MFD and the author's method, in order to save resources e.g. development time, if developing a new similar test rig in the future. The final suggested modular test rig architecture was represented on systems level, to illustrate the modules and the relations between them.
- The chosen modular test rig architecture has 41% less complexity compared with the original integral architecture.
- The final choice of the modules will determine how fast the product can be developed (lead time) and the associated cost.
- The modular test rig will have a high flexibility, allowing up to 57% of the modules to be reused. Hence, the redesign of test rig could be performed with minimal work effort and in a short time, when it needs to be developed in the future.
- The risk of miscommunication will be reduced after modularizing the test rig, due to fewer communication points, leading to less iterations and design problems.
- The lowest possible development time for the studied test rigs is 7,2 months, which is 70% shorter than the current development time.
- A suggestion of an interface documentation and an interface example was created and presented in the thesis. By using a standardized interface documentation, the administration of information will be easier, especially between the design teams.
- It is highly important to investigate the relation weight and strategies when modularizing a product, since it will affect the end result and thereby the product complexity. It will also determine many important aspects of the product lifecycle e.g. how easy the product could be redesigned and maintained.

- If choosing to use the MFD method to modularize the test rigs, or the author's method, clear strategic goals are needed.
- The modules needs to be carefully selected with appropriate methods, otherwise the complexity will build up fast and the modular test rig loses its advantages.

6 RECOMMENDATIONS AND FUTURE WORK

In this chapter, recommendations on more detailed solutions and future work in the field are presented.

6.1 Recommendations

The author of the thesis would like to recommend the project owners the following points, if continuing the modularization process.

- Implementing new methods takes time and should not be rushed. It is also important that everyone is motivated and has the right mind set when modularizing a product.
- There should be a clear reason of why the test rigs should be modularized, modularization itself should not be a strategy or goal, simply because it does not need to result in an improvement.
- Investigate how the studied test rig performance is affected by the modular design, before modularizing any other test rig. The performance (and safety) must always be the first priority when developing test rigs. If the performance cannot be achieved, the test rig will need to have an integral product architecture.
- Divide the design tasks based on the modules, and let teams of engineers develop the modules in parallel.
- Use one or all methods explained in the thesis when modularizing the test rigs, otherwise it is not possible to create a modular architecture that enables the benefits identified in the thesis.
- When designing the interfaces, it is very important to choose a design and performance that is robust.

6.2 Future work

Finally, after conducting the Master of Science thesis project, the author have identified the following work to be interesting and important to study further.

- Perform several more clustering analyses (with other products) based on the author's method of combining a DSM and MIM, in order to understand the usage and limitations of the method. To do this, it would be appropriate to study a modular product, which has been developed by using the MFD or DSM method.
- Create a requirement specification which allows the chosen modular test rig architecture to be verified. The requirement specification needs to contain requirements of e.g. which components/subsystems that should be developed or needs regular maintenance. It should also contain space and layout constraints.
- Translate the overall strategies at Scania into test rig strategies, and evaluate how each component/subsystem will be affected.
- Investigate how the test rig performance will be affected by changing to a modular product architecture. For example, investigate how the signals are transmitted in the modular architecture and if it affects the measuring result.

- Perform a detailed functional analysis in order to determine if the design is coupled or uncoupled. If the design is coupled, design changes are needed before modularizing the product. To assist the work when designing an uncoupled design, a DPM (Design Property Matrix) could be used.
- Investigate how the design tasks are coupled, in order to minimize the product development time. The investigation could be performed by using a project management DSM.
- Investigate if the identify modules should have a submodular or an integral architecture.
- Investigate the PUMA system, since it is connected to many of the modules, it complicates the modularization of the test rig. It is therefore interesting to study how the complexity and performance is affected if the “intelligence” is moved to the modules i.e. decentralizing the PUMA system. This could be investigated by decomposing the PUMA system and adding the new components to the original DSM, followed by a clustering analysis.
- Create a rough geometric layout of the modules e.g. as black boxes and arrange them according to space constraints.
- Create a module documentation, based on the suggested interface documentation.
- Design the modules and interfaces, by using normal product development methods.
- Modularize other test rigs to identify possible modules to share.
- Identify module variants (if needed) to meet the different performance requirements of the test rigs.
- Identify potential modules that could form a module-based product platform.
- Create a modular test rig family, i.e. allowing some modules to be used in all test rigs.

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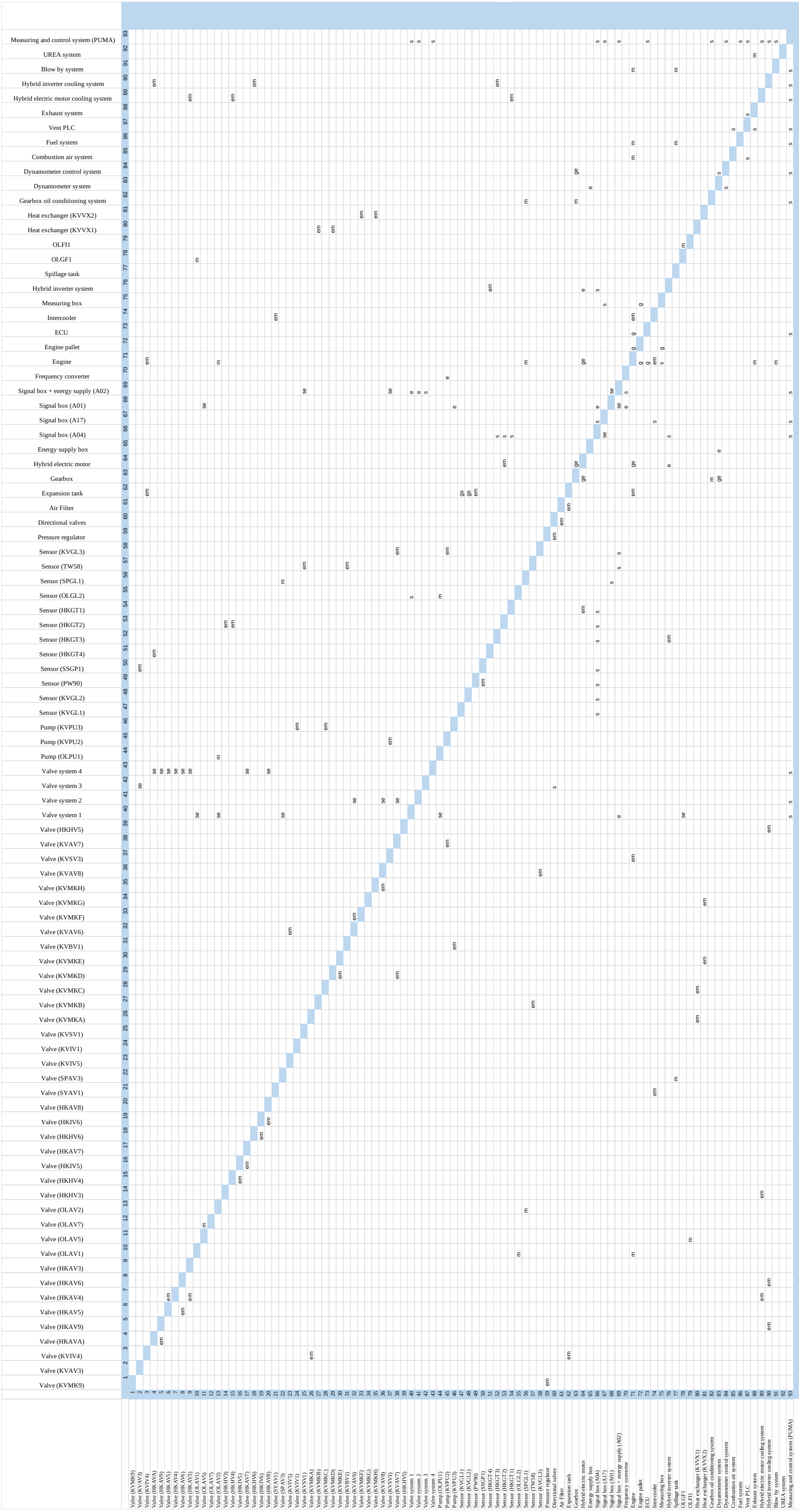
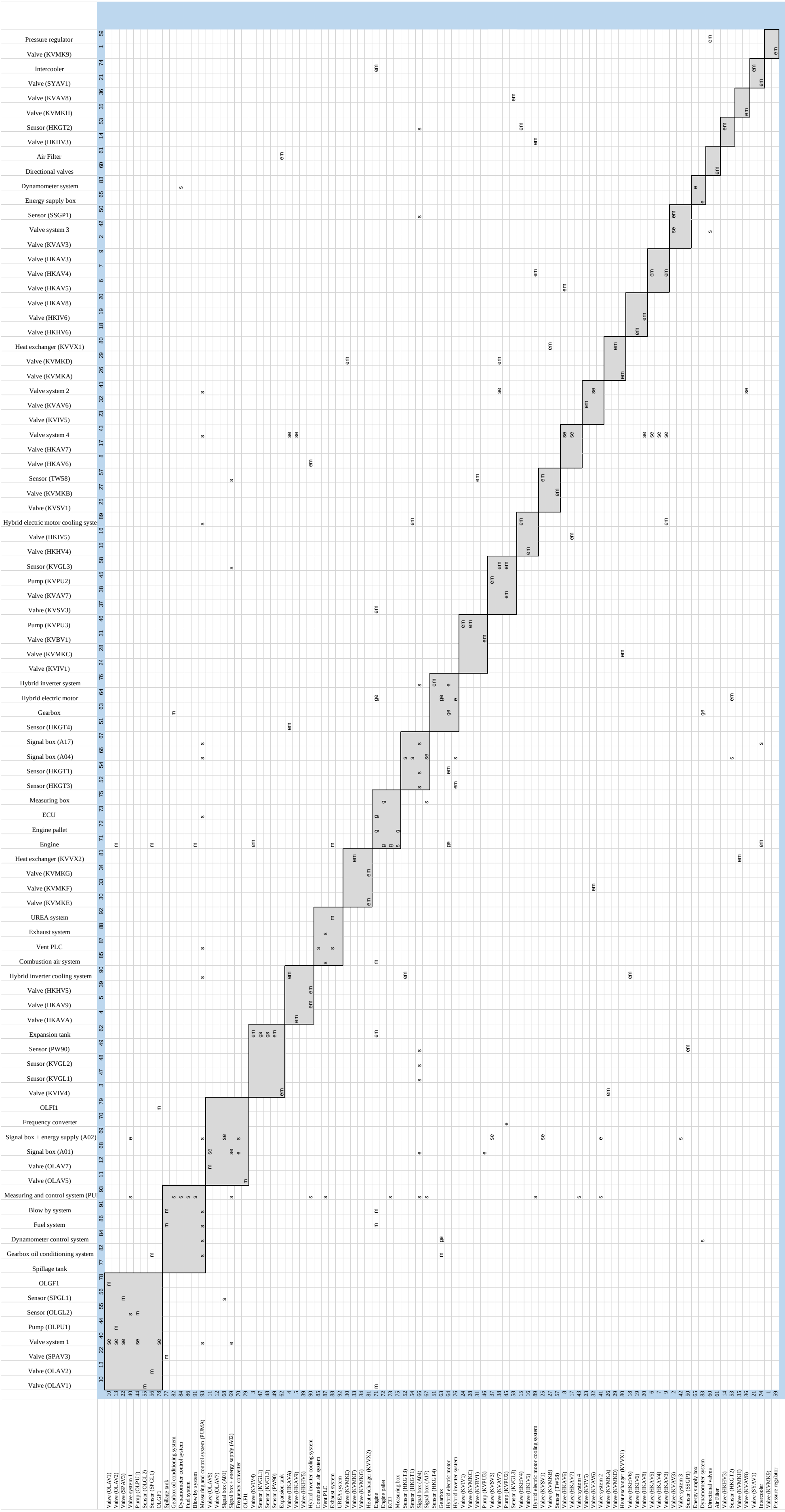
APPENDIX

DSM representation of the F16 engine test rig, Original design.



Clustered DSM, Analysis 1.



MIM

Module Drivers	Valve (KVMK9)	Valve (KVAV3)	Valve (KVIV4)	Valve (HKAVA)	Valve (HKAV9)	Valve (HKAV5)	Valve (HKAV4)	Valve (HKAV6)	Valve (HKAV3)	Valve (OLAV1)	Valve (OLAV5)	Valve (OLAV7)	Valve (OLAV2)	Valve (HKHV3)	Valve (HKHV4)	Valve (HKIV5)	Valve (HKAV7)	Valve (HKHV6)	Valve (HKIV6)	Valve (HKAV8)
Carryover	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Technology evolution																				
Planned product changes																				
Different specifications																				
Styling																				
Common unit																				
Process/organization																				
Separate testing																				
Supplier availability																				
Service/maintenance	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Upgrading																				
Recycling																				
Total:	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

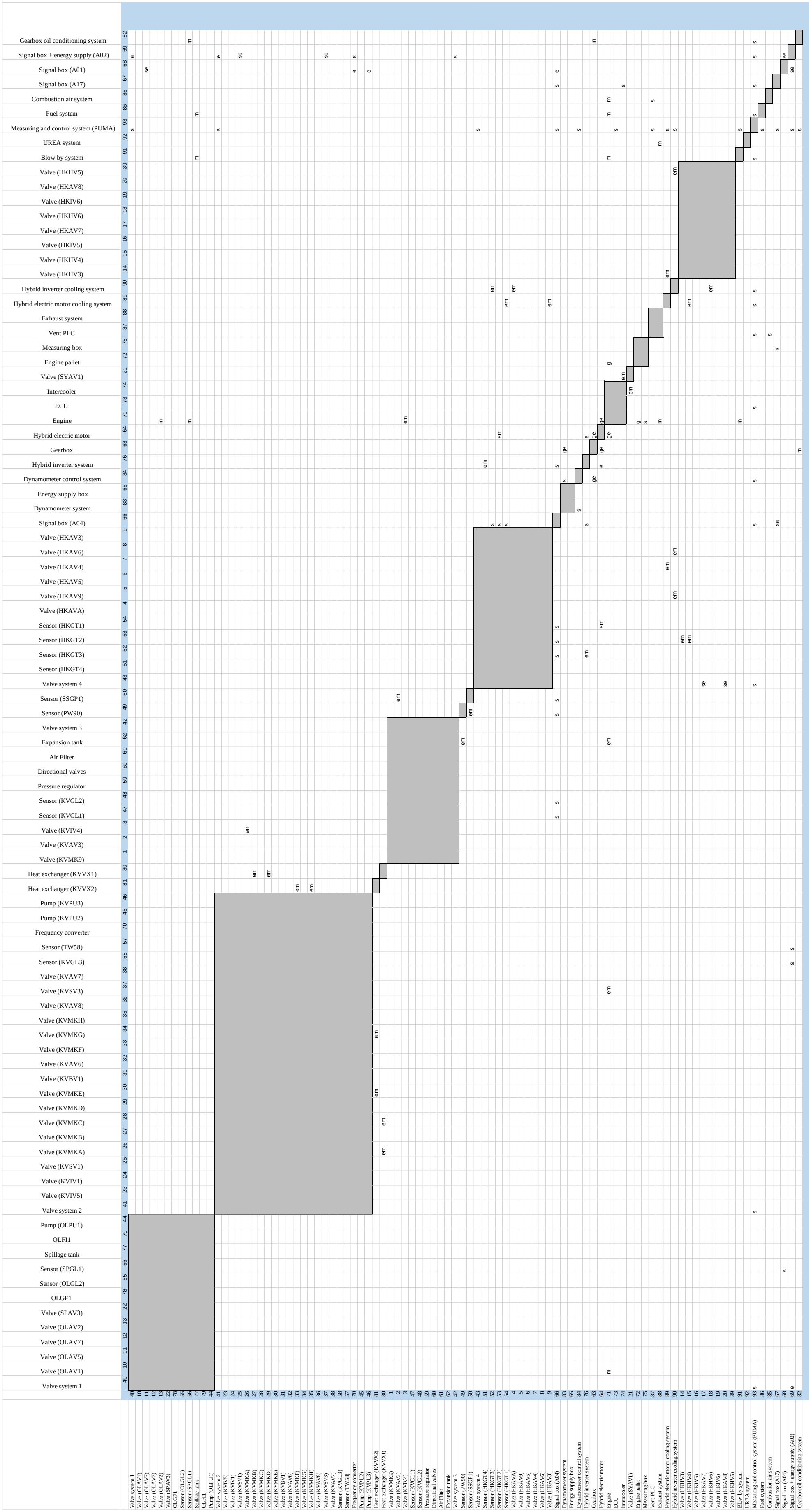
Module Drivers	Valve (SYAV1)	Valve (SPAV3)	Valve (KVIV5)	Valve (KVIV1)	Valve (KVSV1)	Valve (KVMKA)	Valve (KVMKB)	Valve (KVMKC)	Valve (KVMKD)	Valve (KVMKE)	Valve (KVBV1)	Valve (KVAV6)	Valve (KVMKF)	Valve (KVMKG)	Valve (KVMKH)	Valve (KVAV8)	Valve (KVSV3)	Valve (KVAV7)	Valve (HKHV5)
Carryover	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Technology evolution																			
Planned product changes																			
Different specifications																			
Styling																			
Common unit																			
Process/organization																			
Separate testing																			
Supplier availability																			
Service/maintenance	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Upgrading																			
Recycling																			
Total:	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4

Module Drivers	Valve system 1	Valve system 2	Valve system 3	Valve system 4	Pump (OLPU1)	Pump (KVPU2)	Pump (KVPU3)	Sensor (KVGL1)	Sensor (KVGL2)	Sensor (PW90)	Sensor (SSGP1)	Sensor (HKGT4)	Sensor (HKGT3)	Sensor (HKGT2)	Sensor (HKGT1)	Sensor (OLGL2)	Sensor (SPGL1)	Sensor (TW58)	Sensor (OLGF1)	Sensor (KVGL3)
Carryover	9	9	9	9	9	9	9	9	9			9	9	9	9	9	9	9	9	9
Technology evolution																				
Planned product changes										9	9									
Different specifications																				
Styling																				
Common unit																				
Process/organization																				
Separate testing										3	3									
Supplier availability																				
Service/maintenance	9	9	9	9	3	3	3	3	3	9	9	3	3	3	3	3	3	3	3	3
Upgrading																				
Recycling																				
Total:	18	18	18	18	12	12	12	12	12	21	21	12	12	12	12	12	12	12	12	12

Module Drivers	Pressure regulator	Directional valves	Air Filter	Expansion tank	Gearbox	Hybrid electric motor	Energy supply box	Signal box (A04)	Signal box (A17)	Signal box (A01)	Signal box + energy supply (A02)	Frequency converter	Engine	Engine pallet	ECU	Intercooler	Measuring box	Hybrid inverter system	Spillage tank	Filter (OLFI1)	Heat exchanger (KVVX1)	Heat exchanger (KVVX2)
Carryover	9	9	9	9								9		9					9	9	9	9
Technology evolution							9								9		9					
Planned product changes					9	9		9	9	9	9		9			9		9				
Different specifications																						
Styling																						
Common unit																						
Process/organization					9	9							9					9				
Separate testing					9	9							9									
Supplier availability																						
Service/maintenance		3	3		9	9	3	9	9	9	9		9					9		3	9	9
Upgrading								3	3	3	3											
Recycling																						
Total:	9	12	12	9	36	36	12	21	21	21	21	9	36	9	9	9	9	27	9	12	18	18

Module Drivers	Gearbox oil conditioning system	Dynamometer system	Dynamometer control system	Combustion air system	Fuel system	Vent PLC	Exhaust system	Hybrid electric motor cooling system	Hybrid inverter cooling system	Blow by system	UREA system	Measuring and control system (PUMA)
Carryover												
Technology evolution	9	9	9	9	9	9	9	9	9	9	9	9
Planned product changes												
Different specifications												
Styling												
Common unit												
Process/organization												
Separate testing												
Supplier availability	9	9	9	9	9		9	9	9	9	9	9
Service/maintenance	9	9	9	9	9		9	9	9	9	9	9
Upgrading												
Recycling												
Total:	27	27	27	27	27	9	27	27	27	27	27	27

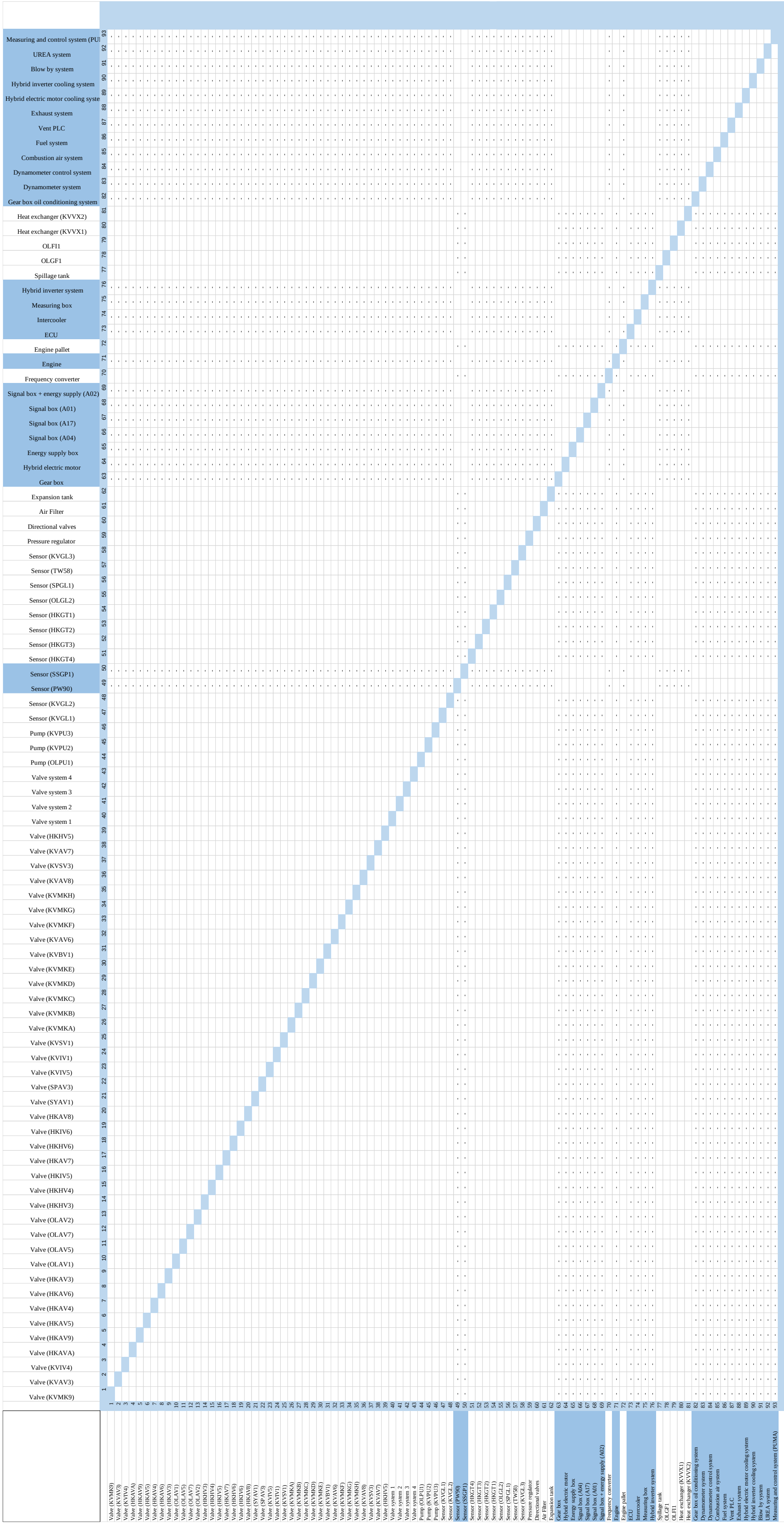
Clustered DSM, Analysis 3.



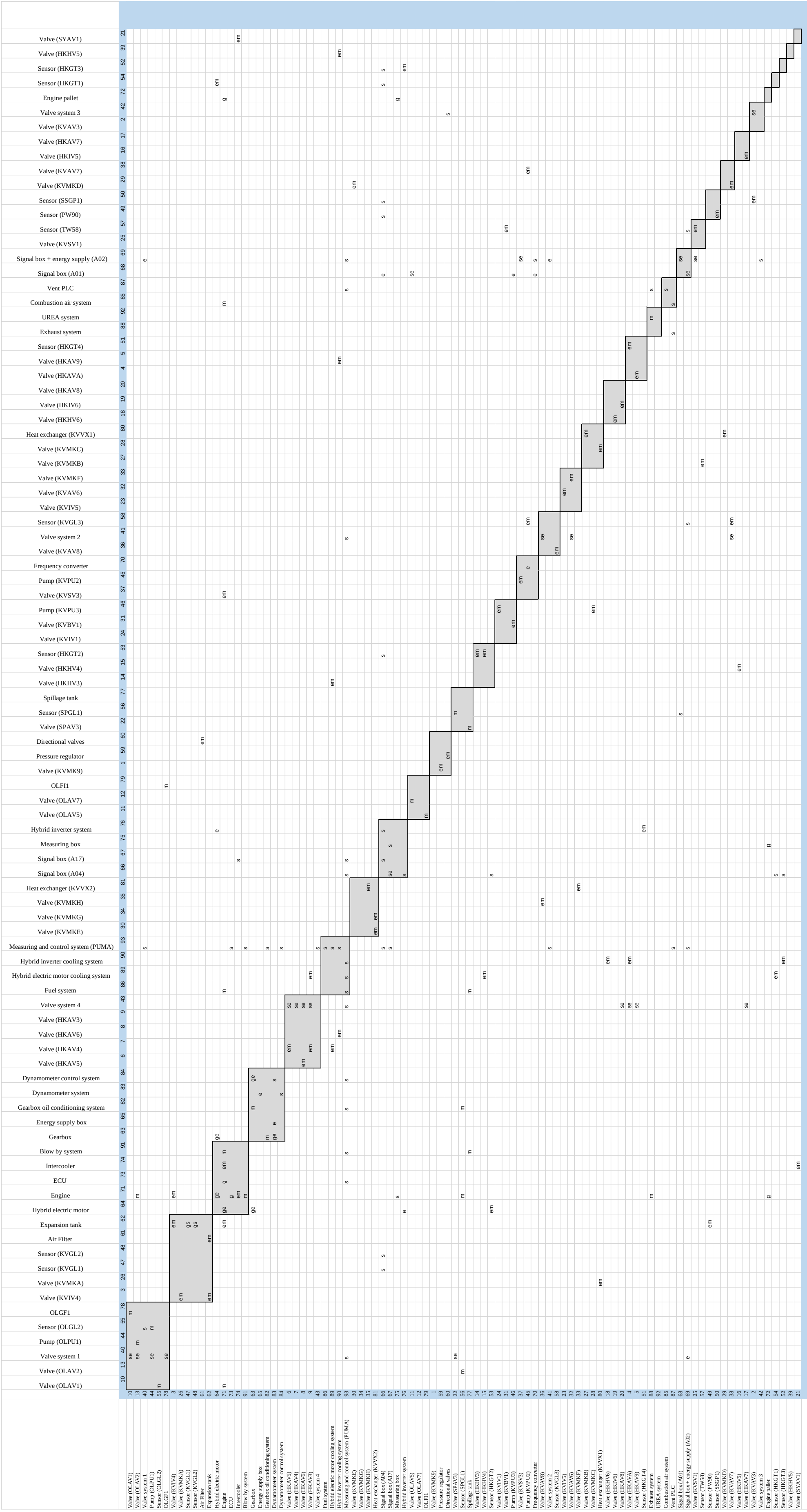
Component/subsystem strategies, based on the MIM result

Needs to be developed	Do not need to be developed (carryover)
Sensor (PW90)	Valve (KVMK9)
Sensor (SSGP1)	Valve (KVAV3)
Gearbox	Valve (KVIV4)
Hybrid electric motor	Valve (HKAVA)
Energy supply box	Valve (HKAV9)
Signal box (A04)	Valve (HKAV5)
Signal box (A17)	Valve (HKAV4)
Signal box (A01)	Valve (HKAV6)
Signal box + energy supply (A02)	Valve (HKAV3)
Engine	Valve (OLAV1)
ECU	Valve (OLAV5)
Intercooler	Valve (OLAV7)
Measuring box	Valve (OLAV2)
Hybrid inverter system	Valve (HKHV3)
Gearbox oil conditioning system	Valve (HKHV4)
Dynamometer system	Valve (HKIV5)
Dynamometer control system	Valve (HKAV7)
Combustion air system	Valve (HKHV6)
Fuel system	Valve (HKIV6)
Vent PLC	Valve (HKAV8)
Exhaust system	Valve (SYAV1)
Hybrid electric motor cooling system	Valve (SPAV3)
Hybrid inverter cooling system	Valve (KVIV5)
Blow by system	Valve (KVIV1)
UREA system	Valve (KVSV1)
Measuring and control system (PUMA)	Valve (KVMKA)
	Valve (KVMKB)
	Valve (KVMKC)
	Valve (KVMKD)
	Valve (KVMKE)
	Valve (KVBV1)
	Valve (KVAV6)
	Valve (KVMKF)
	Valve (KVMKG)
	Valve (KVMKH)
	Valve (KVAV8)
	Valve (KVSV3)
	Valve (KVAV7)
	Valve (HKHV5)
	Valve system 1
	Valve system 2
	Valve system 3
	Valve system 4
	Pump (OLPU1)
	Pump (KVPU2)
	Pump (KVPU3)
	Sensor (KVGL1)
	Sensor (KVGL2)
	Sensor (HKGT4)
	Sensor (HKGT3)
	Sensor (HKGT2)
	Sensor (HKGT1)
	Sensor (OLGL2)
	Sensor (SPGL1)
	Sensor (TW58)
	Sensor (KVGL3)
	Pressure regulator
	Directional valves
	Air Filter
	Expansion tank
	Frequency converter
	Engine pallet
	Spillage tank
	OLGF1
	OLFI1
	Heat exchanger (KVVX1)
	Heat exchanger (KVVX2)

Strategy transfer DSM



Clustered DSM, Analysis 4.



Clustered DSM, Analysis 5.