



Doctoral Thesis in Machine Design

On integrated modularization in heavy-duty truck architecting

DAVID WILLIAMSSON

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Title On integrated modularization in heavy-duty truck architecting		Sponsor(s) SCANIA	
Abstract <p>Road transports face increasing challenges with respect to safety, legislations on lower emissions and traffic congestion, as well as numerous business challenges related to paradigm shifts in technology, tightened delivery times and cost constraints. Combination of <i>truck electrification</i> and <i>automation</i> may be utilized to address some of these issues. Electrified and autonomous transport vehicles may be characterized as <i>Cyber-Physical Systems</i> (CPS). A drawback with CPS is the extensive increase of <i>technical complexity</i>, which introduce new challenges to <i>Systems Engineering</i> (SE). The added complexity is preferably targeted in the <i>product architecting</i> development stage of SE.</p> <p>Product architecting involves conceptual system design, module identification (clustering) and product layout design. A <i>product architecture</i> is the interrelation between physical components and their function, i.e. their purpose. Product architectures can be categorized as being <i>modular</i>, <i>hybrid</i> or <i>integral</i>. A modular architecture is a strategic means to deliver <i>external variety</i> and <i>internal commonality</i>. Modular subsystems enable concurrent development and <i>modularization</i> is, thus, a structured method to manage technical complexity. In this thesis, a new clustering-based methodology and process for heavy-duty truck modularization that integrates <i>technical complexity</i>, company <i>business strategies</i> and <i>physical interference</i> is proposed. The main <i>hypothesis</i> behind the presented research is that computer-based product architecture clustering analysis benefit from a quantitative complexity measure, as well as means to represent (model) and communicate product architecture related complexity. A variety of industrial cases of heavy-duty truck subsystems are used to describe the proposed methodology and to verify its performance, i.e. how well the proposed methodology and process supports the SE process. All investigated subsystems contains synergistic configurations of mechanical, electrical and software technologies, i.e. they may be characterized as CPS.</p> <p>The presented research concludes that the proposed modularization methodology and process is capable of supporting the SE process by improving the quality of the module identification stage, by adding business strategies and physical interference to product architecture clustering. Moreover, it is confirmed that the new methodology is both scalable and flexible, allowing the consequences of different architectural trade-offs to be analyzed independently or combined depending on purpose. Furthermore, the newly developed architectural representations showed to make architectural discussions in general and modularity discussion in particular with and between domain experts efficient. Finally, the case studies clearly shows that the clustering results depend on the relative weights of the different types of component relations that are represented in the product architecture <i>DSM</i> (Design Structure Matrix). However, the importance of these weights are reduced when multiple business strategic and physical interference constraints are introduced.</p>			
Keywords Modularization, Module, Product Architecture, Cyber-Physical System		Language English	

Sammanfattning

Vägtransporter står inför ökade samhällsutmaningar med avseende på säkerhet, lagkrav gällande lägre utsläpp, trafikstockningar, samt affärsutmaningar relaterat till ett paradigmskifte i teknik, kortare leveranstider och kostnadsbesparingar. Lastbils elektrifiering och automation kan användas för att lösa några av dessa problem. Elektrifierade och autonoma transportfordon kan kännetecknas som cyberfysiska system, förkortat CPS. En nackdel med CPS är den avsevärt ökade *tekniska komplexiteten*, vilket introducerar nya utmaningar till *Systems Engineering*, förkortat SE. Den ökade tekniska komplexiteten kan företrädesvis hanteras under utvecklingen av produktens arkitektur inom SE.

Utvecklingen av en produktarkitektur består av följande steg; konceptuell systemkonstruktion, identifiering av moduler (klustringsanalys) och utformning av produktlayouten. En produktarkitektur är sambandet mellan fysiska komponenter och deras funktion, d.v.s. deras syfte. Produktarkitekturer kan kategoriseras som *modulära*, *hybrider* eller *integrerade*. Huvudsyftet med en modulär arkitektur är att möjliggöra en yttre variation och samtidigt inre enhetlighet. Modulära delsystem möjliggör parallell utveckling och *modularisering* kan därför ses som en strukturerad metod för att hantera teknisk komplexitet. I den här avhandlingen föreslås en ny klustringsbaserad metod och process för modularisering av tunga lastbilar som integrerar *teknisk komplexitet*, företagsspecifika *affärsstrategier* och *fysisk interferens*. Den huvudsakliga hypotesen bakom den presenterade forskningen är att datorbaserad klustringsanalys av produktarkitektur förbättras av ett kvantitativt komplexitetsmått, samt nya sätt att representera (modellera) och kommunicera produktarkitekturrelaterad komplexitet. Ett antal olika industriella fallstudier som behandlar delsystem av tunga lastbilar används för att beskriva den föreslagna metoden och för att verifiera dess prestanda, d.v.s. hur väl den föreslagna metoden och processen stödjer SE-processen. Samtliga undersökta delsystem innehåller samverkande konfigurationer av mekaniska, elektriska och mjukvaruteknologier, d.v.s. de kan kännetecknas som CPS.

Slutsatsen av den presenterade forskningen är att den föreslagna modulariseringsmetoden och processen stödjer SE-processen genom att förbättra kvaliteten under identifieringen av moduler. Detta möjliggörs genom att addera affärsstrategier och fysisk interferens under klustringsanalysen av produktarkitekturen. Utöver det bekräftas även att den nya metoden både är skalbar och flexibel, vilket gör att konsekvenserna av olika arkitekturella avvägningar kan analyseras oberoende eller samtidigt beroende på syfte. Därtill bekräftas att de nyligen utvecklade arkitekturrepresentationerna effektiviserar arkitekturrelaterade diskussioner, och i synnerhet diskussioner gällande modularisering mellan domänexperter. Slutligen visar fallstudierna att klustringsresultaten beror på de relativa vikterna för de olika typerna av komponentrelationer som representeras i en produktarkitektur *DSM* (Design Structure Matrix). Betydelsen av dessa vikter minskar dock när affärsstrategiska och fysisk interferens begränsningar införs.

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I am writing these acknowledgments a little under 4 years after starting this project. These years would not have been as interesting and fun, if there weren't for my colleagues both at KTH and Scania.

Finally, I must also thank my family and all my friends outside work for keeping me in touch with other things in life.

Thank you all!

A handwritten signature in black ink, appearing to read 'David Williamsson', with a stylized, flowing script.

David Williamsson

Stockholm, March 2021

List of appended publications

This thesis consists of a summary and the following appended papers:

Paper A

A. Williamsson, D., Sellgren, U. (2016) “An approach to integrated modularization” *Procedia CIRP* 50 (2016), 613-617, Elsevier B.V.

The author performed most of the planning, experimental work, evaluation and writing of the paper. Prof. Ulf Sellgren provided feedback on the structure of the paper and proposed improvements to the text for improved understanding.

Paper B

B. Williamsson, D., Sellgren, U., Söderberg A. (2018) “Product architecture transition in an evolving multi-brand organization”, *Proc. International Design Conference – DESIGN 2018*, May 21-24, 2018, Dubrovnik, Croatia.

The author performed most of the planning, experimental work, evaluation and writing of the paper. Prof. Ulf Sellgren and Associate Prof. Anders Söderberg provided feedback on the structure of the paper and proposed improvements to the text for improved understanding.

This paper was awarded to be an “Outstanding Contribution” and was rated in the top 5% papers (based on the reviewers’ scores) at the DESIGN 2018 conference.

Paper C

C. Williamsson, D., Sellgren, U., Söderberg A. (2018) “The hunt for proper relation weights in product architecture clustering”, *Proc. NordDesign 2018*, August 14-17, 2018, Linköping, Sweden.

The author performed most of the planning, experimental work, evaluation and writing of the paper. Prof. Ulf Sellgren and Associate Prof. Anders Söderberg provided feedback on the structure of the paper and proposed improvements to the text for improved understanding.

Paper D

D. Williamsson, D., Sellgren, U., Söderberg A. (2019) “Product architecture transition in a modular cyber-physical truck”, *ASME. J. Comput. Inf. Sci. Eng.* September 2019; 19(3): 031002. <https://doi.org/10.1115/1.4042961>.

The author performed most of the planning, experimental work, evaluation and writing of the paper. Prof. Ulf Sellgren and Associate Prof. Anders Söderberg provided feedback on the structure of the paper and proposed improvements to the text for improved understanding.

The original version of this paper (i.e. the conference proceeding version) was awarded the SEIKM (Systems Engineering, Information, and Knowledge Management) best paper award at the ASME 2018 IDETC/CIE conference, August 26-29, 2018, Quebec City, Quebec, Canada.

Paper E

E. Williamsson, D., Sellgren, U., Söderberg A. (2018) “A hunt for the hidden reasons behind a product architecture”, *Proc. of the 20th International Dependency and Structure Modeling Conference, DSM 2018*, October 15 – 17, 2018, Trieste, Italy.

The author performed most of the planning, experimental work, evaluation and writing of the paper. Prof. Ulf Sellgren and Associate Prof. Anders Söderberg provided feedback on the structure of the paper and proposed improvements to the text for improved understanding.

Paper F

F. Williamsson, D., Sellgren, U. (2019) “Introducing implementation dependent behavior into integrated product architecture clustering”, Proc. of the 21th International Dependency and Structure Modeling Conference, DSM 2019, September 23 – 25, 2019, Monterey, CA, USA.

The author performed most of the planning, experimental work, evaluation and writing of the paper. Prof. Ulf Sellgren provided feedback on the structure of the paper and proposed improvements to the text for improved understanding.

Paper G

G. Williamsson, D., Sellgren, U. (2020) “Architecting a modular battery electric truck”, Proc. of the ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conferences IDETC/CIE 2020, August 17-19 2020, Online event due to the COVID-19 pandemic.

The author performed most of the planning, experimental work, evaluation and writing of the paper. Prof. Ulf Sellgren provided feedback on the structure of the paper and proposed improvements to the text for improved understanding.

Paper H

H. Williamsson, D., Sellgren, U. (2020) “Integrated modularization methodology and process for heavy-duty trucks”, under review, but accepted with minor modifications to the Systems Engineering Journal.

The author performed most of the planning, experimental work, evaluation and writing of the paper. Prof. Ulf Sellgren provided feedback on the structure of the paper and proposed improvements to the text for improved understanding.

Other academic publications

Williamsson D. (2018) “On integrated modularization for situated product configuration”. Licentiate thesis, Department of Machine Design, KTH Royal Institute of Technology, Stockholm, Sweden.

Williamsson, D., Sellgren, U., Söderberg A. (2018) “Product architecture transition in a modular cyber-physical truck”, Proc. of the ASME 2018 International Design Engineering Technical Conferences and Computers and Information in Engineering Conferences IDETC/CIE 2018, August 26-29 2018, Quebec City, Quebec, Canada.

Sellgren, U., Williamsson, D. (2020) “Architecting Complex Engineered Systems”. Proceedings of the Design Society: DESIGN Conference, 1, 2415-2424. doi:10.1017/dsd.2020.335

Nomenclature

Term	Definition
Part	A physical unit that cannot be physically decomposed, e.g. a screw or an integrated circuit.
Component	Simple physical unit or element of a system, e.g. a pump, which must consist of several parts.
Cluster	A group of function carriers with significant intra-dependencies but very low dependencies to other function carriers. A cluster may therefore be a module candidate.
Function	What the product or part of the product is required to do, e.g. transform chemical energy to mechanical energy, send information, transport matter.
Functional element	One of the functions that the product should perform e.g. heat water or reduce drag.
Interface	Surfaces or volumes creating a common boundary between two modules or parts, allowing exchange of information, energy, material or defining a spatial relation.
Modularization	Identifying the modules for a product, by decomposing it depending on company specific reasons.
Modular system	All necessary and optional modules for configuring a unique product in a product family.
Module	Functional building block with standardized interfaces, which is chosen for company specific reasons.
Module variant	Physical incarnation of a module with a specific performance level.
Product variant	When combining components i different ways, different products are created.
Performance step	A module variant with a specific performance requirement. Families of such modules target different levels of some specified performance measure.
Product architecture	The arrangement of <i>functional elements</i> , the mapping from <i>functional elements</i> to <i>physical components</i> and the specification of the <i>interfaces</i> among interacting physical components.
Product family	Set of products, based on the same product platform and configured from the same modular system.
Product platform	The modules of a modular system that are mandatory for all products in a product family.
Product property	Detailed quantifiable statement that describes the product.
Standardization	Increasing internal commonality by reducing the number of different parts and components.
Structure	The (physical) constituents of a system and their relation.

Abbreviations

ASM	Affordance Structure Matrix
ASME	The American Society of Mechanical Engineers
AUTOSAR	AUTomotive Open System ARchitecture
BEV	Battery Electric Vehicle
CAD (<i>tool</i>)	Computer Aided Design
CAD	Component Architecture Diagram
CCD	Component Cluster Diagram
CMM	Cluster Match Matrix
CPS	Cyber-Physical Systems
CPSoS	Cyber-Physical Systems of Systems
DSM	Design Structure Matrix
paDSM	<i>product architecture</i> DSM
laDSM	<i>layout adapted</i> DSM
saDSM	<i>strategically adapted</i> DSM
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
IDEF0	Icam DEFinition for Function Modeling (version 0)
IGTA++	Idicula-Gutierrez-Thebeau Algorithm, (DSM clustering algorithm)
IMM	Integrated Modularization Methodology
eIMM	extended Integrated Modularization Methodology
INCOSE	International Council on Systems Engineering
IoT	Internet of Things
IT	Information Technology
MATLAB	MATrix LABoratory, (computing software and language)
MBSE	Model-Based Systems Engineering
MD	Module Drivers
MPD	Modular Function Deployment
MIM	Module Indication Matrix
OEM	Original Equipment Manufacturer
PDM	Product Data Management
PLM	Product Lifecycle Management
R&D	Research and Development
RQ	Research Question
SAE	Society of Automotive Engineers
SE	Systems Engineering

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1. INTRODUCTION

This chapter presents the background information to the research project, the objective and research questions, as well as the used research methodology and outlines the structure of this thesis.

1.1 Background

Road transports face increasing challenges with respect to safety, legislations on lower emissions and traffic congestion, as well as numerous business challenges related to paradigm shifts in technology, tightened delivery times and cost constraints. Combination of *truck electrification* and *automation* may be utilized to address some of these issues. Examples of short-term truck electrification can be the integration of electric machines into an existing *Internal Combustion Engine* (ICE)-based powertrain, resulting in a *Hybrid Electric Vehicle* (HEV), or in the long-term plan, developing a completely new *Battery Electric Vehicle* (BEV). Truck automation includes semi- or fully self-driving trucks, as well as truck-to-truck and truck-to-transport system communication. Examples of short-term truck automation can be truck *platooning*, which is the linking of two or more trucks in convoy, using communication technology and automated driving support systems. These vehicles automatically maintain a set, close distance between each other when they are connected for certain parts of a journey. The smaller the distance between the trucks can be, the larger the gains in terms of energy consumption will be. *Platooning* combines existing commercial vehicle safety technology with emerging vehicle-to-vehicle communications and autonomous vehicle control, and it enables a future system of self-driving and fully autonomous transport vehicles. The level of driving automation is commonly categorized from the number of functions that are engaged in the driving operation. The *Society of Automotive Engineers* (SAE) defines these driving automation levels from 0 (fully manual) to 5 (fully autonomous). The term *complex* has been used for centuries in ordinary language to state that something is difficult, uncertain, unpredictable or complicated. Truck automation faces increased complexity, due to a multitude of complex functions that can be implemented as a combination of physical and computational elements with intricate interactions and dependencies, i.e., there is potentially a very large variety of architectural choices.

Electrified and autonomous transport vehicles may be characterized as *Cyber-Physical Systems* (CPS) that are components of *Cyber-Physical Systems of Systems* (CPSoS), i.e. transport systems, see e.g. (CyPhERS, 2013), (CPS, 2016), (NIST, 2017). “A key aspect of CPS is the potential to integrate *Information Technologies* (IT), operational technologies in terms of embedded systems and control systems, and physical electrical and mechanical systems, forming new or improved functionalities and/or levels of performance” (Törnngren & Sellgren, 2018). Hence, CPS development increases the need for innovation within and across traditional engineering and technical domains. A drawback with CPS is the extensive increase of *technical complexity*, which introduce new challenges to *Systems Engineering* (SE) (Törnngren & Sellgren, 2018). Technical complexity is described by Rodriguez-Toro et al. (2004) as not just unavoidable in systems with heterogeneous technology, but could actually be required. Consequently there is a need for complexity management techniques. The added complexity is preferably targeted in the *product architecting* development stage, which is part of the Systems Engineering process, see Figure 1.

A commonly used architectural representation in SE is the *Design Structure Matrix (DSM)*. The DSM is a network modeling tool which represents the system elements and their interactions, thereby allowing the architecture of a product (or system) to be highlighted.

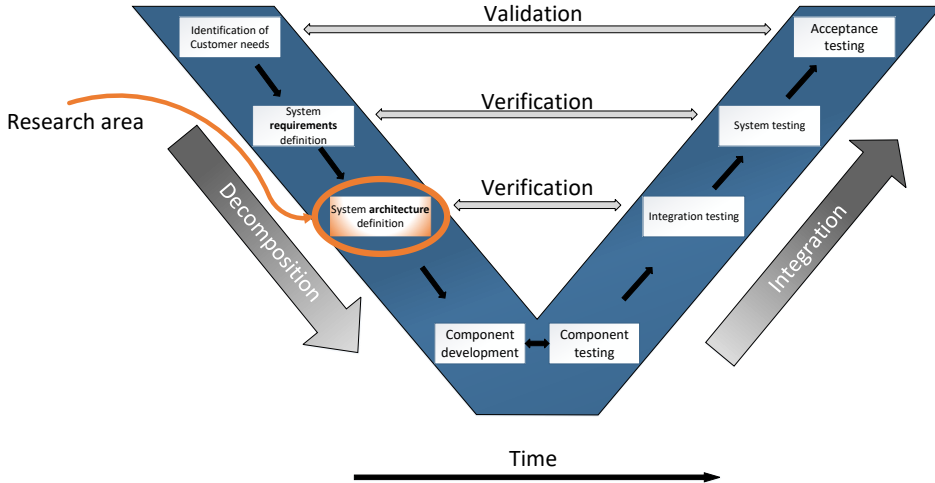


Figure 1. The V-model of the SE process.

The context of the presented PhD thesis is high-performing CPS that are relevant to road transport applications, i.e., the physical systems are complex and contain heterogeneous technologies (mechanical, electrical, and software components) that are constituents of an automated and/or semi-autonomous transport system.

The PhD research project was performed at the Department of Machine Design at KTH Royal Institute of Technology in Stockholm, and at Scania R&D in Södertälje. Scania is one of the leading truck, bus and engine manufacturers in the world and is today a part of the TRATON Group SE, 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. Scania also has a unique way of representing the modular product in their product description, which has a generic product structure in order to efficiently describe the many variants.

However, the Scania product has over the last years been developed into a CPS, with embedded software in focus, demanding the present way of modularizing to support this new dimension. There is also a growing market regarding offline and online services, which also generates new demands. In addition, collaboration within the TRATON Group, and employees changing jobs more frequently, makes it even more important to put "The Scania Way" of modularizing and describing the product on a theoretically more robust base (Williamsson, 2018).

1.2 Objective and research questions

The overall aim of the presented research project is to provide a contribution to SE by proposing a new modularization methodology and process for *product architecture clustering analysis* of CPS within the heavy-duty truck domain. The new methodology and process should assist the task to define functional borders and robust physical interfaces between the modules, to deal with the increased technical complexity. Moreover, the new methodology should enable trade-offs between technical complexity and company specific business strategies to be made, while

still being robust, agile and efficient to use in practice. The aim is also to identify means to facilitate efficient cross-functional communication and collaboration on architecture-related tasks. Furthermore, the objective is to verify, generalize and further improve the robustness and the efficiency of the proposed methodology. Since the case studies used to verify the proposed methodology are all CPS within the heavy-duty truck domain, it is not possible to claim that the presented work will be applicable beyond this product type.

The main *hypothesis* behind the presented research is that computer-based product architecture clustering analysis benefit from a quantitative complexity measure, as well as means to represent (model) and communicate product architecture related complexity.

The first step of the project was to perform a literature review within the area of *Systems Engineering*, *Engineering Design*, *Product architecting* and *PLM* (Product Lifecycle Management), and to investigate the present state at Scania, concerning modularization and product description. This was mainly done in order to identify the main Research Questions (RQs) and to identify important aspects to consider when developing the new methodology and process.

The following main *research questions* (bullets marked in **bold**) were identified during this initial process. In order to answer these main questions, multiple RQs were identified and are listed below. Several of these RQs were also identified during the creation of the appended *Papers A - H*. Hence, the numbering of the RQs reflects the time when first used in the papers and is therefore not presented in numerical order.

- **How can DSM clustering be adapted to support the SE process?**
 - *RQ1: May clustering of a DSM with interactions representing spatial relations and function flows of energy, matter and signals, i.e. a paDSM propose reasonable module candidates?*
 - *RQ2: How does the output from a business strategic or layout constrained DSM clustering approach differ compared to paDSM clustering?*
 - *RQ7: Can business strategic constrained DSM clustering be augmented by also taking physical interferences into consideration?*
- **How can we analyze the consequences of different architectural trade-offs?**
 - *RQ4: Can a business strategic constrained DSM cluster analysis be used to identify reasons for a modular architecture that has been created based on expert judgement?*
 - *RQ5: How can we compare multiple clustering results?*
 - *RQ8: Can a business strategic and layout constrained DSM clustering approach enable effects from technical complexity, strategic aspects and physical interferences to be analyzed in any combination?*

- **How does the modeling of dependencies between components affect the clustering result?**
 - *RQ3: How sensitive is paDSM clustering to the relative weights of the spatial relations and the functional flows of matter, energy and signals?*
 - *RQ6: Does paDSM clustering with negative relation weights, representing undesirable/harmful relations, propose clusters without physical interference?*
- **How can a new methodology and process for product architecture clustering analysis support the SE process?**
 - *RQ9: What process steps, methods and representations may efficiently and effectively support the architecture clustering stage in SE?*
 - *RQ10: How can the proposed methodology and process for product architecture clustering analysis support the SE process?*

1.3 Thesis outline

Chapter 1 gives a brief introduction to the purpose of the thesis and the research questions. Chapter 2 provides some fundamental theory about Complexity management in Systems Engineering, Cyber-Physical Systems (CPS), Architectural representations, Product architecting and Product architecting at Scania. In chapter 3, the research methodology is briefly described. Chapter 4 summarize the results from the appended papers, and Chapter 5 summarizes the proposed architecting methodology and process. The results are discussed in Chapter 6. The research contribution is stated in in Chapter 7, where the identified research questions are answered and where the future work is proposed.

2 FRAME OF REFERENCE

This chapter provides some fundamental theory about Complexity management in Systems Engineering, Cyber-Physical Systems, Architectural representations, Product architecting and Product architecting at Scania.

In this chapter, the theory on which the thesis relies is presented. A more extensive and detailed Frame of Reference chapter in the area of *Product architecting* and *Product description* can be found in (Williamsson, 2018).

2.1 Complexity management in Systems Engineering

The term *complex* has been used for centuries in ordinary language to state that something is difficult, uncertain, unpredictable or complicated. *Complexity science* is rooted in *Chaos theory* and refers to the region between *order* and *chaos*. The main focus in chaos theory is to study nonlinear and dynamical systems with seemingly random behavior that do not fall into predictable states. The essence of *architecting* is structuring, which in its most general form can be defined as *bringing order out of chaos*.

In *Systems Engineering* (SE), *complexity* is commonly viewed as either *objective complexity* (structural-based) or *subjective complexity* (information-based). Objective complexity is typically viewed as a property of the object, and can thus be measured and quantified. This type of complexity can be referred to as *Technical complexity* in the product domain, and frequently depends on the *number of components*, *number of interactions/dependencies* between components and *number of types of components* in a product, etc. Subjective complexity, also referred to as cognitive complexity, is related to how humans perceive a system, i.e., it is considered to be a property of the relation between the system and the knowledge and skills of the human. These two categories of complexity measures have been used to address challenges related to different aspects of SE, e.g., *product design*, *manufacturing*, *assembly* and *logistics*. Törmgren and Sellgren (2018) discussed complexity related to development of CPS and showed five consequences of complexity, as well as six complexity facets causing humans to perceive complexity. The six facets are heterogeneity/diversity, size and computability, uncertainty and change, dynamics and/or structure, incidental/essential, unintended/accidental. In the *Engineering Design* domain, complexity is frequently viewed as a relative measure of the uncertainty of fulfilling the specified *functional requirements*, i.e. it is viewed as a relative measure of the existing knowledge compared to the desired/needed knowledge. Hence, as we gain knowledge during the development process, uncertainty (and thereby complexity) will be reduced.

A multitude of approaches, methods and tools have been proposed in the literature to manage technical complexity. Systems Engineering is a structured product development process, which can be conceptually represented as the V model. The V-model enables technical complexity to be managed by decomposing a large problem into several smaller problems in the process and, by doing so, enabling the development team(s) to “divide and conquer a system”. In product architecting, this principle is referred to as *architectural decomposition*.

2.2 Cyber-Physical Systems

Cyber-Physical Systems (CPS), also known as "smart systems" are co-engineered interacting systems of physical (e.g. mechanical and electrical) and computational components (e.g. embedded software). Examples of CPS technologies include *Internet of Things* (IoT) and *smart cities* etc. These technologies range from small (pace makers) to large-scale (power-grid) systems. Autonomous transport vehicles can be categorized as CPS that are components of *Cyber-Physical Systems of Systems* (CPSoS), i.e. transport systems. A key advantage of CPS is the potential to integrate *Information Technologies* (IT), operational technologies in terms of *embedded systems* and *control systems*, with *mechanical* and *electrical systems*, enabling new or improved functionalities and/or levels of performance. Hence, CPS development increases the need for innovation within and across traditional engineering and technical domains.

Today, modern cars, trucks, aircrafts and trains contain a large amount of networked embedded systems that need communication to perform their tasks. The complexity of these distributed systems has led to the creation of different standards, such as *AUTOSAR* (AUTomotive Open System Architecture) (AUTOSAR, 2020). AUTOSAR enables functions to be shared among the different system components in the network, meaning that one component does not need to only perform one function, which allows for many performance related benefits and possible cost reduction.

The complexity when architecting and designing *Cyber-Physical Systems* has been identified to be substantially higher compared to traditional systems without a large number of computational elements. The main reason for the increase of complexity is due to the complex interaction between physical and computational elements, i.e. the border between software and hardware becomes blurred. A large amount of complexity is also caused by the great variety of architectural choices, since the number of functions that could be implemented with a distributed computing system often is extremely high. Hence, identifying undesirable interactions between components are today a major concern when developing a CPS. Another key concern is to investigate and coordinate how the functions should be allocated to subsystems or modules (CyPhERS, 2013). A structured product architecting approach is therefore absolutely essential during the product development phase of a CPS.

2.3 Architectural representations

In order to get a complete and holistic understanding of a complex product or system, it is common to represent the product from different *viewpoints* and at different *levels of abstraction*. *Conceptual models*, often in graphical or matrix format, have proven valuable for analyzing, communicating and documenting complex products. Hence, these models play an important role in SE, and in this section some of the most common representations will be introduced.

A *product structure diagram* or "tree diagram" is a widely used model (related to *physical decomposition*), which represents the product information and how the information relates hierarchically to other pieces of information, see Figure 2. Though this type of representation can be used to model the complete architecture of a product, it is typically limited to representing the structure, i.e. only the hierarchical (vertical) relations are modeled.

Lateral (horizontal) relations are used to model interactions between elements, such as flows of material and/or information. A common way to model both lateral and hierarchical relations in a compact and scalable way is with a *Design Structure Matrix* (DSM). The DSM is a network modeling tool which represents the system elements and their interactions, thereby allowing the architecture of a system to be highlighted. The main benefit of DSM is the compact and intuitively readable graphical format. A *product architecture DSM* (paDSM) is a specific type

of DSM which represents a product architecture as a network of components and interactions. Pimmler and Eppinger (1994) proposed four generic *relation types* to represent the interactions between pairs of components or functions in a paDSM. These relation types are *spatial relations* and *flow of matter, information and energy*. In order to represent the relative importance of these relation types, *relation weights*, also known as *interaction strengths*, can be used.

Another commonly used architectural representation in SE and Engineering Design is a *function structure*. This type of representation shows how the functional elements of a product interact with the same type of relation as used in the paDSM. The difference between a *product architecture* and *product structure* should be noticed. The product architecture is the main model of a product, which brings together the product structure and the function structure, i.e. the mapping between functions and technical solutions (Brecher, 2012).

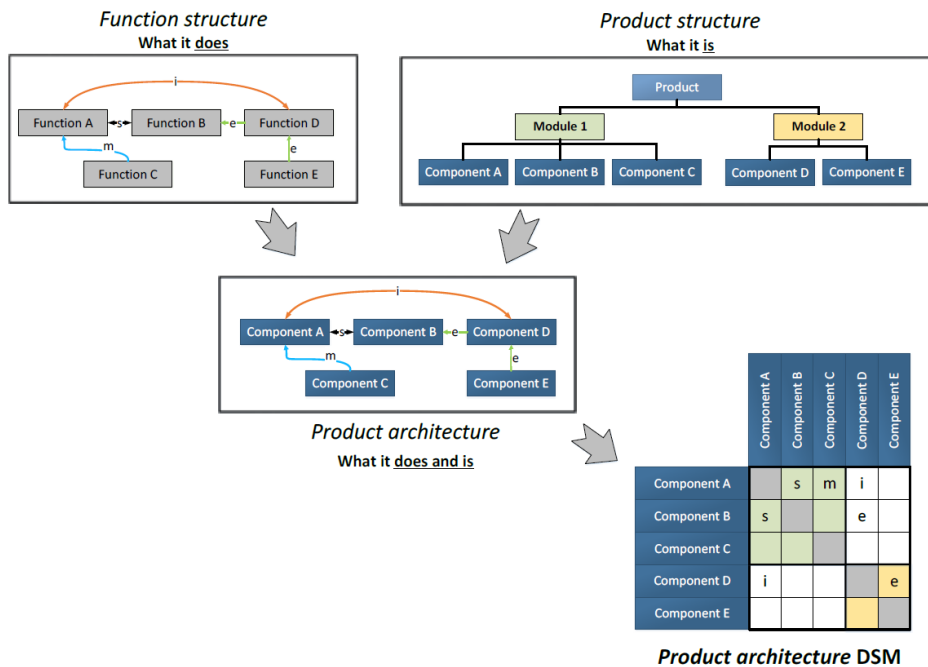


Figure 2. The difference between a *product architecture* and *product structure*.

In *graph theory* and *computer science*, an *adjacency matrix* shares many similarities with the DSM, i.e. it can be seen as the binary version of the DSM (Eppinger & Browning, 2012). An adjacency matrix is a square matrix used to represent a *finite graph* (also known as a *network* in computer science). In this case, the matrix elements represents if pairs of vertices (nodes or points) are related to an *edge* (link or line) or not. Examples of other network modeling tools included *process flow charts*, *N2 charts*, and *Node-link diagrams* (also known as a *Network diagram* or *Network Graph*), see Figure 3.

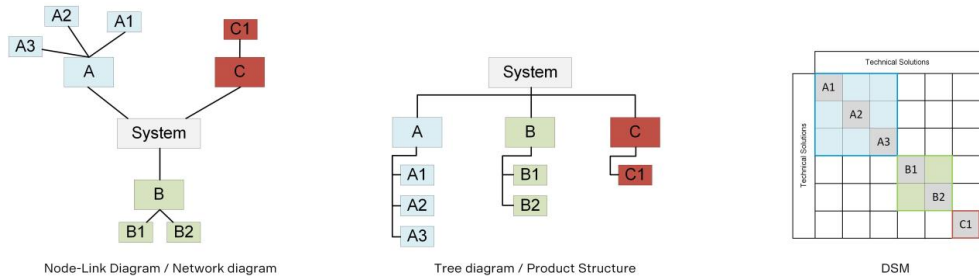


Figure 3. Different representations of the same system.

To facilitate cross-functional communication and collaboration on architecture-related tasks, Williamson (2018) proposed two different and complementary architectural representations to be used in addition to the paDSM: the *Component Architecture Diagram* (CAD) and *Component Cluster Diagram* (CCD). The CAD represents a product architecture as a network of components and interactions, see the example in Figure 4. The layout of the components in the CAD is not representing the final layout of the product, since it focuses on the component interactions. However, it gives a conceptual understanding of the design structure. The new representation was highly appreciated by the domain experts at Scania, and showed to make architectural discussions in general and modularity discussion in particular with and between domain experts efficient. Other researchers have proposed similar representations to the CAD, claiming complementary features and benefits when developing product architectures, see e.g. the *Interface diagram* by Bruun and Mortensen (2014) and the *Module Interface Graph* by Gebhardt et al. (2014). The Interface diagram represents a product architecture as a network of boxes containing component name information, i.e. it is similar to a function structure. One drawback with this representation is that it becomes hard to get an overview of the complete architecture. The Module Interface Graph represents the shapes of the components and connecting flows, making it easier to get an overview of the complete product architecture, though the representation becomes more form dependent (less solution-neutral) and thus less suitable when architecting novel products. In the CAD, the components are represented as simple icons (not showing the final shape of the components), making it less form dependent, while still allowing for an easy overview of the complete product architecture.

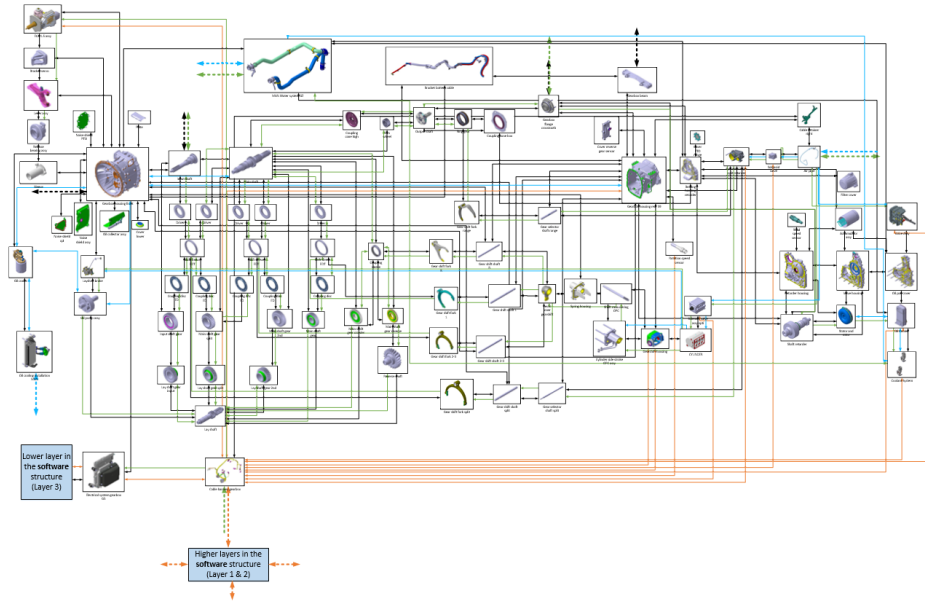


Figure 4. Example of a *Component Architecture Diagram* (CAD) (Williamsson, 2018).

To compare clustering results from different alternative DSM representations, Williamsson (2018) developed a *Component Cluster Diagram* (CCD) and used the CCD to show that the relative weights, or interaction strengths, of the different types of functional relations could have a significant influence on paDSM clustering. The Component Cluster Diagram (CCD), which is a simplification of the CAD since it represents the modular clusters but with no interactions represented, showed to be an efficient tool (Williamsson, 2018) for presenting the modular view of the architecture, see Figure 5.

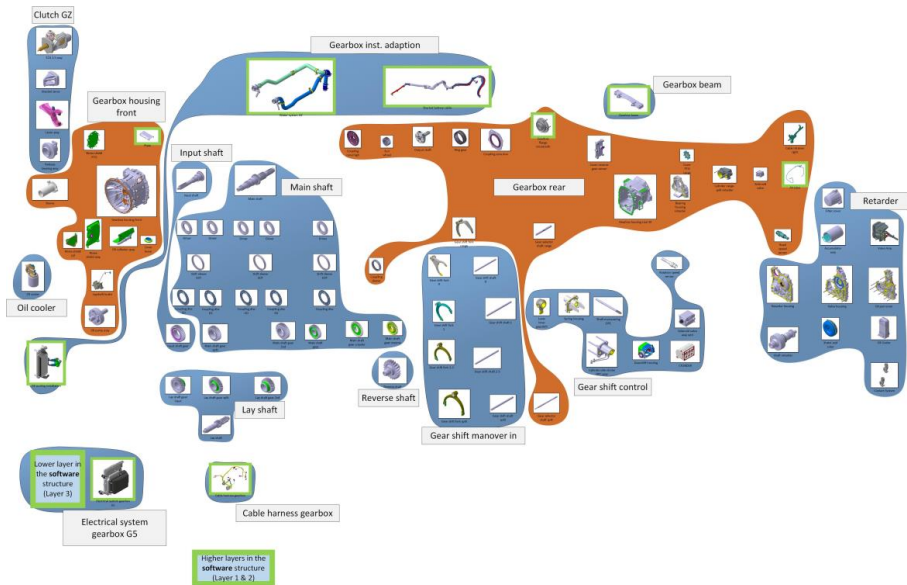


Figure 5. Example of a *Component Cluster Diagram* (CCD) (Williamsson, 2018).

Another important matrix-based tool for modeling system architectures is the *Domain Mapping Matrix* (DMM) (Eppinger & Browning, 2012). The DMM is normally a non-square matrix representing relationships between elements in different domains, e.g. the mapping between functions and components. In addition to the DSM and DMM, there are several other matrix-based tools for modeling system architectures. One example is the *Multidomain Matrix* (MDM), which was originally introduced by Maurer (2007) as a means to represent relationships between elements in different domains. The MDM is an extension of DSM, where two or more DSMs are added together to form one large matrix which can be analyzed holistically, i.e. it is a form of *knowledge integration matrix*. The diagonal of the MDM consists of single-domain DSMs, whereas the off-diagonal blocks are DMMs.

2.4 Product architecting

All engineered systems have some type of architecture. Crawly et al. (2004) stated that “*system architecture* is an abstract description of the entities of a system and the relationships between those entities”. This definition is consistent with IEEE (2000), where system architecture is defined as “the fundamental organization of a system embodied in its components, their relationships to each other, and to the environment, and the principles guiding its design and evolution”. *Product architecture* refers to a certain type of system architecture in the product domain. Some researchers define product architecture on the basis of the physical system components, e.g. Hubka et al. (1988) and Schuh G. (2005). Presently, there seems to be consensus that product architecture is the interrelation between physical components and their function, i.e. their purpose, e.g. (Crawly et al., 2004; Pimmler and Eppinger, 1994; Ulrich, 1993; Suh, 2001; Bonjour et al., 2009 and Browning TR., 2016).

Ulrich (1993) defines product architecture as “the scheme by which the function of a product is allocated to physical components”, and more specifically “(1) the arrangement of physical elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components”. One way to categorize the *architecture type* of a product is to focus on the type of mapping between functional and physical elements. If there is a one-to-one mapping between functional elements and physical components, the design is *uncoupled*, while it is *coupled* if the mapping is nested. In 2005, Hölttä-Otto defined these two types of architectures as being *modular* (uncoupled) and *integral* (coupled), see the example of an aircraft tail in Figure 6. However, most products are neither fully modular nor fully integral, i.e. there is a degree of modularity (and integrality). A hybrid architecture is a mix of these two types of architectures. Suh (1990) proposed a metric called *Reangularity* to determine whether a system is highly coupled (Reangularity close to zero) or uncoupled (Reangularity close to unity).

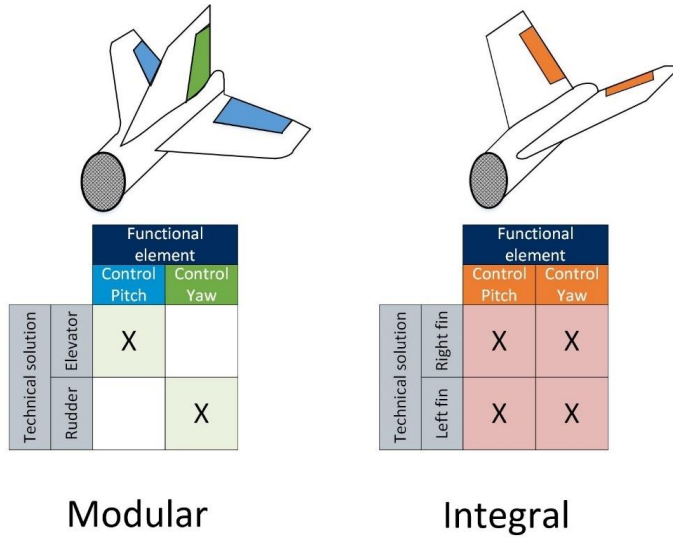


Figure 6. Ideal modular (left) and integral architecture (right).

A complementary way to categorize a product architecture as modular, hybrid or integral is to visually inspect the interactions between the components in a clustered paDSM, i.e. a component-based DSM with functional interactions between the components, see Figure 7. Hence, Ulrich and Eppinger (2000) claimed that a product architecture is also “the scheme by which the chunks (i.e. the modules) of a product interact”. Based on this definition, Sosa et al. (2003) stated that a “hypothetically perfect modular architecture” as one whose components do not have interactions with components that belong to other modules. Moreover, a “hypothetically perfect integral architecture” would be one whose components have interactions with all the modules that comprise the product, even if it may exhibit a modular architecture internally. The term *cluster* refers to a *module candidate* and is visualized as a box in the clustered paDSM. It is important to remember that the internal architecture of a module may be highly integral, but may be used in a highly modular way as a building block in a modular system. Hence, when categorizing a product architecture as modular, hybrid or integral, it is important to specify whether we are looking at the system internally (i.e. the architecture of the modules) or externally (i.e. the architecture of the system).

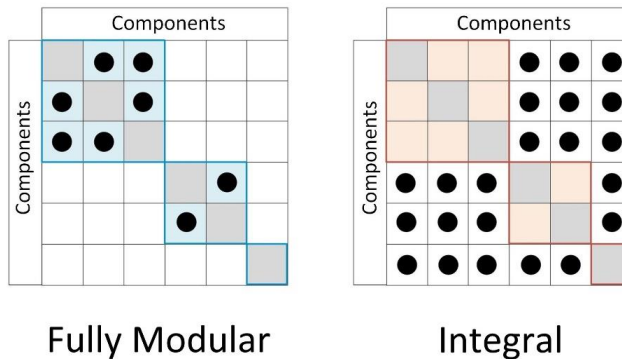


Figure 7. Ideal modular (left) and integral paDSM (right)

Product architecting is a highly iterative sub-process within SE that is used when *designing* a product architecture, and includes *conceptual system design*, *module identification* (clustering) and *product layout design*. When developing the architecture of a complex product, it is common to decompose the product into smaller elements such as subsystems, modules and components that can be further engineered. Modular subsystems enable concurrent development and *modularization* is, thus, a structured method to manage technical complexity.

Products having a modular architecture are configured from predesigned building blocks, i.e. modules. A *module* is a function carrier, with well-defined and standardized interfaces with other modules, that is configured for company-specific strategic reasons (Erixon, 1998). An *interface* can be viewed as a contract between two modules, that defines the *spatial orientation* and/or the flow and exchange of *information*, *matter*, and *energy*, (Börjesson, 2014). A key concern of SE is to deliver system-level performance by planning and controlling these interactions at the interfaces, since the properties of a system are not only determined by the properties of its elements, but also by the structure of the elements and the interaction pattern.

A *module variant* is a physical incarnation of a module with a specific performance level or appearance. Based on this definition, Börjesson (2014) defined a *modular system* as the collection of module variants by which all the required end products, i.e. the family of products, can be built. A *product platform* can be defined as a set of common components, modules or parts from which different products can be efficiently developed and delivered. This definition is product centric, meaning that the main focus is on the physical product and its components. Other researchers have expanded the general platform definition to also include other types of common assets to be shared, for example *knowledge* in the form of *knowledge platforms*, see e.g. (Jagstedt and Persson, 2019; Robertson and Ulrich, 1998).

The main purpose of a modular architecture is to enable *external variety* (many possible product variants to the customers), and *internal commonality* (that is reduction of parts) (Blackenfelt, 2001). A modular architecture can also support various other company specific *business strategies*. For example, modules can reduce *capital needs*, bring economies in *parts sourcing*, enable design *re-use*, enable *outsourcing/insourcing* and allow for easy *product changes* and *upgrades* etc. (Ulrich and Tung, 1991; Baldwin and Clark, 2000; Smith and Duffy, 2001; Ericsson and Erixon, 1999). A well-defined modular architecture can also make the product more *resilient to obsolescence*, i.e. lowering the risk that the product becomes outdated and obsolete. An important analysis when developing the architecture is thus to identify areas where the product most likely will undergo development during its lifecycle. Stake (2000) investigated how Module Drivers (MD) can be used to support company business strategies.

Höltkä-Otto (2005) identified three main and complementary approaches to define modularity. These are; *Heuristics*, *Modular Function Deployment* (MFD), and *Design Structure Matrix* (DSM). In 2000, Stone et al. proposed the *Heuristics*, or “rules of thumb” approach to identify modules that are expected to be good. The Heuristics approach is based on an analysis of the pattern of flow of *matter*, *energy*, and *information* between function blocks in a *functional structure*. Lehtonen (2007) investigated and found limitations with a function-based approach when defining a modular architecture, mainly since modularity is not only related to the functional structure of a product. The core of the *MFD* methodology (Ericsson and Erixon, 1999) is a five-step process for translating customer requirements into a modular architecture, while considering the company-specific *strategic objectives* described using twelve predefined MD that are represented by a module indication matrix (MIM). The MDs are the main reasons or purposes to group elements to modules. The MIM is a *Domain Mapping Matrix* (DMM) that relates the physical function carriers, i.e. the components, and the twelve MDs. The “strategic objectives” are related to *development*, *variety*, *production*, *procurement*, *quality*, and *after*

sales. Ulrich and Eppinger (2000), Sanchez (1994), Smith and Reinertsen (1995), and Ulrich (1995) list a range of reasons that both complement and overlap the MDs of Erixon. DSM-based approaches mainly focus on minimizing technical complexity by clustering the system components in a way that minimize the interactions between clusters of components, i.e. complex interactions are grouped within the clusters, see Figure 8. Börjesson and Sellgren (2013) proposed a very efficient DSM *clustering algorithm* referred to as *IGTA++*. This algorithm is based on *stochastic hill climbing* (within the *local search* family), which is a mathematical optimization technique frequently applied to many hard computational problems, e.g. the *traveling salesman problem*. All algorithms which are based on hill climbing are iterative algorithms, and starts with an arbitrary solution to a problem. The IGTA++ algorithm aims to minimize an *objective function*, where the sum of all Intra- and Inter-cluster relations are used to calculate the *Total Cost complexity index*, i.e. the technical complexity. The algorithm aims to minimize the complexity index by moving one element at a time until stable clusters, i.e. convergence, is found.

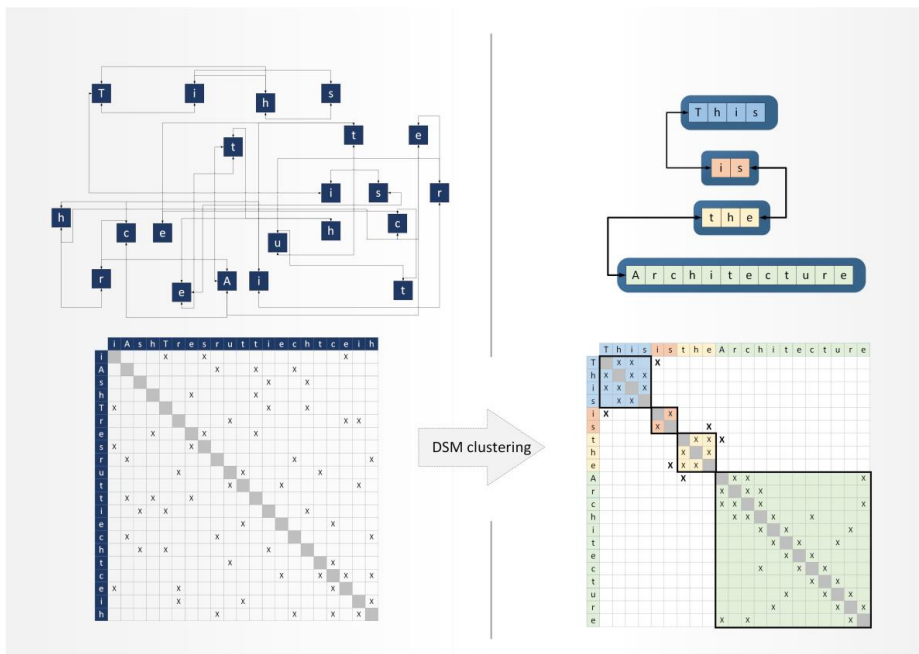


Figure 8. DSM clustering analysis of a system represented in DSM and diagram format.

Both Heuristics and DSM approaches address technical complexity, but not strategic objectives. On the other hand, MFD address strategic objectives but does not explicitly address technical complexity. In an attempt to balance the technical complexity represented by a DSM and business strategies represented by a MIM, Stake (2000) presented examples from manual clustering of a DSM and a MIM. In 2001, Blackenfelt proposed a conceptual approach on how to combine the DSM and MIM, by condensing the MDs into four generic groups (Carry over, Commonality, Make or by, and Life cycle) and representing the relations between those four groups for each component as a DSM, but performed no further analysis.

Browning (2016) made a comprehensive review and found that most existing computer-based product architecture clustering methods do not explicitly take Engineering Design constraints (e.g. business strategic objectives) into consideration, thus potentially lowering the quality of the architectural decomposition. It should be noted that these modularization approaches only

should be used to assist the task when identifying module candidates. The proposed module candidates should therefore only be seen as possible solutions, which experts need to analyze before selecting the final modules.

Module identification is normally followed by *product layout design*, which is a highly iterative sub-process. Making a rough spatial layout of the product enables analyses of potential *spatial*, *thermal*, or *electrical* interferences between components, within and between module candidates.

After completing the product architecture, the development of the modules can typically proceed concurrently. This can be done by dividing the design tasks, including the specialized design teams, based on the modular product architecture. Hence, the module interfaces will naturally form communication points between the design teams. This approach typically requires the *organizational* and *product architecture* to have close to one-to-one mapping between *design teams* and *modules*, that is, module A is designed by team A. This is common when developing complex products in the aerospace and automobile industry (Sosa et al. (2007)). It is therefore important that the interfaces are well understood and documented. Since the interfaces become the communication point, unfavorably chosen modules may increase the amount of communication between the design teams, resulting in a longer product development cycle and increased risk of making design mistakes.

The generic, or general, product structure is a structure developed for a product portfolio, instead of a single product variant. It contains several interchangeable and configurable components, in order to describe all possible product variants. This means that a generic product structure and the corresponding product portfolio is created in the product development process, while the individual product variants are formed in the order-to-delivery process. When a product variant is customized according to a customer wish, it is called *product configuration* or a configuration process. A generic product structure therefore efficiently represents a modular product architecture, especially when it is possible to create many product variants from the product portfolio.

2.5 Product architecting at Scania

The heavy vehicle manufacturer Scania is often used as a role model for modularization. Due to the high number of product variants, Scania represents their modular product as a generic product structure, enabling a compact and effective product description. A generic product structure does not describe a single variant of a product family, but rather the entire product portfolio, which in Scania is referred to as the modular toolbox, see Figure 9. The product architecture at Scania has been identified to be a hybrid between a modular and an integral architecture, meaning that it is modular at a higher system level and integral at a lower level (Williamsson, 2018). This hybrid architecture therefore needs to be defined with configuration rules (conditions), since the modules cannot be combined arbitrarily. The configuration rules at Scania are located at all levels in the generic product structure, which allows the product to be configured in a highly flexible way.

The modularization process is claimed to start and end with the customer, i.e., the purpose of modularization is here to deliver a customized product that is targeting the needs of the specific customer.

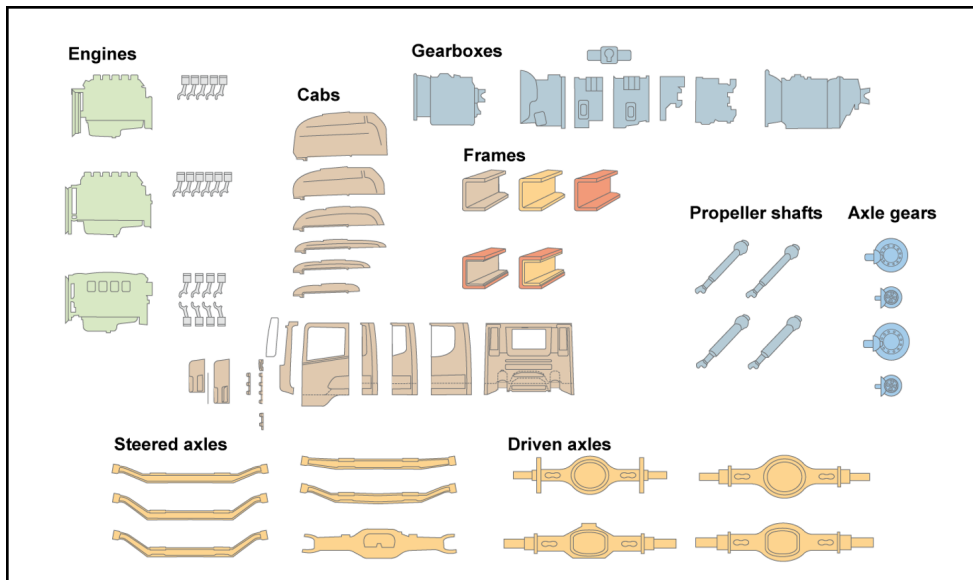


Figure 9. The Scania MODULAR TOOLBOX.

The traditional core of Scania's modularization principle is carefully balanced module variants (referred to as performance steps), with standardized interfaces that can be configured to satisfy different customer needs, with a limited number of components. Scania therefore strives to maximize the number of product variants (external variety), while keeping the number of components low (internal commonality). Furthermore, the product variants are not designed to satisfy some predefined and specific customer requirements and during configuration they are chosen as late as possible (late variant definition) when the actual customer demand is known. The present product architecture at Scania can therefore be seen as the result of the modularization process and principles, which have evolved and been applied over decades.

Notice the difference between *modularization* and *standardization* of a product. Standardization 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 may decrease to some extent if not handled properly. Hence, standardization can be seen as the opposite to modularization in terms of product variety and development approach, see Figure 10.

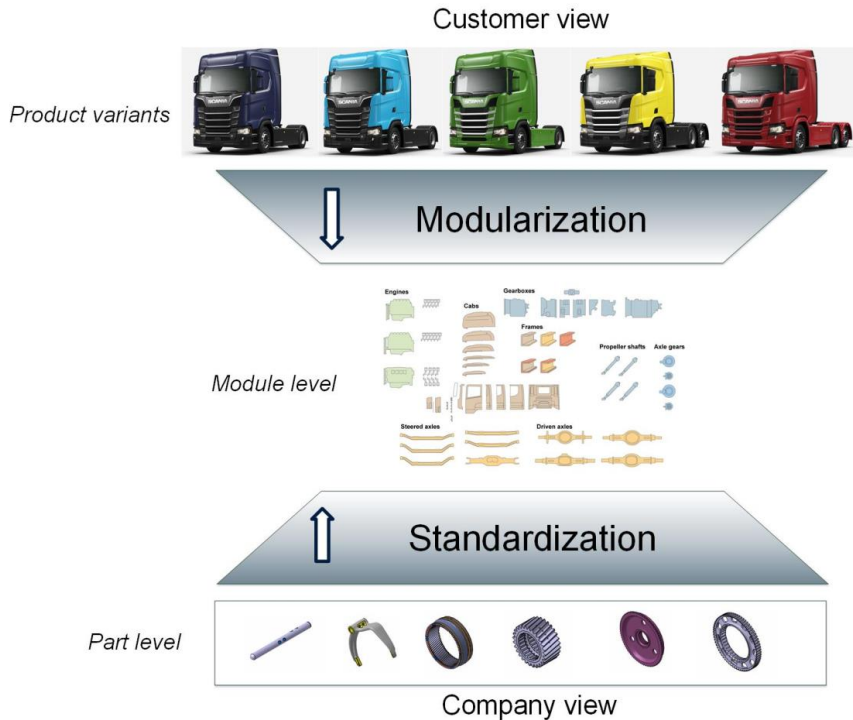


Figure 10. Modularization vs. Standardization.

The main truck components are developed and manufactured in-house at Scania. This means that outsourcing is generally a weak MD at Scania, compared to most performance related MDs. To efficiently enable trade-offs between high degree of configuration flexibility and high overall performance, the electrical system, including the embedded software, has a decentralized architecture, i.e., distributed intelligence. This means that more of the intelligence is embedded in (allocated to) different modules, with multiple electronic control units (ECUs) distributed in the complete vehicle. At Scania, this type of architecture is also believed to increase the functional robustness of the complete electrical system through redundancy, e.g., if one ECU malfunctions, its function can be taken over by other ECUs. In general, all embedded software is included in the ECUs at Scania, independent of the actual configuration of a specific product variant. However, the software still needs to be adapted depending on the hardware configuration for each specific product variant. The software is therefore parametrized to fit the different physical configurations and is consequently architected as a variational module, i.e., it is another type of product module than most modules dominated by hardware. The embedded software is structured in multiple layers, where the highest layer is composed of logical components. Logical components realize logical functions, which has a similar meaning as the general module definition. They are used to link the user functions to the software components. Logical components are also used to specify interface information. The middle software layers carry general software functions, for example, diagnostics, etc. Finally, the lowest layers contain hardware-related software (usually referred to as firmware), and the BIOS (basic input/output system).

3 RESEARCH METHODOLOGY

This chapter provides a brief presentation of the Design Research Methodology framework, as well as the applied research methodology and process in the presented research project.

3.1 Design research methodology

Design research concerns the development of design support, i.e. all possible means, aids and measures that can be used for improving design (e.g. methodologies, guidelines, tools, etc.). The *Design Research Methodology* (DRM) is a framework aimed for doing design research in a more efficient and effective way (Blessing and Chakrabarti, 2009). The DRM provides for a more rigorous research approach by supporting the implementation and planning stage of a design research project, thereby improving the chances of a successful project with useful and valid results.

The DRM framework consists of four main stages: *Research Clarification*, *Descriptive Study I*, *Prescriptive Study* and *Descriptive Study II*, see Figure 11. The aim of the *Research Clarification* stage is to identify the overall goals of a research project, develop a research plan, identify the main RQs/hypotheses and to understand the existing situation (as-is). Most product development methodologies highlight the importance of identifying the needs of the customer/user in the early stage of the development. Developing a new methodology or process is no different. The *Descriptive Study I* aims to obtain a better understanding of the factors that influence the customer needs, including the relevance of the research topic. If the customer needs are not correctly understood, a less optimal methodology may be developed. This can be very expensive in terms of both time and money. The next step in the DRM process is the *Prescriptive Study* where a first concept of the new methodology is developed. The methodology is typically not only developed based on the findings from the earlier stages, but also includes various creativity activities. The result of this activity should result in a description of the new methodology, including how it works and how it can be introduced to the users. Finally, the *Descriptive Study II* aims to verify and validate the new methodology by, for example, performing case studies. This stage also includes how the new methodology should be used, as well as potential methodology improvements.

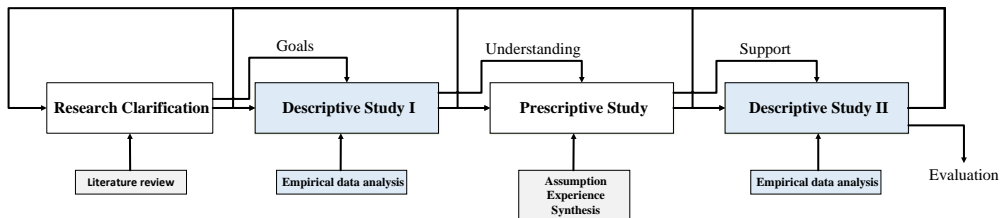


Figure 11. The DRM process.

3.2 Applied research methodology & process

The research methodology & process used in presented research project was inspired by the DRM framework. Hence, the main steps of the presented research project shares many similarities with the DRM.

A combination of *inductive* and *deductive* research approaches was used in the presented thesis, thus requiring both *qualitative* and *quantitative* research methods to be used. The qualitative research process may look different depending on research project, since it is relatively flexible (Backman, 2016). However, in this project a general qualitative research process was used as a guideline, see Figure 12. It should be stated that many of the steps in this process are highly integrated into the practical workflow, and that the illustration therefore only gives a general view of the actual research process. The *inductive* approach or inductive reasoning is a “bottom-up” approach where specific observations are used to identify patterns and develop theories, i.e. explanations for the observed phenomena. In this approach, it is also possible to use existing theory to identify RQs to be explored. When analyzing the results and developing theories, new RQs may also be identified. The *deductive* research approach is a “top-down” approach which aims at testing theory, i.e. it typically begins with a *hypothesis*. The testing part is largely associated with *quantitative* methods, however, *qualitative* methods are also possible.

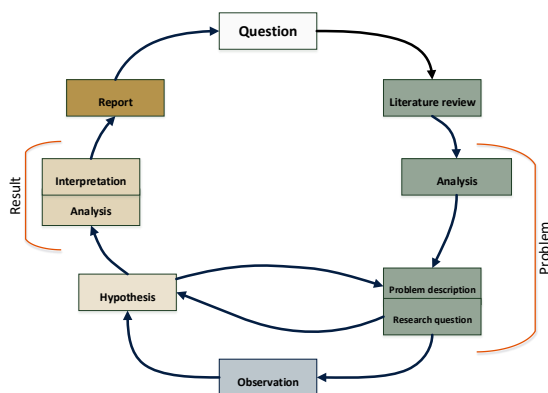


Figure 12. The general qualitative research process (Backman, 2016).

As stated in chapter 1, the main hypothesis behind the presented research is that *computer-based product architecture clustering analysis benefit from a quantitative complexity measure, as well as means to represent (model) and communicate product architecture related complexity*.

The main process of the presented research project is represented with the IDEF0 functional modeling method, see Figure 13. As earlier stated, the overall aim of the presented research project is to provide a contribution to SE by proposing a new modularization methodology and process for product architecture clustering analysis of CPS within the heavy-duty truck domain. The new methodology and process should assist the task to define functional borders and robust physical interfaces between the modules, to deal with the increased technical complexity.

To fulfil this aim, the first milestone of the research project mainly involved “desk research” in a prestudy, meaning that the prestudy research questions were of an applied nature and open-ended (Williamsson, 2018). In DRM, “desk research” is referred as the **Research Clarification**

stage. In this stage, the goals were formulated, and the *state-of-the-art* was identified by performing a *literature review* within the area of *Systems Engineering*, *Engineering Design*, *Product architecting* and *PLM* (Product Lifecycle Management). Hence, in this part of the research project, a qualitative research methods was used in the inductive research approach. The results from the literature review was then used as an input to the research question identification stage, as well as investigating the present state (as-is) concerning product architecting and product description at Scania. All results of this prestudy are presented in a licentiate thesis (Williamsson, 2018), while some of the main finding concerning the present Scania product architecture, as well as new ways to represent product architectures, can be found in the “Frame of Reference”, (chapter 2) in this thesis.

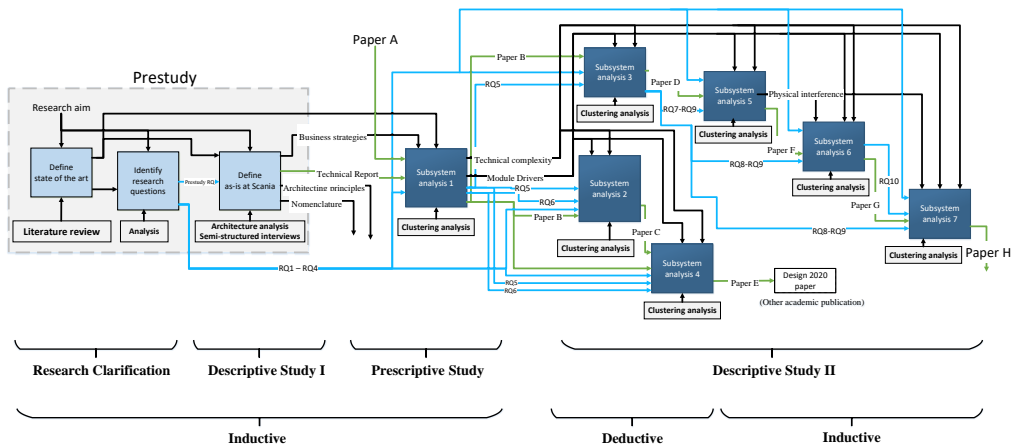


Figure 13. Main process of the presented research project.

To answer the prestudy research questions, specific main Scania components (subsystems) were identified, selected and analyzed in a case study, in order to exemplify the difficulties when architecting a multidisciplinary product, as well as visualizing the existing product architecture. In DRM, this stage is referred as **Descriptive Study I**. During the literature review, it was identified to be especially important and interesting to investigate a subsystem that covers different technical disciplines, in order to exemplify the difficulties when modularizing and describing a multidisciplinary product with complex relations between the components. When selecting the main components to investigate, one criterion was therefore that it should contain *mechanical hardware*, *electrical system* and *embedded software*. After identifying the main components, an extensive architectural analysis was performed by the author in order to identify which type of product architecture the main components had, including the degree of modularity. The analysis involved reverse engineering of the physical and functional structures and their relations, i.e. the architecture, of the main system components, by combining *function-means tree representation* with the *Modular Function Deployment (MFD)* methodology, and *Design Structure Matrix (DSM) clustering*.

By analyzing the present product architecture, it was possible to answer the first prestudy research question regarding *the present state at Scania*. However, in order to answer the second and third prestudy research question regarding *the unique properties in the modular product architecture at Scania*, and *how a product architecture can be represent to facilitates cross-functional communication on architecture-related tasks*, the results of the case study was not

complete. Therefore a phenomenological research analysis was performed with *semi-structured interviews* (Kvale, 1997), to get an insight of the modularization process, from the perspectives of numerous designers within *mechanical hardware, electrical and embedded software* development at Scania. This interview approach was chosen in order to allow the respondents own words and experiences to shine through. This gave the respondents some freedom to talk more about what was important to them, and also made it possible to acquire information which was not thought of in advance. By analyzing the result of the semi-structured interviews, including the case study, it was finally possible to answer the second and third prestudy research question. The result of this investigation, including the complete prestudy research questions, can be found in the licentiate thesis (Williamsson, 2018). The new knowledge from this investigation also resulted in some general architecting principles and suggestions for nomenclature improvement at Scania.

After performing the first case study and interviews, new knowledge was established which led to the conclusion that several other case studies were needed to verify, generalize and further improve the newly proposed integrated modularization methodology into a robust and efficient methodology. In DRM, the stage when a first concept of a new methodology is developed is referred to as ***Prescriptive Study***. The new methodology was not only developed based on the findings from the earlier stages, but also included experience and various creativity activities.

The aim of a case study is to create general knowledge from individual observations. In general, this is an inductive research approach. However, the presented research also involved a deductive research approach by using both quantitative (e.g. clustering analysis) and qualitative methods (e.g. visually analyzing multiple CCDs). Ideally, a case study should generate similar results independent of who is performing it. This becomes difficult when dealing with industrial case studies since they rarely can be fully replicated. The aim of the presented research was thus to maximize reliability by performing multiple case studies with a variety of investigated subsystems and participants at the company. In DRM, the stage when the new methodology is verified and validated is referred to as ***Descriptive Study II***.

It should be stated that the new modularization methodology was originally created in Paper A, which was published by the author prior to the presented research project. Therefore, the findings in Paper A mainly served as an input to research presented in Paper B. The findings in Paper B thereafter served as an input to Paper C, which in turn served as an input to Paper E. In a similar way, the findings in in Paper B served as an input to Paper D, thereafter served as an input to Paper F, which in turn served as an input to Paper G, which in turn served as an input to the last Paper H.

In papers F, G and H, a certain type of qualitative research method was used called *action research* (Avison D. et al., 1999). In action research, the aim is to try out a new theory (e.g. a new methodology) with experts in real situations, learn from this experience, change the theory depending on the outcome, and finally try it again. This allows academic research to be more relevant in real-world situations. Action research allows researchers and experts to act together in an iterative process. Hence, action research is unique in the way it connects research and practice, allowing research to inform practice and practice to inform research synergistically. Action Research can therefore be seen as a form of “rapid prototyping” when developing new methodologies. Hence, in papers F, G and H, the author took part in two different development projects at Scania, which are presented as case studies in the papers. This gave the author a unique opportunity to evaluate how the new modularization methodology and process for product architecture clustering analysis of CPS actually worked in practice. Since the author participated in the projects, some findings were implemented at Scania, thereby partly affecting the outcome of the projects.

4 SUMMARY OF RESULTS AND APPENDED PAPERS

This chapter summarizes the results from the appended papers and the technical report.

4.1 Addressed knowledge domains and scientific communities

Product architecting is a multidisciplinary research area which requires knowledge and acceptance from various scientific communities, each being specialized in a certain research area. Hence, this PhD thesis is a synthesis of eight scientific papers, which all have been reviewed and accepted (except paper H which is under review, but accepted with minor modifications) by leading experts in each specific knowledge domain. The papers were presented at multiple academic conferences, or published as journal articles within the *Design Society*, *ASME* (The American Society of Mechanical Engineers) and *INCOSE* (International Council on Systems Engineering), with a focus on *Systems Engineering* and *Engineering Design*, which is an important subprocess in SE. To further verify and generalize the findings, some of the *Research Questions* (RQs) are input to several case studies and thus elaborated on in more than one paper, see Figure 14. Hence, this figure represent how each research question is explicitly and/or implicitly addressed in the different papers.



Figure 14. This thesis is a synthesis of multiple papers presented at the indicated scientific communities.

4.2 Summary of appended papers

Paper A: An approach to integrated modularization

A new methodology for product modularization that integrates technical complexity and company strategies is proposed and logically verified with an industrial case study. The new method is named *Integrated Modularization Methodology* (IMM) due to the integrated approach for identifying module candidates during the clustering stage. Existing methodologies, such as *Modular Function Deployment* (MFD) with the *Modular Indication Matrix* (MIM) representation of identified company-specific module drivers, can be used to assist the module identification task. Other approaches, such as clustering of the *Design Structure Matrix* (DSM) product representation, may be used to identify modules from a technical complexity point of view. The core of the new IMM is to adapt the *Product Architecture DSM* (paDSM) with MIM-strategies, before clustering this hybrid representation with the *IGTA++* clustering algorithm in MATLAB.

The result of the case study leads to the conclusion that clustering a standard paDSM results in a modular architecture with significantly reduced complexity, but with clusters that contain conflicting module drivers. This result answers **RQ1** (regarding whether clustering of a paDSM may propose reasonable module candidates), though further verification is needed to generalize the finding. The study also identifies that the IMM proposes module candidates with significantly reduced complexity, but without any conflicting module drivers. This result answers **RQ2** (regarding how the output from a business strategic or layout constrained DSM clustering approach differ compared to paDSM clustering), though further verification is needed to generalize the finding.

Paper B: Product architecture transition in an evolving multi-brand organization

The introduced *Integrated Modularization Methodology* (IMM), proposed in *Paper A*, is logically verified with a new industrial case, where a truck manufacturer with a unique business strategy had to modify parts of its modular gearbox architecture to also become a First-Tier OEM-supplier to another large truck manufacturer, with slightly different strategies.

Reverse engineering of the presented case indicates that the IMM is capable of identifying and proposing reasonable module candidates that address technical complexity as well as company specific strategies. This result answers **RQ2**, though further verification is still needed to generalize the finding. Moreover, the case study leads to the conclusion that clustering of a paDSM, with interactions that represent spatial relations and functional flows of energy, matter and signals, may propose module candidates that address technical complexity, but not strategic business concerns, i.e. **RQ1** is confirmed again and is thus further verified. Finally, it is found that the DSM clustering result depends on the relative weights (importance) of the different types of component interactions that are represented by the DSM. The final result answers **RQ3** (Regarding how sensitive paDSM clustering is to the relative weights), though further verification is needed to generalize the finding.

Paper C: The hunt for proper relation weights in product architecture clustering

In this paper, the performance of the *Integrated Modularization Methodology* (IMM) from *Paper A*, is conceptually verified with an industrial case (based on *Paper B*). The case is also used to analyze if clustering could be used to re-engineer the reasons why the original gearbox architecture was rearchitected in the way it was, from technical complexity point of view, by elaborating on the relative weights of the spatial relations and the three different types of functional flows, and from an integrated technical complexity and changed business strategy viewpoint.

Reverse engineering of the investigated architecture indicates that the current modules are most likely not only based on technical complexity concerns. They are rather derived from different types of business strategic aspects, e.g. outsourcing. The study also indicates that the IMM is capable of identifying clusters without strategic conflicts, and with the most similar result to the analyzed architecture, which is assumed to be based on expert judgements. This result answers **RQ2**, though further verification is still needed to generalize the finding. The result of the case study leads to the conclusion that the IMM methodology can be used for analyzing and finding the explicit and/or implicit, technical as well as strategic, reasons behind the architecture of an existing product. This result answers **RQ4** (Regarding if a business strategic constrained DSM cluster analysis can be used to identify reasons for a modular architecture that has been created based on expert judgement), though further investigation is needed to further verify and generalize the finding. To enable comparison of clustering results of the same system, a *Cluster Match Matrix* (CMM) is moreover developed and proposed. This result answers **RQ5** (Regarding how multiple clustering results can be compared), though further investigation is needed to further verify and generalize the finding. Moreover, **RQ1** and **RQ3** are confirmed again and are thus further verified.

Paper D: Product architecture transition in a modular cyber-physical truck

The *Integrated Modularization Methodology* (IMM) is logically verified with a new industrial case, where the architecture of a heavy truck driveline is analyzed in terms of how it has evolved over a couple of decades, due to changed business strategies and the evolution of new technology. The case is also used to identify potential architectural improvements and to identify how the architecture may be transformed in the future due to a larger presence of embedded software and information interfaces.

The results of the case study show that the new IMM is capable of identifying and proposing reasonable module candidates that address technical complexity as well as company specific strategies. This result answers **RQ2** again and is thus further verified. Furthermore, the case study clearly indicates that the business strategic reasons for a specific architecture can be found by analyzing how sensitive the clusters are to changes in the module drivers. This result answers **RQ4** again and is thus further verified. Moreover, **RQ1** and **RQ3** are also confirmed again and are thus further verified.

Paper E: A hunt for the hidden reasons behind a product architecture

In this paper, the performance of the *Integrated Modularization Methodology* (IMM) from *Paper A*, is conceptually verified with an industrial case (based on *Paper B*), where a heavy-duty modular gearbox architecture is represented and analyzed. In focus is re-engineering of hidden technical complexity and business strategy concerns behind the existing product architecture. The architecture of the investigated gearbox is represented and analyzed with a paDSM and the *Integrated Modularization Method* (IMM). Furthermore, the *Cluster Match Matrix* (CMM) from *Paper C* is refined and used as a means to compare multiple clustering results.

The case study concludes that clustering of a paDSM may propose module candidates that address technical complexity, but not strategic business concerns, i.e. **RQ1** is confirmed again and is thus further verified. It is also found that the investigated gearbox architecture most likely is developed to provide company strategic benefits, besides from the aim to reduce technical complexity. This result answers **RQ4** again and is thus further verified. Hence, the case study indicates that the IMM methodology and CMM can be used for analyzing and finding the explicit and/or implicit reason for an existing product architecture. This result answers **RQ5** again and is thus further verified. Moreover, **RQ2** and **RQ3** are confirmed again and are thus further verified.

Paper F: Introducing implementation dependent behavior into integrated product architecture clustering

The *Integrated Modularization Methodology* (IMM) introduced in *Paper A*, is extended to a new version in order to improve the quality of the clustering analysis. The extended IMM (eIMM) adds physical interference and implementation dependent behavior into product architecture clustering. The eIMM methodology is conceptually verified with a new industrial case, where a presently developed battery electric truck is used as a test bench for studying if and how the paDSM and eIMM approach may enable the identification of module candidates that are reasonable trade-offs between technical complexity, business strategies and physical interference.

The result of the case study leads to the conclusion that the eIMM methodology is able to propose a modular product architecture without conflicting business strategies or intra-modular physical interferences, as well as reasonable module candidates from a technical complexity point of view. This result answers **RQ7** (Regarding if business strategic constrained DSM clustering can be augmented by also taking physical interferences into consideration), though further investigation is needed to further verify and generalize the finding. Moreover, it is found that representing undesirable and harmful relations in a paDSM by assigning negative relation weights does not guarantee clusters with no physical interference. This result answers **RQ6** (Regarding if paDSM clustering with negative relation weights, representing undesirable/harmful relations, does propose clusters without physical interference). The eIMM is modular, allowing the effects from technical complexity, strategic aspects and physical interference to be analyzed independently or combined depending on purpose. This result answers **RQ8** (Regarding if a business strategic and layout constrained DSM clustering approach can enable effects from technical complexity, strategic aspects and physical interferences to be analyzed in any combination), though further investigation is needed to further verify and generalize the finding. Moreover, **RQ1**, **RQ2** and **RQ3** are implicitly addressed and are thus further verified, though they are not stated in the conclusions.

Paper G: Architecting a modular battery electric truck

In this paper, the performance of the *extended Integrated Modularization Methodology* (eIMM) from *Paper F*, is further verified with an industrial case (based on *Paper F*), where a presently developed battery electric truck is used as a test bench for studying if and how the paDSM and eIMM approach may enable the identification of module candidates that are reasonable trade-offs between technical complexity, business strategies and physical interference. The aim is also to identify how sensitive DSM and eIMM clustering is to the relative weights of the spatial relations and the functional flows, as well as analyzing how much the technical complexity changes when assigning different relation weight combinations.

The presented case study confirms that the DSM and eIMM clustering results depends on the relative weights of the different types of component relations. The change is larger for the DSM approach compared to the eIMM, due to the introduction of business strategic and physical interference constraints. This result answers **RQ3** again and is thus further verified. In addition, the case study indicates that the eIMM is able to propose a modular product architecture with reasonable module candidates from a technical complexity point of view, and without conflicting business strategies or intra-modular physical interferences. This result answers **RQ7**, though further investigation is needed to further verify and generalize the finding. Moreover, **RQ1**, **RQ2** and **RQ8** are implicitly addressed and are thus further verified, though they are not stated in the conclusions.

Paper H: Integrated modularization methodology and process for heavy-duty trucks

In this paper, the *extended Integrated Modularization Methodology* (eIMM) from *Paper F*, is further verified with a new industrial case, where a conceptual *Battery Electric Vehicle* (BEV) variant is used to describe the proposed methodology and process, and to verify that it is capable of identifying module candidates that are reasonable trade-offs between technical complexity, business strategies and physical interferences. The main objective is to study if and how the eIMM methodology and a new process for Integrated Modularization can support the overall SE process. The aim is also to verify, generalize and further improve the robustness and the efficiency of the proposed methodology.

The presented case confirms that the proposed methodology and process for Integrated Modularization supports the SE process by improving the quality of the architectural decomposition, i.e. the module identification stage by adding business strategies and physical interference to product architecture clustering. This result answers **RQ10** (Regarding how the proposed methodology and process for product architecture clustering analysis can support the SE process). Furthermore, the case study clearly shows that the clustering results depends on the relative weights of the different types of component relations that are represented in the paDSM, though the importance of these weights are reduced when multiple business strategic aspects and physical interference constraints are introduced. This result answers **RQ3** again and is thus further verified. The case study also indicates that the proposed eIMM is capable of identifying and proposing module candidates without conflicting MDs or affordances, as well as reasonable module candidates from a technical complexity point of view. The traditional DSM clustering approach proposed clusters based on technical complexity, but not on strategic business concerns or physical interferences. This result answers **RQ7** again and is thus further verified. Finally, the case study confirms that the eIMM is both scalable and flexible, allowing the consequences of different architectural trade-offs from technical complexity, strategic aspects and physical interferences to be analyzed independently or combined depending on purpose. This result answers **RQ8**. Moreover, **RQ1** and **RQ2** are implicitly addressed and are thus further verified, though they are not stated in the conclusions. Finally, **RQ9** (Regarding what process steps, methods and representations that may efficiently and effectively support the architecture clustering stage in SE), is implicitly addressed, though it is not stated in the conclusions.

5 PROPOSED ARCHITECTING METHODOLOGY AND PROCESS

This chapter summarizes the proposed architecting methodology and process which has been developed in the presented research project.

5.1 Summary of the proposed architecting methodology

The approach used in the proposed modularization methodology is to treat complexity as a quantifiable and intrinsic property of a system or product, which can be used in product architecture clustering analyses to enable management of complexity and, thus, improve the quality of the architectural decomposition in the module identification stage. To quantify this type of objective complexity, I use the concept of *Total Cost*, which I use as a measure of *technical complexity*. The proposed modularization methodology aims to support the SE process by augmenting the traditional DSM clustering approach by taking strategic aspects and physical interference (layout) constraints into consideration during the architecture clustering stage. The final version of the proposed modularization methodology is named *extended Integrated Modularization Methodology* (eIMM) due to the integrated approach for identifying module candidates during the clustering stage. The eIMM contains multiple newly developed representations, e.g. the CAD and CCD, to facilitate efficient cross-functional communication and collaboration on architecture-related tasks. The eIMM consists of multiple matrices, which can be included in any combination depending on the purpose of each analysis. By separating the information into multiple matrices, it becomes possible for the user of the methodology to e.g. analyze if and how the clusters are changed when business strategies and/or physical interferences are introduced. It also becomes possible to capture new knowledge (as new matrices) when it emerges in the development process. This allows the eIMM to be both scalable and flexible.

The core of the eIMM is a *layout adapted DSM* (laDSM), which is a DSM that integrates a paDSM with the *Module Indication Matrix* (MIM) and *Affordance Structure Matrix* (ASM). If the paDSM is integrated with the MIM, the resulting DSM is referred to as a strategically adapted DSM (saDSM). The MIM is a central tool in the MFD method and describes how the components in the paDSM relate to the company-specific strategic objectives, i.e. the twelve predefined MDs shown in Table 1. According to the MFD method, components having strategically conflicting MDs, i.e. mismatches in strategies within a module candidate, should not be grouped together. A key concern of the MIM is thus to identify components having strategically conflicting MDs. In eIMM, the MIM (see upper left part of Figure 15) is represented by a strategy transfer DSM (see lower left matrix in Figure 15), with all conflicting MDs represented by a minus sign.

Table 1. The Module Drivers (MDs).

Module Driver group	MD #	Module Driver description
Development and design	1	Carry over
	2	Technology push
	3	Product planning
Variance	4	Different specification
	5	Styling
Production	6	Common unit
	7	Process/organization
Quality	8	Separate testing
Purchase	9	Black-box engineering
After sales	10	Service/maintenance
	11	Upgrading
	12	Recycling

ASM is an important representation tool in the *Affordance Based Design theory*, and can be used in the product architecting phase to augment DSM capabilities. The ASM primarily represents how the components in the paDSM relate to the affordances. These relations can either be helpful (+), harmful (-), or neutral (). An affordance is what one system provides to another system (or part of a system, e.g. a component). Unlike functions, affordances are form-dependent and are therefore useful when dealing with product layout aspects. By adding the number of affordances which each component has a helpful, harmful or neutral relation with, a total score can be calculated. This score is used to identify components which may be harmful to components having conflicting affordances, i.e. components having physical interferences which should not be clustered together. In this way, physical interference within clusters is avoided. However, undesirable and harmful effects between clusters still need to be resolved in the trial layout, or (if required) in the *detail design* phase. In eIMM, the ASM (see upper right part of Figure 15) is represented by an affordance transfer DSM. The “roof” of the ASM in eIMM is therefore used to represent components having conflicting affordances, indicated with minus signs. This is a similar approach as how conflicting MDs are treated.

5.2 Summary of the proposed architecting process

The starting point of the proposed Integrated Modularization process is to create a product architecture representation, i.e. a CAD and paDSM, see Figure 16. In addition, the business strategies and physical interferences needs to be identified. This is typically done by interviewing domain experts and senior business managers. The results from these interviews are represented in a MIM and ASM respectively. The next stage in the process is *module identification* by using the DSM and eIMM clustering analysis. DSM clustering is performed on the paDSM, while eIMM clustering is performed on the saDSM or laDSM (depending on purpose). All clustering analyses are performed with the clustering algorithm *IGTA++*. The last stage in the product architecting phase is product layout design, where the module candidates (from the earlier clustering analysis) are placed within the spatial boundaries of the product. It is of great importance to avoid interference between clusters during this stage.

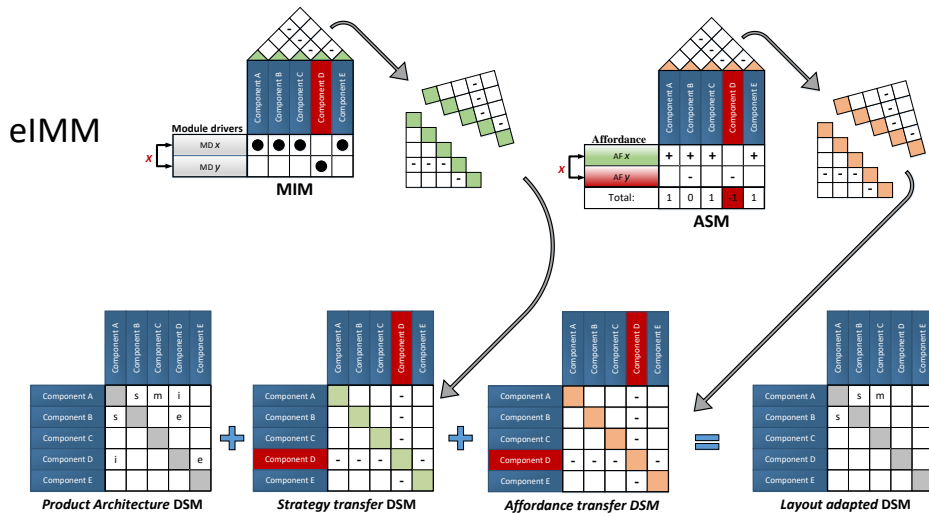


Figure 15. The Integrated DSM-based product architecting methodology eIMM.

After completing the product architecting phase, the next step is to verify if the concept architecture fulfills the *system requirements* and the *business strategies*. If the system requirements and business strategies are satisfied, and all stakeholders agree that the product architecture is approved, the remaining task is to document the modules and their interfaces, which will serve as input to the trailing detail design phase. However, if the concept architecture does not satisfy the requirements and business strategies, the product layout stage must be redone, i.e. positioning module candidates in an alternative layout. If the requirements and business strategies are still not satisfied after layout redesign, the module identification stage must also needs be redone. In such a case, it is important to identify proper relation weights between pairs of components, based on factors such as product *novelty*, and *performance and safety criticality*.

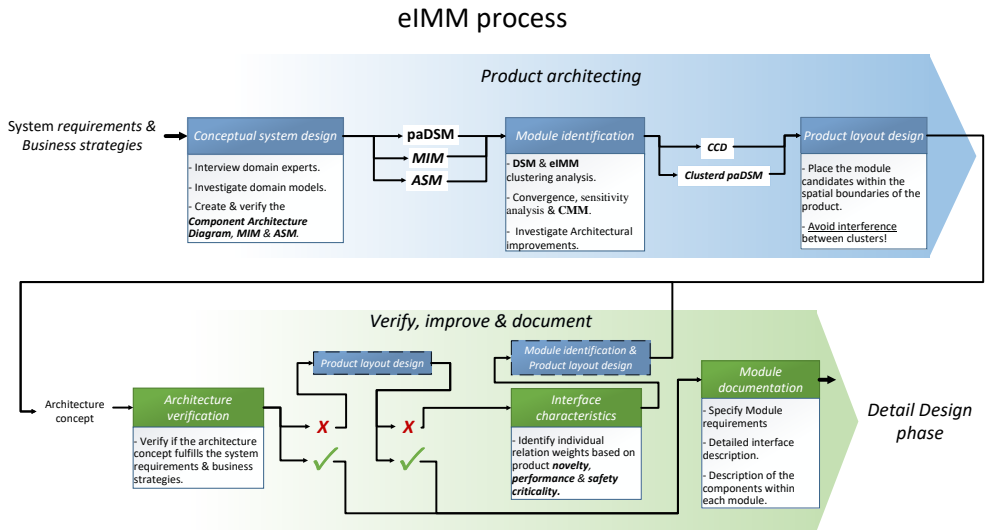


Figure 16. Proposed process for the Integrated Modularization Methodology.

It is important to highlight that the proposed eIMM methodology and process should assist and not replace the designers knowledge and experience when architecting a product, i.e. it should be a knowledge level that enhances human capabilities. When designing a new product, the designers usually do not start from a blank sheet of paper, but rather from an existing product which then is redesigned. Hence, an important consideration when developing the eIMM was the re-architecting phase, including what drives change and what effects it has to an existing product architecture. At the same time, it was identified that it should be possible to use the eIMM if the reasons behind the architecture of an existing product need to be identified, or if a fully new product should be developed, see Figure 17.

Potential business benefits by using eIMM methodology include reduced *development time* and *cost* (lower complexity), reduced *lead time*, increased *robustness* and increased *flexibility*. A well performed product architecting phase may therefore be a very good, if not absolutely essential, investment for a company.

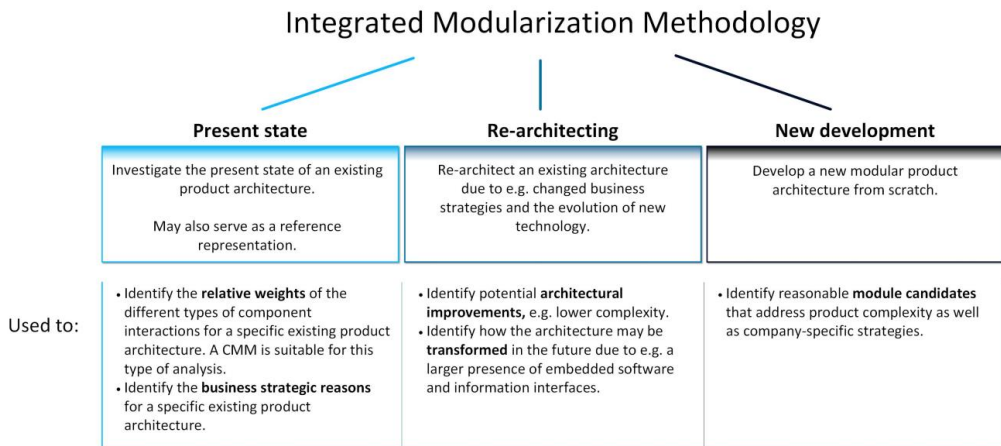


Figure 17. Situations where the Integrated Modularization methodology can be applicable.

6 DISCUSSION

The results are discussed in this chapter.

6.1 Road transport and business challenges

Road transports face increasing societal challenges with respect to emissions, safety, and traffic congestion, as well as various business challenges. Combination of *truck electrification* and *automation* may be utilized to address some of these issues. Electrified and autonomous transport vehicles may be characterized as Cyber-Physical Systems (CPS). A drawback of CPS is that it significantly increases technical complexity and thus introduce new challenges to SE. This is mainly due to the complex interactions and dependencies between physical and computational elements, but also due to the great variety of architectural choices. The added complexity is preferably targeted in the product architecting development stage of SE.

In addition to technology related changes, (e.g. electrification of a system due to paradigm shifts in technology), changed business strategies may affect a product architecture in various ways, see Figure 18. For example, becoming a First-Tier supplier, or starting to sell transport services instead of vehicles, are large business related changes that may affect the relative importance of some of the MDs, which in turn may require the product architecture to be changed in order to enable efficient and effective operations.

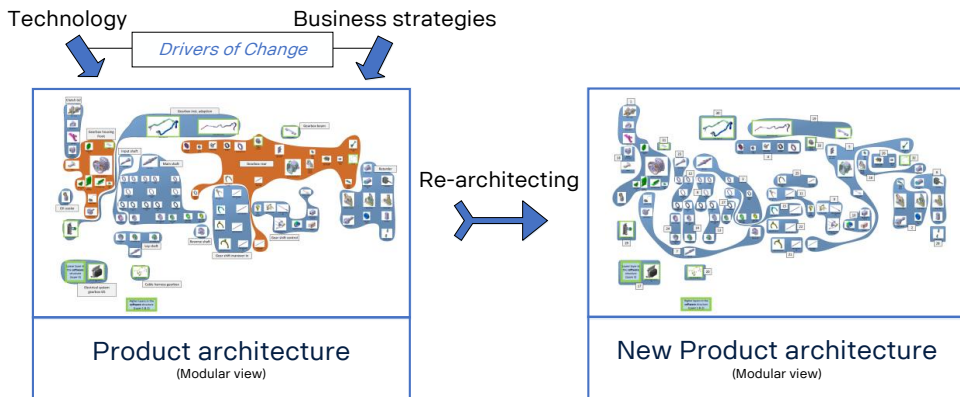


Figure 18. Drivers of change to a product architecture.

In the heavy vehicle industry, the future is in many ways uncertain when it comes to both technology and business strategies, making it highly important for an OEM to be flexible and react rapidly to changes. For example, a combination of different powertrain technologies are expected to be used in the near future at Scania. Different types of ICEs with *diesel*, *renewables* and *gas* will most likely still play an important role in long-distance operations, while BEVs may be suitable for deliveries in densely populated areas. Developing separately dedicated platforms for each of these technologies would involve high overall cost (mainly due to the low internal commonality). Consequently, it is simply not economically feasible to create a new BEV platform from scratch without considering the current architecture and its legacy. This makes it highly important for the present modular truck system at Scania to support multiple powertrain technologies, which makes it necessary to modularize the product even more and at

a higher level in order to be profitable. However, within the vehicle modules the need for high performance (mainly in terms of volume and weight) as well as the integration of more sensors, electronics and embedded software for monitoring and control will most likely result in an even more integral design, i.e. the modules will have an integral architecture. A similar trend can be seen from a business strategic point of view. As strategic uncertainty tends to decrease with time, the internal architecture of the modules may evolve from a more modular to an integral architecture. For example, if the MD for all components in a module changes from *technology push* to *common unit*, the internal module architecture may become more integral since flexibility is no longer a major objective.

Applying function sharing and creating an integral architecture is a well-known method for increasing performance in various ways, e.g. reducing the weight and size of a product. It is also used to reduce manufacturing cost. However, an integral architecture makes the redesign phase much more costly and complex, since a change in one specific function may require redesign of multiple components, or in the extreme case redesign of the entire product. As both technical and strategic uncertainty tends to decrease with time (due to the increase of knowledge), it is desirable not to reduce the design *Degrees of Freedom* (DOF's) too early when uncertainty still is high, see Figure 19. Therefore, in short term, it is important to have some extra flexibility and space for changes when developing a complex product. These changes make it highly important to have a clear view of and strategy for the product architecture, and to do trade-offs between modular and integral architecture at both the system and module level, allowing the modules to be developed and maintained as independent as possible while still fulfilling the performance related requirements.

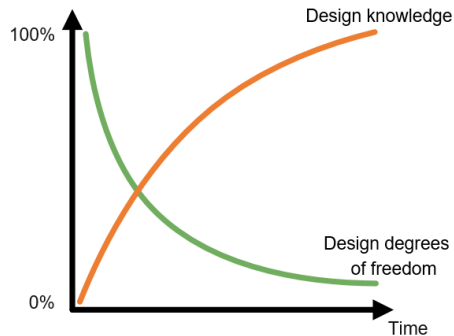


Figure 19. Design knowledge vs. Design Degrees of Freedom.

6.2 Innovation management

Complex and high-performing products like heavy-duty trucks are often developed with an incremental development approach, i.e. making a large number of small design changes over many years without disrupting a pre-established product architecture. In *innovation management*, this approach is frequently referred to as *incremental* or *modular innovation* and has been identified to be beneficial to some extent. For example, it may improve quality and lower risk when introducing new technology etc. However, sometimes larger architecture changes could be preferable, e.g. electrification of a system due to paradigm shifts in technology, or due to new legislation or changed business strategy. This type of change can be referred to as *architectural innovation*, and involves making changes to how the elements of a product are organized, e.g. clustering the components into a different set of modules. Large benefits can be achieved simply by changing the way the components are clustered. If only

small changes are made over a long period of time, there is a high risk that the transformed product architecture becomes sub-optimized for the new task.

The well-known polymath of the Renaissance, *Leonardo Da Vinci*, recognized the importance of “systems thinking” and how all things and phenomena are interconnected in one of “the Seven Da Vincian Principles”, named “Connessione” (Gelb, 1998). Hence, one of Leonardo’s main approaches to develop innovative and creative solutions was by combining and connecting existing elements in new ways, i.e. architectural innovation.

Due to the complex nature of CPS, a structured product architecting methodology with efficient tools and representations which brings rigor and robustness to the highly complex task is essential means in the product development phase, both when dealing with incremental, modular or architectural innovation, otherwise important aspects may not be treated properly.

Numerous researchers have investigated and found that many established companies facing paradigm shifts in technology, or a large change in business strategy, have experienced great difficulties when responding to these changes. Henderson & Clark (1990) claimed that many of these problems can be traced back to the gradual loss of product architecture knowledge. The main cause of this knowledge loss is claimed to be the result of having a stable architecture over many years, thus taking the architecture knowledge for granted before it is gradually reduced in the communication patterns within the organization. Hence, while having a stable architecture can enable an incremental development approach of a product, it may also hinder a company’s ability to develop novel architectures, especially for CPS.

The development of complex products typically relies on harmonized efforts from a large number of engineers in different organizational units. As earlier stated, the design tasks, including the specialized design teams, are frequently based on the product architecture. Hence, the module interfaces will naturally form communication points between the design teams. This approach naturally requires the *organizational* and *product architecture* to have close to one-to-one mapping between *design teams* and *modules*, that is, module A is designed by team A. Hence, it is clear that the organizational and product architecture has some form of dependency (Sosa et al., 2007). Changing any of these two architectures will therefore most likely result in a change to the other one in order to continue efficient and effective operations. For example, changing the organization architecture requires a great understanding of the product architecture to reduce the likelihood that important component interactions are lost in the new organization, while a change in product architecture may require new information channels to be established to intensify communication within the new organization.

6.3 Integrated Modularization

The proposed methodology and process for Integrated Modularization aims to support the SE process by augmenting the traditional DSM clustering approach. A paDSM represents aspects of technical complexity. Consequently, it does not contain any strategic and only limited physical interference information (layout constraints) and is therefore not capable of handling these aspects in the architecture clustering stage. This limitation of DSM clustering has been illustrated and confirmed in several of the papers presented in this thesis. A clear advantage of the eIMM methodology is thus that it is capable to represent and analyze effects from technical complexity, strategic concerns and physical interferences, and to do so in any combination, see Figure 20. Hence, the eIMM improves the quality of the architectural decomposition.

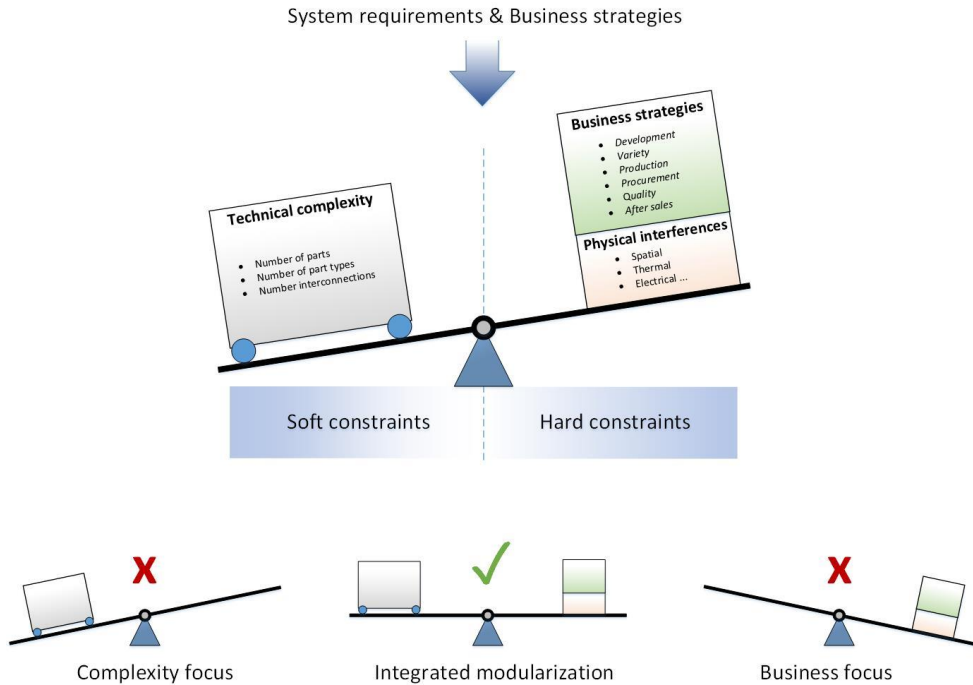


Figure 20. Integrated modularization enables architecture trade-off studies.

One approach to identify harmful or undesirable effects in a system is to model desirable and undesirable relations between components in the DSM. In order to distinguish desirable from undesirable relations, positive and negative values can be used. However, this approach does not guarantee that components with negative relations are not clustered together, i.e. the clusters may contain physical/affordance conflicts, see Figure 21.

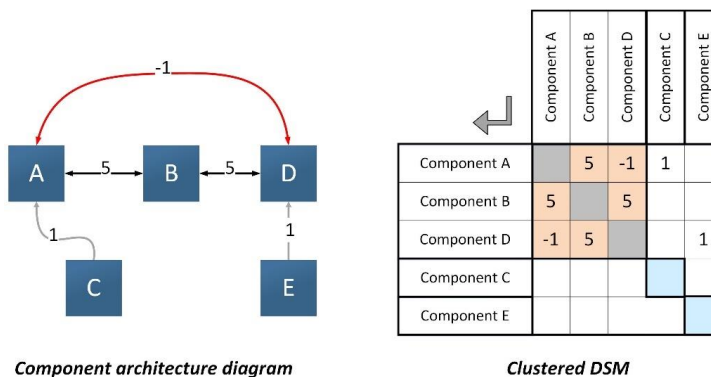


Figure 21. Example of a CAD and clustered DSM with negative relation weights.

One aim of the eIMM methodology is therefore to propose a modular product architecture without intra-cluster physical interference, since interference between clusters in most cases can be resolved with physical separation, i.e. orienting module candidates in an alternative

physical product layout. However, this does not prevent the clustering result from containing undesirable and harmful effects between clusters. Interference between clusters must therefore be resolved in the trial layout or, if required, in the *detail design* phase. To make sure that the designers do not forget about interference between clusters, these relations should be clearly highlighted in the DSM.

When analyzing the DSM clustering results in several of the papers, it was clear that only clustering according to technical complexity did not result in a solution close to the present modular architecture at Scania. This indicated that the existing modules were most likely not only created according to complexity concerns, but rather to other strategic aspects related how the product is *manufactured* and the need for *different performance* etc. In addition to the findings from the literature review, this insight gave the author further understanding of other important aspects to consider in product architecting, e.g. investigating an existing architecture.

As earlier mentioned, the eIMM can be used to investigate the present state of an existing product architecture. To enable comparison of clustering results of the same system, a *Cluster Match Matrix* (CMM) was developed and is proposed in *Paper C*. A refined version of the CMM is moreover proposed in *Paper E*. A CMM is a matrix containing a representation of an existing modular architecture (reference architecture), and the clustering results based on different relational weight combinations. The numerical values in the CMM represent the cluster which the component is assigned to by the clustering algorithm. The original modules are also specified. With the CMM, it is possible to compare how close a clustering result is to an existing or base modular architecture in a quantitative and repeatable way.

In the example seen in Figure 22, components *A*, *B* and *C* are located in Module 1 in the reference architecture. In a similar way, components *D* and *E* are located in Module 2. Notice that the MDs are unknown for all components in this example, i.e. we do not know that component *D* has a conflicting MD with the other components. In the left column in Figure 22 (equal relation weights, or dependencies of the same strength), components *A*, *B* and *D* are all assigned to *cluster 1*. In a similar way, component *C* is assigned to *cluster 2* and *E* to *cluster 3*. However, since component *D* is not in the same original module as components *A* and *B*, it is marked with red, indicating that the clustered component is in the “wrong” module compared to the reference architecture. The cluster match is finally calculated based on how many components compared to the total amount of components that are in the same module as in the actual system. With this comparison method, multiple clusters may be located in the same original module and still fulfil the criteria of a full match. For example, the original module containing component *A*, *B* and *C* is an integration of *cluster 1* and *2* in the left column in Figure 22. Hence, only components which are split from their assigned cluster, to fit the existing modular architecture, are treated as being in the wrong module. The relation weight combination with the highest cluster match score is the one closest to the base architecture, i.e. the hidden relation weights are thus partly revealed.

Components with conflicting MDs may also be identified in the CMM. In the example seen in Figure 22, component *D* frequently end up in the “wrong” clusters and is therefore identified as potentially being in conflict with the other components in the cluster, and consequently has been grouped not to reduce technical complexity, but because of some (hidden) strategic reason. There is also a possibility that some of the original modules were selected based on other (subjective) aspects, i.e. there may not be any pure strategic reason behind a choice. Hence, the CMM can be used for analyzing and finding the explicit and/or implicit reasons behind the architecture of an existing product.

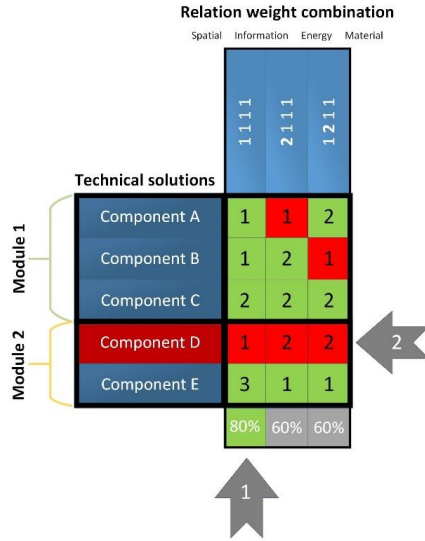


Figure 22. Example of a *Cluster Match Matrices* (CMM).

It is important to highlight that the proposed eIMM methodology should assist and not replace the designers knowledge and experience when architecting a product. Presently, the designers at Scania are not used to get this type of assistance and may therefore not fully identify the need or the benefits of such a method. On the other hand, the designers are used to get other types of assistance in their work, e.g. when designing with a CAD tool or when writing a technical report in e.g. Microsoft Word. These tools make the work easier and faster in many aspects, but they still rely on humans performing most of the actual work and thinking. In a similar way, the eIMM methodology should assist and simplify the work and should therefore not be a method which the designers strictly rely on and that replace their own experience, i.e. it should be a knowledge level that enhances human capabilities.

The exact degree of financial success resulting from the use of any product architecting methodology is virtually impossible to measure in a controlled way, though it is still possible to discuss some of the common benefits. Potential business benefits by using a robust product architecting methodology include (but is not limited to) *reduced development time* and *cost* (lower complexity), *reduced lead time*, *increased robustness* and *increased flexibility*. A well performed product architecting phase may therefore be a very good, if not absolutely essential, investment for a company. It should be stated that other modularization approaches are available in addition to the methods presented in this thesis, which may also offer several complementary benefits.

The clustering results of both the DSM and eIMM methodologies depend on the quality of the paDSM, i.e. that the different system elements have been decomposed deep enough and to a similar depth all over the system, and that the interactions and their weights are reasonably represented. A potential future work is to create a framework for the eIMM methodology. A framework that is capable of automatically generating the main eIMM representations (i.e. CAD and CCD) from a *generic information model*. Potential benefits of such a framework include; reduced time for the product architecting phase and increased quality of the representations and clustering results. One modeling language for this type of information model is SysML, which is frequently used to represent complex systems. SysML is based on a variety of diagrams in order to specify system *requirements*, *behavior*, *structure*, and

parametric relations. These models help the design teams to *define, design, analyze* and *document* a system under development.

6.4 Complexity in product architecture clustering

As stated earlier, complexity is typically viewed in terms of subjective complexity or objective complexity in SE. In Integrated modularization, the importance of identifying objective complexity is first estimate by determining if the clustering result is sensitive to the relative relation weights. This sensitivity analysis is done by visually comparing multiple CCDs. If the clustering result shows to be sensitive, it is important to quantify *how* sensitive the clustering result is by analyzing how much the technical complexity (from the clustering analysis) changes when assigning different relation weight combinations.

It is confirmed in paper *B, C, D, E, F, G* and *H* that the result of the DSM and eIMM clustering depend on the relative weights (importance) of the different types of functional and spatial interactions that are represented in the paDSM. Moreover, several of the case studies revealed that the relation weights become less important in eIMM clustering, compared to DSM clustering, when multiple strategic and interference aspects are introduced, i.e. the imposed constraints reduce the solution space. This is true for any other optimization problem, over-constraining the search space may reduce the solution space and thereby potentially missing a globally more optimal solution. In the opposite way, the relation weights will become more important if the strategic and/or interference aspects are removed for some reason, e.g. due to a changed business strategy.

After completing the product architecting phase, the next step is to verify if the concept architecture fulfills the *system requirements* and the *business strategies*. If the system requirements and business strategies are satisfied, and all stakeholders agree that the product architecture is approved, the remaining task is to document the modules and their interfaces, which will serve as input to the trailing detail design phase. However, if the concept architecture phase does not satisfy the requirements and business strategies, the product layout stage must be redone.

If the requirements and business strategies are still not satisfied after layout redesign, the module identification stage must also be redone. In such a case, it is important to identify proper relation weights between pairs of components, based on factors such as product *novelty, and performance and safety criticality* (Sellgren & Williamsson, 2020). It is still an open question how these relation weights preferably should be selected, including other potential reasons behind the weights e.g. requirements concerning *reliability, signal transfer speed, and manufacturing cost* etc. Hence, further research is needed to get a better understanding of this challenge. In addition, further research is also needed to investigate alternative *complexity measures* which can be used during the product architecture clustering analysis to propose reasonable module candidates, including how the choice of clustering algorithm affects the clustering result.

6.5 Research reliability and validity

To evaluate the quality of the presented research project and the proposed methodology and process, the concept of reliability and validity of the *semi-structured interviews* (from the licentiate thesis) and *case studies* are discussed in this chapter. *Reliability* defines how consistent a result can be achieved by using the same procedures under the same conditions, while *validity* defines the accuracy of a result, i.e. how well a result measure what it is supposed to measure.

To get an insight of the modularization process, from the perspectives of numerous designers within *mechanical hardware*, *electrical* and *embedded software* development at Scania, *semi-structured interviews* was performed. This interview approach was chosen in order to allow the respondents own words and experiences to shine through. This gave the respondents some freedom to talk more about what was important to them, and also made it possible to acquire information which was not thought of in advance.

Ideally, an interview should generate similar results independent of who is performing it. This becomes difficult when performing semi-structured interviews, since they cannot be fully replicated. The aim of the presented research was thus to maximize reliability by performing multiple interviews with a variety of respondents at the company. All respondents which were interviewed worked with gearbox development at Scania (Williamsson, 2018). In order to investigate if there were any difference between the different technical disciplines, engineers within hardware, electrical system and embedded software design were interviewed. In addition to that, both senior and junior engineers were interviewed at each technical discipline, which resulted in a total amount of 6 respondents. This was done in order to study if the amount of experience affected the answers in any way. The selection of respondents was performed with the assistance of engineers and senior business managers working with the overall gearbox design and configuration.

To visualize the various studied product architectures in the case studies, its constituents and functional relations was first identified. This was done by interviewing domain experts and senior business managers, as well as investigating the logical structure of the electrical and software components. In addition, various other domain specific diagrams were also analyzed depending on investigated subsystem, e.g. cooling system diagram and CAD models. In Integrated modularization, the results from this type of investigation are represented in a paDSM, MIM and ASM respectively. Two different and complementary architectural representations are important in addition to the paDSM, i.e. the CAD and CCD. After completing these representations, each domain expert and senior business manager (from the interviews) were asked to verify that the model represented their domain in a correct and appropriate way, see Figure 23.

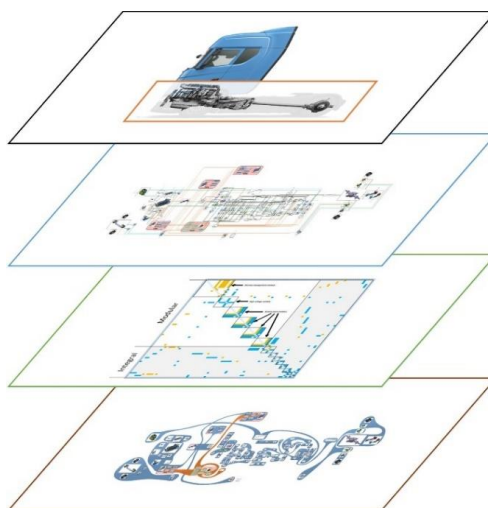


Figure 23. Key architectural representations in Integrated Modularization.

Ideally, a case study should generate similar results independent of who is performing it. This becomes difficult when dealing with industrial case studies since they rarely can be fully replicated. The aim of the presented research was thus to maximize reliability by performing multiple case studies with a variety of investigated subsystems and participants at the company. The participants in the case studies were mainly domain experts, who was chosen based on the development projects of the investigated subsystems. The choice of domain experts was also discussed with senior business managers to verify that the candidates had both excellent systems and detailed design knowledge within their domain.

Still, another researcher performing the exact same case study would most likely end up with slightly different paDSM, MIM and ASM. This would affect the clustering results, though the main patterns would most likely be fairly similar. However, if a researcher would perform the same clustering analysis by using the exact same paDSM, MIM and ASM as used in any of the case studies, the results should be identical. Hence, the eIMM is reliable but depends on the quality of the eIMM representations.

To overcome this quality problem, other researchers in product architecting often use standard “table projects” of already analyzed products. In this way, the result of using different methods and tools can easily be identified since the underlying product architecture data is identical. However, a clear drawback of this approach is that it does not capture the complexity found in many industrial cases, thus potentially missing important aspects.

In papers F, G and H, action research, which is a specific type of qualitative research method was used. As earlier stated, action research allows researchers and experts to act together in an iterative process. Hence, in papers F, G and H, the author took part in two different development projects at Scania. This gave the author a unique opportunity to evaluate how the new Integrated modularization methodology and process actually worked in practice. Since the author participated in the projects, thereby partly affecting the outcome of the projects, it would not be possible to fully replicate the case studies in these papers.

To determine the validity of the case studies, the results needed to be checked against how well it corresponds to established methodologies. Hence, the clustering results from the proposed eIMM was always compared to the traditional DSM clustering approach, which is the standard approach in SE. In addition, domain experts and senior business managers at Scania were asked if they thought that the eIMM and its new representations would assist their architecting related work, and if so, in what way? This gave the author an opportunity to validate the benefits of the proposed methodology and process.

The aim of the presented research was to develop a robust, agile and efficient modularization methodology, which could support the designers to identify module candidates or when making larger changes to a product architecture. To be able to verify, generalize, and improve the proposed eIMM approach, a larger range of products and development cases have been analyzed in the presented research project. However, since all case studies are CPS within the heavy-duty truck domain, it is not possible to claim that the presented work will be applicable beyond this product type. Hence, in the future, it would be highly interesting to analyze other types of products outside the heavy-duty truck domain to identify if the eIMM methodology can propose reasonable module candidates for these products as well.

Case studies of extremes/outliers can often offer more valuable results since they allow some phenomena to appear more easily, which can be hard to observe in “standard cases”. Since Scania is a well-known company for having a modular architecture, which has been observed in the presented research project, it would most likely be valuable to investigate another company in the heavy-duty truck domain with limited knowledge in modularization, or product

architecting in general, i.e. another extreme. In this way, other unique features about the Scania architecture and way of modularizing their product may appear.

7 CONCLUSIONS AND FUTURE WORK

This chapter presents answers to the research questions and future work is suggested.

7.1 Answers to the research questions

As stated in chapter 1, the overall aim of the presented research project is to provide a contribution to SE by proposing a new modularization methodology and process for *product architecture clustering analysis* of CPS within the heavy-duty truck domain. The proposed methodology and process for Integrated Modularization aims to support the SE process by augmenting the traditional DSM clustering approach. A variety of industrial cases of heavy-duty truck subsystems are used to describe the proposed eIMM approach and to verify its performance.

In this section, the research questions (RQ1 – RQ10) and their condensed answers are summarized. The appended papers address all identified RQs and answers them in order to confirm the performance of the eIMM, i.e. how well the proposed methodology and process supports the SE process. To further verify and generalize the findings, some of the RQs are input to several case studies and thus elaborated on in more than one paper. A *Domain Mapping Matrix* (DMM) is used to represent how each RQ is explicitly and/or implicitly addressed in the different papers, see Figure 24. In addition, the mapping between case studies and papers can be found in the same figure.

		Research question										Case study					
		RQ1	RQ2	RQ3	RQ4	RQ5	RQ6	RQ7	RQ8	RQ9	RQ10	Test rig	Heavy duty gearbox	Powertrain	BEV e-axis	BEV energy storage system	
Paper	A	X	X									X					
	B	X	X	X									X				
	C	X	X	X	X	X							X				
	D	X	X	X	X									X			
	E	X	X	X	X	X							X				
	F	X	X	X			X	X	X							X	
	G	X	X	X				X	X						X		
	H	X	X	X				X	X	X	X						X
<div>Action research</div>																	

Action research

Figure 24. Research questions which are explicitly and/or implicitly addressed in the papers.

RQ1: May clustering of a DSM with interactions representing spatial relations and function flows of energy, matter and signals, i.e. a paDSM propose reasonable module candidates?

- Clustering a paDSM with interactions that represent spatial relations and flows of energy, matter and signals may propose module candidates that reduce technical complexity, but not on strategic business concerns.

RQ2: How does the output from a business strategic or layout constrained DSM clustering approach differ compared to paDSM clustering?

- It is confirmed in all presented papers that (e)IMM clustering proposes modules that reduce technical complexity and also takes the effects from corporate specific business strategies and plans into consideration.
- The results of all IMM clustering analyses in *Paper C* gained the highest cluster match scores according to the proposed Cluster Match Matrix method in *Paper C*, thus the IMM proposed module candidates that are most similar with the architecture designed by domain experts.

RQ3: How sensitive is paDSM clustering to the relative weights of the spatial relations and the functional flows of matter, energy and signals?

- The result of the DSM and (e)IMM clustering depends on the relative weights (importance) of the different types of functional and spatial interactions that are represented by the paDSM. This is confirmed in *Paper B, C, D, E, F, G* and *H*. The technical complexity index changes when assigning different combinations of relation weights. The importance is larger for the DSM approach compared to the (e)IMM, due to the introduction of business strategic and/or physical interference (layout) constraints.

RQ4: Can a business strategic constrained DSM cluster analysis be used to identify reasons for a modular architecture that has been created based on expert judgement?

- In both *Paper C, D* and *E* it is confirmed that the proposed eIMM methodology can be used to re-engineer i.e. analyze and find, the explicit and/or implicit reasons behind the architecture of an existing product.
- Clustering of the studied system in *Paper D* clearly indicates that the strategic reasons for a specific architecture can be found by doing analysis of how sensitive the clusters are to changes in the module drivers.

RQ5: How can we compare multiple clustering results?

- To enable comparison of clustering results of the same system, a Cluster Match Matrix (CMM) is developed and proposed in *Paper C*. A refined version of the CMM is moreover proposed in *Paper E*. A CMM is a matrix containing a representation of an existing modular architecture, and the clustering results based on different relational weight combinations. With the CMM, it is possible to compare how close a clustering result is to an existing or base modular architecture in a quantitative and repeatable way.

RQ6: Does paDSM clustering with negative relation weights, representing undesirable/harmful relations, propose clusters without physical interference?

- Paper F concludes that this approach is not useful to find clusters with no physical interference.

RQ7: Can business strategic constrained DSM clustering be augmented by also taking physical interferences into consideration?

- The presented case study in paper F, G and H indicates that the proposed eIMM is capable of identifying and proposing module candidates without conflicting MDs or affordances, as well as reasonable module candidates from a technical complexity point of view. The traditional DSM clustering approach proposed clusters based on technical complexity, but not on strategic business concerns or physical interferences.

RQ8: Can a business strategic and layout constrained DSM clustering approach enable effects from technical complexity, strategic aspects and physical interferences to be analyzed in any combination?

- The eIMM is both scalable and flexible, allowing the consequences of different architectural trade-offs from technical complexity, strategic aspects and physical interferences to be analyzed independently or combined depending on purpose.

RQ9: What process steps, methods and representations may efficiently and effectively support the architecture clustering stage in SE?

- In Paper H, the proposed *process steps, methods and representations* for Integrated Modularization are presented in a complete *product architecting* process. Product architecting is a highly iterative sub-process within SE and includes the following main steps; *conceptual system design*, *module identification* (clustering) and *product layout design*. Integrated Modularization *mainly involves the module identification* (clustering) stage, though information and representations are required from the *conceptual system design* and *product layout design* stage.

RQ10: How can the proposed methodology and process for product architecture clustering analysis support the SE process?

- The proposed methodology and process for Integrated Modularization supports the SE process by improving the quality of the architectural decomposition, i.e. the module identification stage by adding business strategies and physical interference to product architecture clustering. In addition, the CAD and CCD representations were highly appreciated by the domain experts and showed to make architectural discussions in general and modularity discussion in particular with and between domain experts efficient.

7.2 Future work

After conducting the presented research project, the author has identified the following work and research questions to be interesting and important to study further.

To be able to verify, generalize, and improve the proposed eIMM approach into a robust, agile and efficient modularization methodology, a larger range of products and development cases have been analyzed in the presented research project. However, since all case studies are CPS within the heavy-duty truck domain, it is not possible to claim that the presented work will be applicable beyond this product type. Hence, in the future, it would be highly interesting to analyze other types of products, including product-service solutions, outside the heavy-duty truck domain to identify if the eIMM methodology can propose reasonable module candidates for these products as well. Additionally, it would be interesting to further investigate what the different domain experts more explicitly liked with the proposed eIMM approach in a future case study.

Since it is confirmed that the result of both DSM and eIMM clustering depends on the relative relation weights that are represented by the paDSM, the reasons for chosen proper weights, e.g. *novelty, performance, safety criticality, reliability, signal transfer speed, and manufacturing cost* etc. clearly needs to be investigated further.

In addition to the architecture related approaches to reduce the increased amount of complexity when developing a CPS (which is addressed in this thesis), a *Model-Based Systems Engineering (MBSE)* approach is another potential process related way to master complexity (Törngren & Sellgren, 2018). Hence, further research within the area of MBSE is proposed by the author in order to identify and resolve process related challenges in developing existing and future CPS products at Scania.

Further research questions:

The following main future research questions have been identified (bullets marked in **bold**). In order to answer these main questions, multiple RQs were identified and are listed below.

How can Integrated Modularization be improved to further support the SE process?

- In what other ways can the proposed methodology and process for Integrated Modularization support the SE process?
- Can eIMM be used in the development of integrated product-service solutions or other types of products beyond the heavy-duty truck domain?
- Can the eIMM be useful during the functional allocation of an electrical and electronic (E/E) system architecture?
- How is the robustness to change and variation of an architecture preferably analyzed?
- How could the investigated modular architectures be optimized for the complete modular truck system?
- How should the identified module candidates be oriented in the physical product configuration?
- How should tradeoffs between organizational and product architecture be made?

How can we automate the generation of architectural representations?

- How can the key eIMM representations, i.e. CAD and CCD be generated automatically from a generic information model?

- How can an architectural information model be automatically transformed to a MODELICA model to simulate the performance and behavior of the evolving product architecture?

What alternative complexity measures are useful in product architecture clustering?

- What alternative *complexity measures* can be used during product architecture clustering analysis to propose reasonable module candidates?
- What are the most common factors that drives complexity when developing complex engineered products?
- What are the proper weights for different components and interactions based on their consequence on system availability, reliability and safety etc.?
- How does the relation weights change depending on layout of the module candidates?
- How does the choice of clustering algorithm affect the clustering result?

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