DEVELOPMENT OF A METHODOLOGY FOR EFFICIENT FEM PRE-PROCESSES TO AID SIMULATION-DRIVEN DESIGN

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“We thought this was going to be easy peasy lemon squeezy, but it turned out to be difficult difficult lemon difficult.”

– Unknown
Abstract

With both tougher competition and legislations, companies always strive to improve their products while cutting unnecessary costs. This master’s thesis investigates if the after-treatment systems department at the heavy-duty vehicle company Scania CV AB in Södertälje, Sweden can improve their development process by implementing automated FEM pre-processes for welded sheet metal components. The research is based upon theory from various fields within product development, knowledge-based engineering, FEM and design optimization, contributing to an understanding of what effects this project could have on the development process as a whole.

Large parts of the pre-processes used at the department today were identified as repetitive and suitable for automation. Using a simplified CAD model of an after-treatment system as a case study, a methodology for more efficient FEM pre-processes was developed. The methodology includes changes to the workflow between the design engineer and the CAE engineer as well as a software that automatically meshes welded sheet metal products. First of all, the design engineer inserts lines representing the weld positions in the CAD model and exports the model to the CAE engineer. Hereafter, the CAE engineer simply selects necessary settings for the mesh and launches the developed software that automatically meshes the sheet metal components as well as identifies and meshes the welds.

The technique used to mesh the welds in HyperMesh fails for certain weld characteristics, resulting in a robustness of 54 % of the total weld length for the worst case in the case study. These characteristics are welds crossing other welds, welds adjacent to a sharp corner and welds containing a sharp corner. By excluding these problem areas when defining the lines in CATIA, the robustness increases substantially to between 72 % and 88 % of the total weld length in the case study, where the exclusion zones represent 3 % of the total weld length.

Based on the case study, the developed methodology could potentially shorten the iterative development process between the design and CAE engineer with a total of 25 %, while the CAE engineer’s tasks in the development process can be cut with up to 60 %. This allows for more time being focused on value-adding tasks, resulting in higher quality products and an increased profit for the company.
Acknowledgements

This report completes a master’s program within mechanical engineering at the Institute of Technology at Linköping University. The work was performed at Scania CV AB in Södertälje, Sweden, during a period of 20 weeks, which corresponds to 30 ECTS credits.

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Södertälje, June 2018

Mattias Bäckman

Josef Kling
## Nomenclature

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
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<tr>
<td>2D</td>
<td>Two-dimensional</td>
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<tr>
<td>3D</td>
<td>Three-dimensional</td>
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<tr>
<td>AI</td>
<td>Artificial Intelligence</td>
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<td>BIW</td>
<td>Body-in-White</td>
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<tr>
<td>CAD</td>
<td>Computer-aided Design</td>
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<td>CAE</td>
<td>Computer-aided Engineering</td>
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<tr>
<td>CFD</td>
<td>Computational Fluid Dynamics</td>
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<td>DA</td>
<td>Design Automation</td>
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<tr>
<td>DOE</td>
<td>Design of Experiments</td>
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<tr>
<td>FEM</td>
<td>Finite Element Method</td>
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<td>GAS</td>
<td>Generative Assembly Structural Analysis</td>
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<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
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<tr>
<td>KBE</td>
<td>Knowledge-based Engineering</td>
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<tr>
<td>M.Sc.</td>
<td>Master of Science</td>
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<tr>
<td>MDO</td>
<td>Multidisciplinary Design Optimization</td>
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<tr>
<td>MM</td>
<td>Master Model</td>
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<tr>
<td>MMG</td>
<td>Multi-Model Generator</td>
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<tr>
<td>PD</td>
<td>Product Development</td>
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<td>Ph.D.</td>
<td>Doctor of Philosophy</td>
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<tr>
<td>PLM</td>
<td>Product Lifecycle Management</td>
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<td>Scania CV AB</td>
<td>Scania Commercial Vehicles Aktiebolag</td>
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<tr>
<td>UX</td>
<td>User Experience</td>
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<td>VBA</td>
<td>Visual Basic for Applications</td>
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1 Introduction

The process of developing and evaluating new designs and concepts at large heavy-duty vehicle companies has proven to be very time-consuming; demanding the excellence and experience of numerous engineers. Decreasing the time spent on any specific activity in the development process can both reduce costs and increase the likelihood of excelling faster than competitors. By using simulation-driven design, a method in constant development, inefficient and expensive physical tests can be replaced with far more profitable simulations. Also, implementing parameterization and automation of 3D models in Computer-aided Design (CAD), potentially enables faster design iterations.

1.1 Background

Today, heavy-duty vehicle companies all over the world constantly must adapt to tougher regulations concerning emission standards and stricter environmental laws. To maintain their respective positions on the market, it is of uttermost importance the companies conform to mentioned environmental legislations. When it comes to cutting edge products, sustainability and modular thinking, Scania CV AB (herein referred to as "Scania") is a model company. To further establish its position as a front-runner within the field, not only do they have to maintain focus on an eco-friendly product development process, but also shorten lead times. This, whilst preserving a high product quality. Because of this, Scania would benefit from a methodology that promotes fast and easy transitions of information between company divisions to shorten internal lead times, while still delivering products of the same or better standard than before.

In recent years, projects with the aim of implementing parameterization and Design Automation (DA) at Scania have shown great success within fields such as turbine houses, inlet ports and after-treatment systems. Because of the success in these projects, the after-treatment systems department at Scania now investigates how these methods can be further developed. This has, inter alia, resulted in multiple theses at Scania within this specific area, mainly during the past three consecutive years. With the combined experience from the engineers at Scania and the thesis reports, it has been discovered that parts of the pre-processing¹ of CAD models before Finite Element Method (FEM) analysis as well as Computational Fluid Dynamics (CFD) and acoustics simulations are labor-intensive and repetitive. The company therefore believes that automating these pre-processes could increase the efficiency of the evaluating phase, as well as benefiting the synergies of parameterized CAD models in a Multidisciplinary Design Optimization (MDO) framework. By improving this connection, the parameterized CAD models could be automatically optimized based on the objectives set in the MDO framework, directly after being modeled by the design engineer.

1.2 Scania CV AB

Scania is a multi-national cooperation with services in over 100 countries and employs around 49 000 workers all around the world. The company, which was founded 1897 in Södertälje, Sweden, is today a part of Volkswagen Truck & Bus and manufactures trucks, buses and

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¹ Pre-processes are necessary steps taken to prepare a CAD model before analysis by creating finite elements, also called mesh. Meshing a 3D model can be very time-consuming even for an experienced engineer. (Liu & Quek, 2013)
Combustion engines for heavy-duty vehicles as well as for marine applications. Their main goal is to always have the customer in focus and to produce sustainable vehicles while eliminating waste and minimizing their global footprint. (Scania CV AB, 2018)

1.3 Purpose and Objectives
Continuing the work previously done on the subject, the purpose of this thesis is to investigate how the main concept of DA – elimination of repetitive tasks – could be applied to the FEM pre-processes used by the after-treatment systems department at a heavy-duty vehicle company. The research includes investigation of relevant literature and software, development of an appropriate methodology as well as full documentation of the work accomplished. The main objective is to develop a methodology that allows for shorter lead times and a more efficient iteration process between design and Computer-aided Engineering (CAE) engineers. More specifically, the objective is to develop a methodology that enables automated FEM meshing of sheet metal components and welds, joining mentioned components.

Thus, the research questions discussed and answered in this report are as follows:

**Research Question 1.** How could FEM pre-processes of welded sheet metal components be automated?
**Research Question 2.** How could the design development process be improved by implementing automated FEM pre-processes at an after-treatment systems department?

1.4 Delimitations
This thesis work is performed at Scania’s after-treatment systems department and continues during a period of 20 weeks. The software used during the project includes CATIA V5 R26, Altair HyperMesh 2017 and Visual Basic for Applications (VBA), which is integrated in Microsoft Office Excel 2016. The work focuses on developing a methodology for preparation of CAD models in CATIA V5 R26 and automation of meshing, with focus on weld meshing, in Altair HyperMesh 2017. Also, no specific modeling techniques are taken into consideration, since this has been thoroughly investigated in previous master’s theses.

When developing a Graphical User Interface (GUI) in this thesis, no consideration to User Experience (UX) design is taken. Also, the methodology developed do not consider Scania’s Product Lifecycle Management (PLM) systems.
2 Theoretical Framework

This chapter presents the relevant theory upon which this thesis is based.

2.1 Product Development

As reported by Ulrich & Eppinger (2008), product development is defined as “...the set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product.”

![Diagram of the design and product development process](image)

*Figure 2.1 – The design and product development process as seen in "Product Design and Development (Int'l Ed)" (Ulrich & Eppinger, 2011).*

In Figure 2.1, the fundamentals of the Product Development (PD) process according to Ulrich & Eppinger (2011) are visualized. The process begins with data collection and benchmarking to understand the problem and to investigate the needs. This is followed by a documentation phase as well as an iterative design process. This iterative phase begins with a broad perspective that is narrowed down until a final product is ready for launch. (Ulrich & Eppinger, 2011)

Lindahl & Tingström (2006) claim that product development can be divided into two different operation modes – sequential and integrated PD. Sequential PD is a linear process and means that a new phase cannot begin until the previous one is finished. The authors argue that there are a few drawbacks concerning this PD technique. They describe the so called “over the wall problem”, which refers to the communicational complication that can occur when utilizing sequential PD. More specifically, this means that there is no methodology for transferring information between work groups and departments. This might lead to prolonged lead times and a less effective iteration process since time is unnecessarily spent on understanding the task received, instead of concentrating on developing the product further. (Lindahl & Tingström, 2006)

Integrated PD is considered a better method since it can handle multiple processes in parallel. Applying it requires good communication and collaboration between different departments, which results in a shorter and better PD process. (Lindahl & Tingström, 2006)

Furthermore, the PD procedure is a complex and non-linear process. In Figure 2.2 below, the chain of events is visualized in what is known as “the design paradox”. In the beginning of the project the possibility for change is large and the price for this is low, though the knowledge about the
product is limited. The room for change decreases throughout the project. This, while the knowledge about the product and the cost for change increases. (Lindahl & Tingström, 2006)

![Diagram of the design paradox, with inspiration from Lindahl & Tingström (2006).](image)

**Figure 2.2 – The design paradox, with inspiration from Lindahl & Tingström (2006).**

2.1.1 Simulation-driven Design
Simulation-driven design is, according to Sellgren (1999), defined as “…a design process where decisions related to the behavior and performance of the artifact are significantly supported by computer-based product modeling and simulation”, while the term “simulation” can be described as “…imitating the behavior of a real system by constructing and experimenting with a computer model of the system”, as reported by Neelamkavil (1987).

These simulations can be implemented on a wide variation of disciplines, ranging from vibration and acoustics to aerodynamics and fluid mechanics. They can be used as a tool for the engineers in the creative and iterative part of the PD process, which enables an early analysis of possible problems which can be addressed while the project’s acting space is large. Utilizing simulation-driven design eliminates further development of bad concepts, as well as cuts costs and decreases development time. Physical tests are often expensive and time-consuming to develop and execute. Though, simulations are often limited concerning the complexity of what is being analyzed. This means physical tests cannot be replaced fully by simulations. (Thomke & Fujimoto, 2000)

Using the benefits of simulations together with physical tests could lead to a very efficient and complete design process. In one example from the car company BMW, they did 91 crash simulations and two physical tests. This resulted in a 30 % improvement of the side-impact crashworthiness even before doing the verifying physical tests. The cost of one simulation was
about one hundredth of that of a physical test and the time to plan and conduct the physical tests was longer than the entire development project. (Thomke & Fujimoto, 2000)

2.1.2 Product Development at Scania
The PD process at Scania is a cross-functional, scalable, flow-oriented, paced and property-based procedure aiming to have a global perspective and to promote parallel work to the extent possible. The PD mainly consists of three different stages; Concept Development, Product Development and Product Follow-up. These are each represented in Figure 2.3 below. (Scania CV AB, 2018)

![Figure 2.3 – A visualization of the product development process at Scania. The picture is inspired by Scania CV AB (2018).](image)

The first stage is the Concept Development phase. Here, the company investigates business possibilities and technical solutions. The work is performed in small groups with a high degree of cross-functionality to utilize as much knowledge as possible. This is where much of the iterative CAD and simulation work are performed, as well as implementation of product requirements. Depending on the product in question, research and advanced engineering might be required. If a small part on an existing product needs an upgrade, a team of researchers and experienced engineers develop a solution, which is then further examined in the Concept Development phase. (Scania CV AB, 2018)

Next, there is the Product Development step. During this part of the process, the CAD and simulation work continues and further development and iterations are performed. Product specifications are updated, and physical tests are carried out. When the product has passed all tests, it is given the green light for start of production. Now larger cross-functional groups assemble to deliver the product to market. (Scania CV AB, 2018)
Lastly, the Product Follow-up phase aims to maintain and follow up on earlier delivered products. While having a smaller window of opportunity, this stage in the process includes many of the steps comprised in the Product Development phase. How much work is needed depends on the product and the severity of the problem at hand. (Scania CV AB, 2018)

All steps in the PD process apply lessons learned\(^2\) to keep knowledge and thereby improve products and profitability. (Scania CV AB, 2018)

2.2 After-treatment Systems
The after-treatment system in a heavy-duty vehicle is integrated in the exhaust system. Its main purpose is to get rid of pollutants and reduce noise. Below in Figure 2.4, a simplified flow chart is presented, describing the different steps in the process. A CAD model of an actual after-treatment system is presented in Figure 2.5 below.

![Figure 2.4 – A highly simplified example of the different components in the after-treatment system of a heavy-duty vehicle.](image)

The engine produces exhausts containing hazardous gases. In the first phase of the after-treatment system, the Diesel Oxidation Catalyst’s (DOC) main purpose is to oxidize carbon monoxide (CO), unburned hydrocarbons (HC) and nitric oxide (NO) (Rusell & Epling, 2011). The remaining pollutants then passes on to the Diesel Particle Filter (DPF). Here, the soot is trapped by the filter and nitrogen dioxide (NO\(_2\)) is used to regenerate the diesel soot by oxidation (Kim, et al., 2010). Next, a liquid called urea (CH\(_4\)N\(_2\)O) is injected into the system to neutralize the enduring nitrogen oxide gases (NO\(_x\)). Together with the ammonia (NH\(_3\)) in the urea substance, it triggers a reaction that converts the toxic NO\(_x\) gases into nitrogen gas (N\(_2\)) and water (H\(_2\)O). This process is what is referred to as Selective Catalytic Reduction, or SCR. (Wiesche, 2007) After the SCR phase, there might still be some NH\(_3\) left, which is also toxic and prohibited to release into nature. Therefore, the last step is the Ammonia Slip Catalyst (ASC) which converts the NH\(_3\) into the environmentally friendly N\(_2\), given the engine is active under normal circumstances. Then, finally, the exhaust gases, consisting of N\(_2\) and H\(_2\)O, are released into the air through the exhaust pipe. (Walker, 2016)

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\(^2\)Lessons learned is a method to capture, store and share an organization’s verified lessons gained during different projects (Weber, et al., 2000).
2.2.1 Euro VI

The European Commission are responsible for introducing legislations concerning tolerated emission levels for heavy-duty vehicles. The first legislation was introduced 1988 and implemented 1992. This law was then called Euro I (also known as Euro 1). Since then, six emission standards have been implemented and today’s active standard is Euro VI (also known as Euro 6). The new environmental laws put pressure on vehicle companies to update their after-treatment systems (see previous Chapter 2.2) to follow up-to-date legal acts. In this chapter, a diagram with current emission standards is visualized together with earlier versions. As can be seen in Figure 2.6, current standards are very different from earlier versions, which makes a fast PD process necessary. (Dieselnet, 2018)
2.3 Intelligent CAD Models

With both increasing competition and tougher legislations, efficiency has become a key factor regarding designing new products to make a business profitable. Being able to shorten development processes by implementing intelligent methods in the whole development process is something companies strive for.

In a typical design process, decisions made in early stages have a huge impact on the final product and its life cycle, as visualized in the design paradox in Figure 2.2. Increasing the knowledge about the product in these stages could potentially shorten the development process and improve the final result. With the evolution of CAD systems, many tools can be utilized to aid this improvement. Though, one bottleneck seen in many industries is the transition of the CAD models between the design department and the analysis department. Frequently, the initial CAD models cannot be used directly in the analysis tools, and according to Sandberg, et al. (2017), the analysis department therefore usually must create their own 3D model, not linked with the one developed at the design department. The development of different 3D models of the same design is a complex and time-consuming process, leading to fewer design iterations and a sub-optimal final design. (Sandberg, et al., 2017)

This problem can be addressed with the use of CAD models containing different discipline specific models and information all relevant stakeholders might need, called Master Models (MM) by Sandberg, et al. (2017). This enables a link between the models used in the different departments working with the design, updating all models automatically if one is modified. By integrating MMs
with other methods like Knowledge-based Engineering (KBE) (see Chapter 2.6), the CAD model can, in addition to the benefits with MM, enable flexible designs in both a morphological and topological fashion as well as enable DA (see Chapter 2.5). (Sandberg, et al., 2017) In this case, morphological transformations are alterations in the geometry of an instantiation, while topological transformations change the number of instantiations, by adding, removing or replacing instances (Amadori, et al., 2012).

2.4 Parameterization
One part of making the PD process more efficient is reusing CAD models in multiple projects. By reusing already modeled 3D geometries and modifying them instead of modeling from scratch, unnecessary repetitive tasks are reduced for the design engineer. Camba, et al. (2016) refers to the word “reusability” as a measure of how intuitive and quick modifications of an already modeled geometry can be executed. To reach a high level of reusability, feature-based parametric CAD models could be utilized. These CAD models, already being the industry standard, store information in parameters easily accessible and adjustable by the design engineer. (Camba, et al., 2016) The parameters can be categorized as input and output parameters. Input parameters control the geometry. This can be done in multiple ways, ranging from, for example, a numerical value or a text string to a line or a surface. Output parameters describe the geometry for a specific set of input parameters. In addition to parameters, variables also exist. These are internal, dependent objects in the model itself. (Amadori, 2012)

2.5 Design Automation
The concept of DA contains a full range of interpretations regarding both the term “design” and the degree of automation. However, the main idea of DA is to automate design tasks, by letting a model use inputs to generate outputs. The complexity of DA can range from simple equations to multifaceted CAD models developed utilizing morphological and topological transformations where the outputs are generated from computer simulations such as FEM or CFD. (Amadori, 2012) The reason for DA is mainly to eliminate repetitive tasks to enable more focus on value-adding work. In the development process at companies around the world, a few studies suggest that 90 % of the activities in the design phase are repetitive and non-creative. It is also shown that these tasks are suitable for automation in the means of implementation simplicity and success rate. (Tarkian, 2012)

2.6 Knowledge-based Engineering
Tough competition in the growing aerospace and automotive industries has led to the development of methods trying to achieve an even higher degree of efficiency in the design process. Because of the rivalry, the companies in these industries have kept the methods secret, not wanting to give away anything for free to their competitors. KBE is a method connecting and using the strengths of multiple disciplines such as CAD, Artificial Intelligence (AI) and programming to aid design processes. Because of the in-house development of these methods, academic research regarding KBE has been sparse. (La Rocca, 2012) This has also led to the lack of a community consensus of how to define KBE (La Rocca, 2012); (Sandberg, et al., 2017), but the research from La Rocca (2012), led to a definition, taking the available perspectives in consideration:
Knowledge based engineering (KBE) is a technology based on the use of dedicated software tools called KBE systems, which are able to capture and systematically reuse product and process engineering knowledge, with the final goal of reducing time and costs of product development by means of the following:

– Automation of repetitive and non-creative design tasks
– Support of multidisciplinary design optimization in all the phases of the design process

(La Rocca, 2012)

By implementing KBE in the design process, multiple advantages can be achieved. Reddy, et al. (2015) presents several examples where KBE has been implemented in an industry setting, achieving a significant improvement in efficiency. One example is of a wing box design where British Aerospace managed to decrease the development time from 8000 hours to only 10 hours. Another example is a mesh generation of a Body-in-White (BIW) concept design that, with the help of KBE, was finished in “minutes” instead of in fifteen-man weeks. (Reddy, et al., 2015)

The benefits of KBE are many, ranging from a reduced cost and lead time to making trial and error of designs easier which increases the time available for innovation (Reddy, et al., 2015). The latter is a key factor when it comes to successful projects according to Skakra (2007), stating that KBE does not decrease the workload of the designer, but instead moves focus from routine-like tasks to innovation. How KBE changes the design process according to Skakra (2007) is presented in Figure 2.7.

![Figure 2.7 - KBE changes the development process radically, shortening the overall time, as well as drastically increases the time for innovation. Illustration inspired by Skakra (2007).](image)

3 BIW refers to the basic structure of an automotive vehicle and comprises of many sub-structures fastened together (Chapman & Pinfold, 2000).
KBE systems changes the overall role of CAD software. In the past, the CAD software was a tool that executed simple drafting and analysis tasks. Today CAD can automate limited and often isolated phases in the full design process. With KBE, the importance of CAD increases, and should be viewed more as an active participant that can, within the design constraints, make its own decisions or propose alternative approaches to problems. This can be achieved by designing a model able to access information about the product and design process. The model can then use this information to automate parts or the complete process. The information can come from multiple disciplines and sources available at the company. (Chapman & Pinfold, 1999)

2.6.1 Knowledge-based Engineering Methodologies
There are many methodologies available, describing how a KBE system can be developed. These are often described as too generic. Because of this, a European 30-month long project was initiated in the late 1990s with the objective of reaching a final methodology for developing and maintaining a KBE system in a time and cost-effective manner. The project resulted in "Methodology and tools Oriented to KBE Applications" (MOKA), the most widely spread KBE methodology today. (Kuhn, 2010)

**MOKA**
MOKA consists of six steps as illustrated in Figure 2.8.

---

Figure 2.8 - The six steps of the KBE method MOKA, inspired by the presentation of Kuhn (2010) and Curran, et al. (2010).

### Identify:
The first step is to identify and determine the main characteristics of the project. In this step, the objective, requirements and scope are set.
Justify: Here, the project’s potential risks are identified, the cost and other required resources are estimated.

Capture: This is a data collection phase, where all the necessary knowledge from different stakeholders is collected and structured.

Formalize: The previously collected data is in this step converted into product and process models.

Package: Relevant software applications for the models are developed.

Activate: The KBE system is released to the end user. This step also includes necessary maintenance.

(Kuhn (2010), Curran, et al. (2010))

KNOMAD
To further advance KBE methodologies and to highlight the multiple disciplines often represented in a design process, "Knowledge Nurture for Optimal Multidisciplinary Analysis and Design" (KNOMAD) was developed. The methodology consists of six steps, presented in Figure 2.9. (Curran, et al., 2010)

![Figure 2.9 – The KNOMAD process inspired by Curran, et al. (2010).](image)

**Knowledge capture:** In this first step, the project’s scope is determined, objectives are set and relevant knowledge is collected and documented.

**Normalization:** The knowledge collected in the previous step is in the normalization phase analyzed and goes through extensive quality checks. When the raw knowledge is checked and approved, normalization of the knowledge is conducted, meaning it is standardized during the rest of the methodology.

**Organization:** The standardized knowledge is then organized to allow all stakeholders to retrieve different types of knowledge.

**Modeling:** In the modeling phase, a specific type of modeling framework is utilized, called Multi-Model Generator (MMG)\(^4\).

\(^4\) MMG is a KBE application enabling automatic generation of wildly spread product configurations along with all necessary meta data. (Wang, et al., 2014)
**Analysis:** It is in the analysis step that the methodology's focus on multiple disciplines is shown the most. Here, analyses on discipline-specific areas can be executed, but the analysis step also consists of single- or multi-objective MDOs.

**Delivery:** Lastly, the suggested solution is presented to the stakeholders. It is reviewed against the previously established project objectives, and necessary actions are initiated to be able to finalize the product.

(Curran, et al., 2010)

2.7 Finite Element Method

FEM is a vital part of a modern design process, acting as a test and verification phase in the typical iterative steps taken to develop a product. It is used to analyze many different disciplines such as solid mechanics, thermal analysis, and electrical analysis. Using FEM, unknown, distributed field variables can be obtained numerically. This is achieved by dividing the analyzed geometry into smaller elements, which are of much less geometric complexity than the complete design. Applying physical and mathematical principles on these elements lead to a system of equations that solves the required distributed field variable. (Liu & Quek, 2013)

2.7.1 General Methodology

The general steps used when conducting a FEM analysis are presented in Figure 2.10, and can be divided into three main phases: pre-processes, the actual calculations and results visualization.

![Diagram showing the general methodology of FEM](image)

*Figure 2.10 – The general methodology of FEM. Visualization inspired by Liu & Quek (2013).*

In Figure 2.10 above, the computational modeling phase corresponds to pre-processes, while solution procedure represents the calculation phase.

2.7.2 FEM Preparations of an After-treatment System

An exhaust silencer model usually requires several types of FEM simulations. These are performed on bolts, plates and welds. The main focus is high and low frequency cycle fatigue and the simulations are conducted to ensure the exhaust silencer will pass the physical tests it is subjected to later in the developing process. Also, a dynamic modal analysis is performed to check that the exhaust silencer’s parts are not subject to resonance. (Nowicki, 2018)

2.7.3 FEM Pre-processing

When modeling for FEM analysis, multiple factors need to be taken into consideration and the engineer's judgement is required in both the modeling of the product and the analysis of the results. The geometry of 3D models can often be very detailed and complex and approximating
small intricate 3D objects can require lots of elements with small size. This increases the number of elements used, which adds to the computational complexity of the problem. Restrictions in the computational power, or time available, limits the number of elements that can be used. To approach this challenge, the engineer must analyze which parts in the geometry are vital to get results closely approximating reality, and which parts can be ignored or simplified. In some cases, 3D geometry can be mathematically represented as 2D or even 1D elements, decreasing the complexity even more. Using techniques like these can make the FEM analyses more efficient. (Liu & Quek, 2013)

When the modeling is done, the next step in the pre-process is meshing, the creation of elements. Meshing a 3D model can be very time-consuming and requires the excellence of an experienced engineer for complex products but is a vital step in the preparation of the model before FEM analysis. Meshing can be performed in either full FEM software packages, or in specific software designed for meshing, so called pre-processors. This software usually offers semi-automated meshing tools, aiding the engineers in the meshing process. Fully automated meshing tools are yet not commercially available. (Liu & Quek, 2013)

The reason meshing is time-consuming is partially because of the quality demands on the elements. Here, quality is tightly connected to the size and shape of the element, affecting both the overall accuracy and the efficiency of the analysis. There are multiple factors to take into consideration when determining the quality of a mesh. It is shown that three of the main factors are aspect ratios, angle idealization and element Jacobians. (Burkhart, et al., 2013)

Aspect ratio
The aspect ratio describes the relation between the longest edge or diagonal and the shortest edge in an element. By keeping this value as close to unity as possible, the most accurate results are found. However, achieving a mesh containing only elements with an aspect ratio of one is hard, especially for thin geometries with high curvature. Therefore, it is stated that elements with an aspect ratio less than three can be considered acceptable, less than seven treated with caution and more than 10 treated with alarm. (Burkhart, et al., 2013)

Angle idealization
The angles between every pair of edges in each corner should be kept close to the ideal angle of 60° for tetrahedral elements and 90° for hexahedral elements, to avoid inaccurate deformation results. Just as with the aspect ratio, this can be hard to achieve in regions with thin geometry with high curvature. Generally, keeping the deviations of the angels to less than 30° for most of the elements and at the same time letting less than 5% have a deviation of more than 70° generates an acceptable mesh. (Burkhart, et al., 2013)

Element Jacobian
The Jacobian matrix is vital in FEM calculations, containing information about the element geometries. The element Jacobian is the determinate of the Jacobian matrix and describes how distorted the element is compared to an ideal element. For elements of very low quality, the Jacobian can be negative, preventing analyses from finishing. The Jacobians should therefore be positive, and generally a value of 0.2 or higher is desired. (Burkhart, et al., 2013)
Mesh criteria and parameters

The quality and parameters for the mesh when using a pre-processor depends on the initial criteria and parameter settings. The criteria setting sets the constraints for the mesh quality and can be configured in different ways. For example, if the user wants all the elements to have a Jacobian value higher than 0.7, the CAE engineer can specify this in the criteria editor. To make sure the mesh fulfills the criteria values, the engineer can later manually do an element check in the pre-processor. (Altair Engineering AB, 2017)

Another important factor when generating a suitable mesh is the parameter settings. Here, the settings for said mesh is determined and includes for example mesh size, type of mesh and type of elements generated. (Altair Engineering AB, 2017)

2.8 Design Optimization

Optimization is about finding the best possible solution in a pre-defined design space\(^5\). This is done by mathematically defining an objective function to be minimized or maximized. The objective function has variables, called design variables which are limited to an upper and lower limit. Furthermore, constraints that restrict the optimization problem can be defined. According to Arora (2015), an arbitrary optimization problem can be defined as follows:

\[
\begin{align*}
\text{Minimize} & \quad f(x) \\
\text{subject to} & \quad g_i(x) \leq 0 \quad i = 1,2,\ldots,m < n \\
& \quad h_j(x) = 0 \quad j = 1,2,\ldots,r < n \\
& \quad x_l < x < x_u \\
\end{align*}
\]

where \(x\) is a vector of \(n\) design variables given by:

\[
x = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{bmatrix}
\]

The functions \(f\), \(g_i\) and \(h_j\) are all differentiable. The design variables are bounded by \(x_l\) and \(x_u\).

(Arora, 2015)

An optimization problem can have a different number of objective functions, making it either single-objective or multi-objective (Amadori, 2012).

\(^5\)The parameterized space in which the model is constrained. Depending on the constraints, there are different kinds of design spaces. For example, the customer, product and company design spaces are different and the space binding them together is considered the actual design space. (Cederfeldt, 2007)
2.8.1 Multidisciplinary Design Optimization
To reach a high level of understanding about how a complex product behaves, it is of great importance to optimize the models concerning different disciplines simultaneously. Optimizing the different sub-systems in a complex product without considering the interactions between them might lead to optimal sub-systems, but that is not equivalent with the optimal solution for the whole product. (Amadori, 2012) Taking these interaction into consideration when optimizing, usually leads to a better design (Amadori (2012), Domeij Bäckryd (2013))

MDO does not only optimize a product in development on a global level but implementing an MDO framework early in the design process is expected to increase the overall knowledge and understanding of the product and problem. This leads to more well-founded decisions in the early stages of development. MDO also aids the number of iterations for a design, making it more probable to find an optimal solution. (Tarkian, 2012)

2.9 Previous Master’s Thesis Work
During the past three consecutive years (2015–2017), master’s theses about KBE, DA and MDO have been written at Scania. Also, a master’s thesis was conducted on the subject the spring of 2008. Since it has been an evolving process and many of the theses are based on previous ones, a summary of the former KBE- and MDO-related master’s theses at Scania is therefore documented. In addition, this master’s project will also take into account preceding thesis works when developing the methodology.

2.9.1 Early Work
The first master’s thesis written at Scania on the subject were Lundin & Sköldebrand’s (2008), and it discussed rather elementary topics. The purpose with the thesis was to investigate whether using KBE tools in CATIA V5 (herein referred to as “CATIA”) is a good way to transfer knowledge about products to future projects and how Scania could implement this in their PD process. The authors Lundin & Sköldebrand (2008) argues that there are both benefits and disadvantages concerning KBE. A difficulty is to decide whether it is suitable applying KBE on the product in question or not, while the advantages include quality assurance and a considerable decrease in lead time.

Lundin & Sköldebrand (2008) recommends that Scania should consider implementing KBE. To do this, a focus group should be appointed that will be responsible for educating remaining employees. (Lundin & Sköldebrand, 2008)

2.9.2 Recent Research
During the past three consecutive years leading up to this thesis, at least eight thesis works on the subject have been written at Scania, looking at new aspects of the implementation of KBE, DA and MDO in the PD process at the company. The main focus of the theses has been to develop methodologies to aid the implementation of these methods. Below, a summary of what research has been done is presented. Also, the previous theses have been continuing the development of the same methodology, adding a few new steps every time. In Figure 2.11, the development of the methodology throughout the years is visualized. This methodology has later been further developed by more recent Master of Science (M.Sc.) students. These results are described later in this chapter.
Blomberg (2015) investigated the role of parametric modeling in the PD process, when it should be used and when it is redundant. He states that robustness and formulation of the parameters were the two main issues. However, the author concludes that the opportunities for implementation of parametric CAD modeling at Scania are good and that it is encouraged.

The pre-phase consists of letting the designer familiarize with the work and start planning what approach should be taken when modeling the product. The main reason for this phase is to, early in the process, establish and document the connecting geometries. This documentation should be standardized and available to all stakeholders to enable quick insights in different projects. (Blomberg, 2015)

After the pre-phase, the methodology suggests a modeling phase, where the CAD model is realized based on the previous preparations. There are no methods the designer can follow exactly, but Blomberg (2015) presents a guideline on which steps should be included in the modeling phase to enable a robust CAD model. Robustness is tested in the third and final phase of the methodology, the evaluation phase. Here the model should be verified against requirements set in the pre-phase, checked if it contains all necessary information and a Design of Experiments (DOE) should be run to verify the robustness.

Luu (2015) also presented a methodology for implementing parametric CAD modeling at the company, but with the focus to use parameters to aid CFD simulation. This led to an improvement of the previously mentioned methodology, including CFD simulations after the evaluation phase. Luu (2015) concludes that such a methodology would result in decreased lead times, enhanced component performance and that it would promote collaboration between company departments.

Jansson & Wiberg’s (2016) focus is on including multiple disciplines in the overall methodology. Their contribution to the general process is how the FEM simulations should be included, but also an even more substantial evaluation phase. The authors state that including initial simulations in the evaluation phase will decrease the amount of critical errors as well as reducing the number of design iterations needed.

With this developed fundamental methodology, three theses conducted in parallel 2017 focused on a standardized modeling practice, optimization for CFD application and optimization for FEM

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6 Design of Experiments is a tool used for quality improvement and can be utilized when determining cause and effect relationships. By altering the input variables, the output variables will change and from this, one might draw certain conclusions concerning the design. (Anderson & Whitcomb, 2015)
application respectively. These three theses, all based on the previous thesis works, resulted in three methodologies, which are presented below.

**Baber & Shankar**
This project aimed to develop a methodology that with the help of smart CAD models would shorten lead times in the product development process. After having finished the work, a methodology consisting of three main phases had been developed by the authors Baber and Shankar (2017). The steps were as follows: pre-CAD phase, CAD phase and collaboration phase. In the first procedure, the product is analyzed so – among other things – proper parameters will be set in the CAD phase. Then, the product is modeled, and relevant parameters are created. In the last step, the modeled product is integrated in an MDO framework to optimize it. In this thesis, the model was optimized in regard to CFD. Below in Figure 2.12 is the flow chart of the methodology developed by the M.Sc. students. (Baber & Shankar, 2017)

![Figure 2.12 – The proposed methodology developed by Baber and Shankar (2017).](image)

**Grandicki & Lokgård**
Grandicki & Lokgård (2017) conclude that while parametric modeling would aid simulation-driven design at the company, it is crucial that a uniform modeling practice is implemented. From this, they develop a new methodology aiming to perform this task. If implemented, Grandicki & Lokgård (2017) argue that this would lead to shorter lead times, faster and easier adaption to change and reduced development costs. In Figure 2.13 the proposed methodology can be seen. (Grandicki & Lokgård, 2017)
Figure 2.13 – The proposed methodology developed by Grandicki & Lokgård (2017).

**Hallqvist & Hellberg**

In this thesis, a more detailed methodology is presented, originating from the thesis project carried out by M.Sc. students Jansson & Wiberg (2016). The number of steps is the same, but the content is altered. Hallqvist & Hellberg (2017) says that the methodology developed can be summarized as “…an explanation of how to model, calculate on and optimize load bearing geometries.” They also created different templates about welding seams, meant to be used in future master’s thesis projects.

In the methodology, which is visualized in Figure 2.14 below, they focus on what is said to be a bottleneck in the development process, id est the transition between the design engineering division and the calculation division. (Hallqvist & Hellberg, 2017)

Figure 2.14 – The proposed methodology developed by Hallqvist and Hellberg (2017).

The steps that make this methodology differentiate from the previous ones are partially the optimization steps, but also that more analyses are conducted by the design engineer. The pre-optimization is an early topology optimization used by the design engineer to get more knowledge about the product and to get hints on how an optimal design could look, aiding the design process. Hallqvist & Hellberg (2017) states that this potentially leads to better results. The later FEM, optimization and manufacturability steps are also supposed to be executed by the design engineer. For the FEM analysis, the authors recommend Generative Assembly Structural Analysis (GAS) in CATIA, for the optimization step, HEEDS MDO 2017 is recommended and finally, to check manufacturability an arbitrary, suitable software could be utilized.
2.10 Interview Techniques

When conducting interviews, there are a few different approaches to consider. The three main techniques are, according to Hancock, et al. (2009):

**Unstructured interviews:** This is a technique that does not require any specific preparation, instead it works like a free-flowing conversation.

**Semi-structured interviews:** This is the most common among interviewing techniques. Open-ended questions about the subject are prepared beforehand to allow for further conversation about specific topics. This is a good approach if the interviewee provides the interviewer with limited answers. If so, the interviewer can ask follow-up questions until he or she gets a satisfying answer.

**Structured interviews:** This way of interviewing is limited to only predetermined questions. The same questions are asked to each respondent and no unscripted follow-up questions are asked.

(Hancock, et al., 2009)
3 Thesis Methodology

This chapter presents the procedure and steps taken during this thesis work. To reach the final methodology, the thesis work was divided into three main phases. Firstly, to gather the necessary information and to establish similar or relevant research, a data collection phase was conducted. After the theoretical framework was set, a pre-phase was initiated to widen the knowledge of available software. Following these two knowledge-enhancing phases, development of the methodology begun as an iterative process applied on a case study.

The thesis methodology adopted is similar to the one visualized in Figure 2.1 by Ulrich & Eppinger (2011), where the authors reason that the PD process should begin with data collection and benchmarking to understand the problem and to investigate the needs. After documentation of the data collected, Ulrich & Eppinger (2011) argue that an iterative design process is instituted where one starts with a broad perspective, exploring possibilities and then narrows it down accordingly through different PD methods, until a final product is ready for launch. This thesis’ methodology can be viewed in Figure 3.1 below.

![Figure 3.1 – The thesis work was divided into three main phases to aid the workflow and conducted research.](image)

3.1 Data Collection

In the early stages of the thesis project, different kinds of data were gathered to lay a solid foundation for the task at hand. Literature concerning relevant topics were studied and interviews with suitable people were conducted. As a supplement to this, previous theses on the subject were read, and in some cases implemented in the project. More about earlier thesis works is stated in Chapter 2.9.

3.1.1 Literature Study

The literature referred to in this report is mainly academic and consists mostly of peer reviewed reports, journals, articles and books. These publications discuss the theories concerning DA, KBE, parameterization, FEM and MDO, but also PD in general as well as information regarding after-treatment systems and environmental laws connected to it. As previously stated, this thesis is a development of previously executed thesis works in the same area, with focus on automated FEM
pre-processes. To understand the area better, and to find relevant resources, preceding master’s thesis reports has also been studied during this project.

The main source for finding relevant literature has been Linköping University’s online literature database and the academic search engine Google Scholar.

3.1.2 Interviews
Interviews were carried out to gain inside knowledge from employees at Scania. The questions comprised of current methodologies and line of action as well as problems or areas of improvement that the respondent had identified. The interviewees consisted of design engineers, calculation engineers and former M.Sc students within the same thesis area. Before constituting the questions, literature concerning different interviewing techniques were studied (see Chapter 2.10).

After reviewing the different interview approaches, it was decided that the method applied in this project was to be semi-structured interviews since that method was thought to result in the most valuable information. This, because it was considered beneficial to have questions prepared beforehand but conducting fully structured interviews could result in less information gained due to the interviewer’s lack of knowledge on the subject. Therefore, semi-structured interviews were thought most suitable for the task at hand.

3.1.3 Former Theses Work
As mentioned above in Chapter 2.9, a study of previous theses work within the same area at Scania has been conducted. The research covers nine former master’s theses and focuses on examining the results respectively. More about the findings can be read in Chapter 2.9.

3.2 Pre-phase
To further concretize the foundation of this thesis, another knowledge-enhancing stage, after the data collection phase, was conducted. In this stage, called the pre-phase, more hands-on knowledge about available software was obtained. The software included in this stage was mainly exploration of the pre-processor for FEM applications – Altair HyperMesh 2017 (herein referred to as “HyperMesh”) – but also other relevant software connected to the project that was available. This other software included CATIA, the FEM solver Abaqus 2018 (herein referred to as “Abaqus”), and the programming software VBA. This stage consisted of exploring how these different software work and of investigating the possibility of a collaboration between HyperMesh and CATIA and VBA. By doing this, more concrete knowledge about how later stages in the thesis could be executed, was obtained.

3.3 Case study
An important step in the methodology development process was the case study, whose phases were inspired by the KBE methodology MOKA (presented in Chapter 2.6.1). After concluding the data collection and pre-phase, the gathered data was analyzed to understand what had to be done in each step and how to enforce it. Three of MOKA’s phases; capture, formalize and package were represented in the case study methodology as specification, approach and problem implementation. During the specification stage, all necessary information from relevant stakeholders was collected. In the approach stage, the methodology was defined with different
steps in a flowchart to visualize and concretize the solution which was then developed in the problem implementation stage. The implementation was executed on a simplified CAD model of an after-treatment system. After executing previous steps, an evaluation was made to ensure the methodology’s success and to find ways to further enhance it. The whole procedure was then iterated within the project’s time frame. When the evaluation yielded a satisfactory result, fulfilling the desired criteria, the iteration process was interrupted, and the final methodology was delivered. An illustration of the case study adopted is visualized in Figure 3.2.

![Figure 3.2 - The iterative case study process conducted.](image)

3.3.1 Specification
The first step of the actual development phase was to create a specification on what steps the final methodology should include, what the inputs and outputs of the different steps were and in what order the steps were to be executed. This was done to decompose and organize the problem and to more easily be able to overview the problem. As a positive side effect of this, possible risks are easier to identify early in the process. This is beneficial, according to Lindahl & Tingström (2006), since the possibility to do changes in a project is greater in earlier phases of the project, than in latter ones, as illustrated in Figure 2.2.

3.3.2 Approach
In the approach stage, the individual steps defined in the specification were decomposed, to further analyze and investigate their characteristics. This included, for example, categorizing the different tasks according to what kind of interactions each task had, for example if specific tasks required human interaction or a script with a specific programming language. The goal of this stage was to clearly define the whole methodology including the individual steps, before realizing them.
3.3.3 Problem Implementation
Following the specification and approach, the actual methodology was realized in the problem implementation phase. Here, the necessary code was written and GUIs developed, along with everything else essential to get the methodology working, such as implementing meshing-specific details.

3.3.4 Evaluation
When the proposed methodology was realized, it was evaluated with the case study’s simplified CAD model of the exhaust silencer. The results were analyzed, and possible improvements were identified. In this stage, the methodology was also compared to earlier iterations to conclude if any improvements had been made.

3.3.5 Improvement
If it was concluded during the evaluation phase that the methodology still had flaws, an improvement phase was initiated to further develop and enhance the methodology. After improvements had been made, the case study was re-performed and re-evaluated to see if the results reached the desired standard.

3.4 Final methodology
After performing the different steps mentioned above, the thesis methodology resulted in a final project methodology, which is further described in Chapter 6.
4 Interview Results

Seven interviews with one interviewee each were conducted to deepen the knowledge about the overall workflow and collaboration between the design department and the FEM department. Three of the interviewees were design engineers, three were CAE engineers with focus on FEM, and the last interviewee also a CAE engineer with focus on FEM but with additional experience in a project about utilizing KBE in the calculation phase of the development process to make the workflow more efficient. Below, is the author’s interpretation of the interviewee’s answers. The interview questionnaires can be seen in Appendix A – Interview Questionnaire.

4.1 Design Engineer Interviews

From the interviews with the design engineers, a few main areas of interest for this thesis were identified. These are presented below.

4.1.1 Robust CAD models
The design engineers focus a lot on the development of the CAD model in early phases of the process. The interviewees experience that building CAD models intelligently, in a robust fashion, takes longer time initially but improves the control and modifiability of the model in later stages substantially. In collaboration with the CAE engineers, the CAD model often goes through an iterative analysis loop, and with a model that is easy to modify, more iteration loops can be achieved within the same time span. Also, a more thought-through CAD model saves time, especially since without a smart CAD model, the whole geometry might have to be remodeled from scratch.

4.1.2 Information Dissemination between Departments
In some cases, problems with information dissemination between departments has been identified. This is mainly expressed as a lack of knowledge about what work other departments perform. If the delivering department does not know how the receiving department uses the model, it could be difficult to deliver a suitable model. This might lead to unnecessary preparation work for the receiving department, having to modify the model to make it ready for the meshing procedure performed.

4.1.3 Parallel Work with Design and Analysis
During the iteration process, the design engineers send their CAD models to the CAE engineers for analysis. During a couple of weeks, the CAE engineers prepare the model for analysis, run the analyses and submit a report containing the results. During this time, the design engineers continue with the development of the models, without knowing the results from the analyses, trying to work on parts not affecting the analysis results notably. If the design engineers could receive the results within a shorter time frame, more justifiable adjustments to the model could be made.

4.2 CAE Engineer Interviews

The remaining four interviewees were CAE engineers with focus on FEM. One of them had a leading role in a project about implementing methods to increase the traceability of CAE models. Another one had some experience with scripting mesh for FEM analysis, as the interviewee had
taken the initiative to automate mesh generation to enable MDO, along with some colleagues. The most interesting topics revealed during the interviews are presented below.

4.2.1 Time-consuming Weld Meshing

The procedure of meshing welds is very time-consuming and is regarded as a bottleneck in the development process. Sheet metal parts and cast-iron details can be meshed quite efficiently with an automatic mesh generator in the pre-processor. Welds however, need to be manually connected, which is a labor-intensive task. When updating a mesh on a part connected with welds, the weld mesh needs to be reconnected. This means that a simple and quick modification of the geometry for the design engineer can lead to a very time-consuming remesh for the CAE engineer, if the modified geometry relates to several long welds.

4.2.2 No Standardized Methods for Deliveries

A lack of standardized methods for how a model should be delivered from the design engineer to the CAE engineer leads to more work for the employees at the calculation department. Depending on which design engineer that delivers the model to the CAE department, the models can differentiate and need different amounts of preparation by the CAE engineer. Even if the model is fully prepared, the CAE engineer needs to thoroughly investigate the model, since there is no way of knowing in advance if the model is ready for pre-processing directly after delivery from the design engineer or if it needs cleanup.

4.2.3 Information Dissemination between Departments

The problems with information dissemination that the design engineers stated during the interviews were mentioned in the interviews with the CAE engineers as well. This is partially reflected in the above presented problem – that no standardized methods for delivery exist. The different departments lack the required knowledge about how the other departments work and how they use the models.

4.2.4 MDO Enablement

Automated meshing is a key factor in enabling an MDO framework. Some of the previous work by the CAE engineers regarding automated meshing was initiated with the sole purpose of creating an MDO framework to utilize optimization in the design process. As a result of the automated mesh, repetitive tasks are reduced for the CAE engineers, and they can focus more on value-adding tasks such as analyzing load cases or post-processing. If MDO early in the process is the sole purpose of automating meshing, one interviewee states that more rudimentary software, like GAS in CATIA could be used for FEM analysis. GAS utilizes a direct connection between geometry and mesh and can automatically update a mesh if the geometry is modified. The optimization with FEM analyses in GAS would yield similar results as with a more complex FEM solver on a general scale. However, the absolute values are not to be trusted blindly. Therefore, an early MDO with GAS, and a later, verifying, calculation in a more advanced FEM solver is recommended by the interviewee.
5 Case Study Results

The case study was performed according to the flowchart presented in Chapter 3.3. In order to develop the methodology in a structured manner, the process used at the after-treatment systems department at Scania to mesh a CAD model made with sheet metal components and welds was analyzed in detail. This process was then structured in a way suitable for automation, adapting it to the current process used at the department. In the following chapters, the results from the last iteration of the case study is presented, leading to the final methodology.

5.1 Specification and Approach

During the specification and approach phases of the case study, focus was on identifying what steps had to be taken to concretize the problem to lay the foundation for being able to implement the findings in later case study phases. Below, the results of the initial phases of the case study are presented with emphasis on how the meshing procedure should be carried out. Here, specific software is not taken into consideration, but the overall methodology is a general flowchart showing the main concept of the methodology. Specific software is chosen in the problem implementation phase.

5.1.1 Meshing Procedure

To mesh a welded sheet metal product, four main steps are needed in order to go from a CAD model to a fully meshed model. Initially, the sheet metal components should be meshed. This can easily be achieved using automated batch meshing software available commercially, for example Batchmesher in HyperMesh. Often, this automatic mesh software does not represent the model graphically on the screen, but the user only inputs what files are to be meshed and specific mesh settings. This automatic mesher outputs a 2D mesh, instead of a 3D mesh, for sheet metal components, to reduce the complexity of the problem. The next stage is to apply material and thickness to the mesh, this is often done in a graphical interface.

When the sheet metal components are fully meshed, the next step is to create the mesh for the welds. To achieve this, the location of the welds must be identified, the weld mesh must be placed along the identified line and in most cases, the sheet metal components have to be locally remeshed to meet the quality criteria. There is commercially available software that automates some parts of this stage, for example a feature called Connectors in HyperMesh. Using connectors, the software searches for nodes on both components within a specified radius from the defined line. This feature lets the user control certain parameters regarding, for instance, remeshing of the sheet metal components.

The fourth and final step of the meshing should be a manual quality check, to investigate if there are any elements of low quality that would interfere with the analysis results (see Chapter 5.3.1).

Many of the steps in this pre-process are very repetitive, which makes them suitable for automation as confirmed by Tarkian (2012) in Chapter 2.5. This is accurate for all mentioned steps except the quality check, which varies from project to project, depending on how the earlier mesh generation has succeeded. With this insight in how the meshing is executed, the process was broken down further, to increase the understanding of the problem and to be able to categorize the different steps for potential scripts.
5.1.2 Proposed Methodology
The specification and approach phases in the case study resulted in a flowchart which is displayed below in Figure 5.1. Firstly, before the meshing begins, the CAD model is prepared with lines that describe the weld positions. Thereafter, the user interacts with a GUI to load the CAD files to be meshed and sets relevant mesh parameters. Then, the user initiates the automatic mesher, which calls a number of scripts that executes the whole process automatically.

Outputs from this process would be a finished mesh along with an automatically generated mesh report, describing the final quality of the mesh.

5.2 Problem Implementation
To implement the steps presented in the flowchart above (Figure 5.1), different software and scripting languages were used. The CAD models were developed in CATIA and the pre-processor used was HyperMesh. A GUI was developed in Microsoft Office Excel 2016 (herein referred to as “Excel”) to enable simple interaction with the automated mesher. VBA in Excel was used for the GUI, batch files were used to initiate the pre-processor and the scripting language Tcl was used to automate commands in HyperMesh.

Below, the methodology’s steps and their characteristics are presented more in-depth.

5.2.1 CAD
Automated processes benefit from being able to extract the same information in the same way from different sources. That way, the scripts can easily loop through all sources and execute the same extraction in each step. By defining certain parameters in the same way in all CAD parts in a project, later stages in the development process can be drastically improved by automation. In the suggested methodology flowchart presented above in Figure 5.1, three main things should be defined in the CAD model to achieve a fully automated meshing process after the CAD model is delivered.
**Welds**
Firstly, in order for the pre-processor to mesh welds, it needs to know where the welds are located as well as being able to access certain mesh data to mesh the component correctly. Usually, this is manually defined by a CAE engineer in the pre-processor itself. To automate the weld mesh phase, the weld definition needs to be set in an earlier stage. The approach taken in this case study was to, for every weld, define a line in CATIA which follows the path of the weld. How the line is defined is up to the design engineer but should be in contact with one of the plates that are to be meshed. Other than the line itself, more data can be saved in the feature. In this case, the articles to be welded together and the throat thickness\(^7\) parameter is saved in the name of the line for easy identification in the pre-processor.

**Parameters**
To easily access other variables interesting for FEM analysis, such as thickness of the sheet metal and the material of the component, parameters in CATIA were used. Defining features other than the geometry itself leads to a more complete CAD model, enabling extraction of important data for anyone with access to the model. This also makes the delivery of the CAD model to different departments more efficient, already having everything defined in one single file, rather than having information in different locations.

**CAD Template**
To effortlessly develop CAD models with similar characteristics and features suitable for this methodology, a CAD model template was used, which could be utilized together with other CAD templates used to keep track of features and how the geometry is modeled. This template only considers the features needed specifically for this methodology and can easily be utilized together with other templates. The template is presented in Figure 5.2.

---

\(^7\) The distance from the root of a fillet weld to the center of the hypotenuse. (Weman, 2007).
The CAD template contains two parameters which decides the thickness of a sheet metal component and the material, and two geometrical sets where the designer can place construction features for the lines defining the welds in “FEM_Construction_Geometry” and the actual lines defining the welds in "FEM_Welds".

5.2.2 GUI
The developed GUI contains two sheets, one developed for the design engineer and one for the CAE engineer. In this report, the different sheets are referred to as “CAD Excel GUI” and “CAE Excel GUI” respectively.

Firstly, there is the CAD Excel GUI which is intended for the design engineer. After creating the CAD model and adding the required weld lines, the GUI is launched. Here, the design engineer can choose to check if all weld lines in CATIA are named correctly, show and hide all lines and export thickness and material parameters to a text file. This text file is later loaded by the CAE engineer. The CAD Excel GUI can be viewed in Figure 5.3.

The CAE Excel GUI allows the user to easily load CAD files to be meshed, load parameter and criteria files that determine the mesh size and mesh quality (see Chapter 2.7.3), set the weld mesh size as well as loading the thickness of the sheet metal and initiate the automated mesher. Since the GUI is based on Excel VBA, it helps to control buttons and execute batch files to launch HyperMesh and load the necessary Tcl scripts. The GUI is used to easily interact with the scripts and is designed to be user-friendly, both for design and CAE engineers. The GUI lets the user mesh a CAD model with default settings if desired, but also allows an experienced CAE engineer to modify the settings for specific needs if necessary. The CAE Excel GUI presented in Figure 5.4 can easily be modified and expanded for future development of the software.

Figure 5.3 – The CAD Excel GUI.
5.2.3 Pre-processor

When all the settings in the GUI are established, the user initiates the automatic mesher. This executes HyperMesh in two steps. Firstly, the loaded sheet metal components are run through Batchmesher with the specified settings from the CAE Excel GUI. In the second step, the batch meshed components are loaded into HyperMesh. Here Tcl scripts firstly apply thickness and material individually on all components. Then the weld lines are identified with a Tcl script that searches for lines with specific meta data set in CATIA, when these are identified, connectors are applied on all weld lines, and the weld mesh is created.

5.3 Evaluation and Improvement

Mainly after, and partly during, the implementation phase, evaluation and improvement of the methodology was performed to improve the overall quality of the methodology. The results of the evaluation process are presented in more detail below.

5.3.1 Mesh Quality

The quality of the mesh is, as previously stated in Chapter 2.7.3, determined by the parameter and criteria files loaded into the GUI. These play a large role in the accuracy of results of subsequent analyses and should therefore be developed and maintained for specific purposes.

In the methodology, a quality report is automatically generated after the meshing sequence. To control the quality, the CAE engineer should analyze this report. It displays if there are any failed elements (that is to say if there are any elements not fulfilling the criteria set in the criteria files), the number of ideal and good elements, as well as elements that are on the verge of failing. These ideal, good and almost-failed values can be set in the criteria file before meshing. An example of a mesh quality report is shown in Table 5.1.
Table 5.1 – An example of the automatically generated mesh quality report.

<table>
<thead>
<tr>
<th>Q.I.</th>
<th>Worst Value</th>
<th>Ideal</th>
<th>% Ideal</th>
<th>Good</th>
<th>% Good</th>
<th>Warn</th>
<th>% Warn</th>
<th>Fail</th>
<th>% Fail</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Length</td>
<td>0.15</td>
<td>3.52</td>
<td>5.00</td>
<td>10024</td>
<td>61.48</td>
<td>3.83</td>
<td>2959</td>
<td>18.74</td>
<td>2.67</td>
</tr>
<tr>
<td>Maximum Length</td>
<td>0.02</td>
<td>9.73</td>
<td>5.00</td>
<td>14356</td>
<td>90.97</td>
<td>6.50</td>
<td>1344</td>
<td>8.51</td>
<td>7.90</td>
</tr>
<tr>
<td>Aspect Ratio</td>
<td>0.02</td>
<td>4.99</td>
<td>1.00</td>
<td>13291</td>
<td>84.16</td>
<td>2.00</td>
<td>2384</td>
<td>17.73</td>
<td>4.00</td>
</tr>
<tr>
<td>Warpage</td>
<td>0.00</td>
<td>4.99</td>
<td>1.00</td>
<td>15281</td>
<td>98.06</td>
<td>1.75</td>
<td>282</td>
<td>1.38</td>
<td>11.25</td>
</tr>
<tr>
<td>Max Quad Angle</td>
<td>0.01</td>
<td>148.50</td>
<td>60.00</td>
<td>14782</td>
<td>94.17</td>
<td>110.00</td>
<td>917</td>
<td>5.81</td>
<td>140.00</td>
</tr>
<tr>
<td>Min Quad Angle</td>
<td>0.01</td>
<td>40.92</td>
<td>90.00</td>
<td>14846</td>
<td>94.04</td>
<td>70.00</td>
<td>946</td>
<td>5.99</td>
<td>40.00</td>
</tr>
<tr>
<td>Max Tetra Angle</td>
<td>0.01</td>
<td>110.43</td>
<td>60.00</td>
<td>15740</td>
<td>99.72</td>
<td>80.00</td>
<td>44</td>
<td>0.28</td>
<td>120.00</td>
</tr>
<tr>
<td>Min Tetra Angle</td>
<td>0.12</td>
<td>20.20</td>
<td>60.00</td>
<td>14609</td>
<td>98.78</td>
<td>50.00</td>
<td>177</td>
<td>1.12</td>
<td>30.00</td>
</tr>
<tr>
<td>Skew</td>
<td>0.02</td>
<td>56.72</td>
<td>9.00</td>
<td>12046</td>
<td>81.98</td>
<td>10.00</td>
<td>2840</td>
<td>17.98</td>
<td>50.00</td>
</tr>
<tr>
<td>Jacobian</td>
<td>0.01</td>
<td>0.52</td>
<td>1.00</td>
<td>14168</td>
<td>89.72</td>
<td>0.90</td>
<td>1618</td>
<td>10.25</td>
<td>0.60</td>
</tr>
</tbody>
</table>

The quality check can also be visualized on the mesh itself, if the CAE engineer so prefers. This enables easy identification of areas with certain mesh qualities, and an easy overview of the full mesh at once. Different criteria can be checked individually and elements with bad quality is highlighted. A quality check of the Jacobian is presented in Figure 5.5. This quality check can be used to check other relevant values such as aspect ratio and angle idealization, which are important values to keep track of to ensure a reliable analysis, more about this in Chapter 2.7.3.

Weld mesh configurations
During the improvement phase, enhancement concerning the weld mesh configuration was an important part of the work. This, so the developed methodology would be applicable for the CAE engineers in their daily work. The quality advancement process resulted in weld meshes that are
configured in a way that along all the welds there is a line of elements following the path of the welds on either side of the weld. These element lines represent the throat thickness and their respective values are set during the design process and are later automatically implemented during the meshing procedure. When remeshing the components to implement the weld meshes using connectors, the elements are adjusted to fit the weld. This can be done in two ways – with or without the throat thickness imprint, also known as pitch. In Figure 5.6 the results from the different settings are illustrated. Also, the throat thickness element lines after remeshing of the components are visualized in Figure 5.7.

Figure 5.6 – Shows how the original 2D sheet metal mesh (left picture) can be adjusted after the weld mesh has been introduced. Either with a simple remesh (middle picture) or with a remesh containing an element row representing the throat thickness imprint with fixed width along the weld (right picture).

Figure 5.7 – A remeshed plate after insertion of the throat thickness element lines. The remesh is highlighted with arrows.

The developed mesh features were the result of continuous communication with the CAE engineers throughout the project and a lot of the improvement work during the case study consisted, as previously stated, of further enhancement of the mesh quality and implementation of features. This, so that the product would be as prepared as possible for the later verifying FEM calculations. Also, if required, it is easy to use HyperMesh’s cleanup tool to manually edit the mesh in the places it does not fulfill the desired quality criteria, though, as can be seen in Table 5.1 and
Figure 5.5, this is rarely necessary. In the Tcl script that controls the meshing of the welds there is also room for adjustments since a vast amount of case specific settings can be accessed from there, if desired.

Moreover, the automatic mesh takes holes and washers into consideration as well when remeshing the plates for weld meshes and therefore preserves them, as illustrated in Figure 5.8.

![Figure 5.8 – The automatically generated weld mesh with its germane throat thickness and preserved washer.](image)

5.3.2 Robustness
The robustness of the weld meshing was an important factor when evaluating the methodology. From the case study, it could be concluded that the methodology had different robustness levels depending on the weld specifications. The case study, conducted on a simplified model of an after-treatment system, was modeled with a total of 41 welds. These welds were divided into five different categories, depending on the location and characteristics of the weld – two main factors regarding the robustness level. The categories were as follows:
**Intermittent welds:** Short welds, located far from edges or other welds, joining two sheet metal components, visualized in Figure 5.9.

![Intermittent welds](image)

*Figure 5.9 – The figure shows the intermittent welds circled*

**Fully circular welds:** Welds joining a tube to a plate with a continuous weld, mostly used for the inner tubes holding the substrates in the after-treatment system. These are visualized in Figure 5.10.

![Fully circular welds](image)

*Figure 5.10 – Shows the inner tubes that are welded to plates on either end to make the inner volume gastight.*
**Welds adjacent to a corner:** Welds joining two sheet metal components, and which are in direct contact with a corner, two examples are presented in Figure 5.11.

*Figure 5.11 – Visualizes two welds with direct contact with a corner.*

**Welds containing a corner:** Welds joining two sheet metal components that contain a sharp corner, visualized in Figure 5.12.

*Figure 5.12 – Shows a weld joining two sheet metal components containing a sharp corner.*
Welds crossing other welds: Welds that are in direct contact with other welds or other weld pitches, see Figure 5.13.

Figure 5.13 – Visualizes three different sheet metal components (the different shades of gray) welded together in a way where the welds cross each other.

These five weld categories were tested during the case study and three stages of the mesh generation were recorded: creation of connector, success rate of the pitch remesh and connector realization. These three stages are presented more in detail below:

Connector created: Creation of the connector is the first step of meshing a weld with the connector panels in HyperMesh. If this is completed, the software has identified the location of the weld and at least one of the components to be welded together. Creation of all connectors is important, to avoid the time-consuming task of having to thoroughly go through the model and identifying potentially missing welds.

Successful pitch remesh: The pitch remesh referrers to the remesh of the sheet metal components which creates the element row along the weld.

Connector realized: The final step is getting the connector realized, meaning HyperMesh did not discover any problems with the connector, implying a satisfactory meshed weld.

The robustness of these categories of welds were tested on three different mesh sizes to retrieve data of how well the methodology performed on the different weld categories on the model used in the case study. The results from these tests are presented in Table 5.2. The table presents both the robustness regarding number of welds and the total weld length.
Table 5.2 – Robustness table for case study results with mesh size of 1 mm, 2 mm and 5 mm.

<table>
<thead>
<tr>
<th>Weld type</th>
<th>1 mm mesh</th>
<th>2 mm mesh</th>
<th>5 mm mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Connector created</td>
<td>Successful pitch remesh</td>
</tr>
<tr>
<td>Intermittent</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Circular</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Adjacent to corner</td>
<td>6</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Containing corner</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Crossing welds</td>
<td>6</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>41</td>
<td>41</td>
<td>34</td>
</tr>
</tbody>
</table>

**Success rate # welds**

<table>
<thead>
<tr>
<th>Weld type</th>
<th>1 mm mesh</th>
<th>2 mm mesh</th>
<th>5 mm mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intermittent</td>
<td>100%</td>
<td>83%</td>
<td>78%</td>
</tr>
<tr>
<td>Circular</td>
<td>100%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Adjacent to corner</td>
<td>100%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Containing corner</td>
<td>100%</td>
<td>80%</td>
<td>78%</td>
</tr>
<tr>
<td>Crossing welds</td>
<td>100%</td>
<td>60%</td>
<td>54%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>60%</td>
<td>54%</td>
</tr>
</tbody>
</table>

The robustness results show that the methodology is 100% successful creating the connectors, but also show that later stages of the weld mesh generation have a lower success rate, mainly for the three mesh categories “welds adjacent to a corner”, “welds containing a corner”, and “welds crossing other welds”, where the latter has a robustness of 0% concerning fulfilling the mesh completely. This is due to a flaw in the Connectors feature in HyperMesh, resulting in the program not being able to create such weld. By using a technique where the weld lines in CATIA are cut around the problem areas, leaving spaces in the lines over these areas, the methodology can be utilized at its maximum. By approaching the problem this way, the CAE engineer can focus solely on the problem areas of the mesh, eliminating the majority of repetitive tasks. This, while increasing the robustness of the methodology, both considering the number of welds and the total weld length. Figure 5.14 shows a detail visualization of a problem area, displaying a comparison between utilizing the full weld line and the technique leaving a space over a problem area.

![Figure 5.14](image-url) – The figure shows the difference between using the complete line where the weld should be (left) compared to the technique used to improve the robustness of the methodology by leaving spaces in the lines for the problem areas (right). The circle in the left image marks a weld that completely failed because of crossing welds, something that can be avoided by ignoring these areas when creating the lines in CATIA, illustrated in the right image.
In Figure 5.15, the full welds are visualized, displaying that the vast majority of the weld can be automatically meshed by leaving spaces in the weld line over known problem areas.

Table 5.3 displays the results of the methodology robustness with the technique using spaces in the lines over problem areas. Since the problem areas are removed, 100 % of the weld's actual length can never be meshed automatically. In the CAD model used, approximately 3 % of the length of the weld lines were trimmed to avoid problem areas, and therefore a maximum of 97 % of the total weld length can be meshed automatically.
Table 5.3 – Robustness table for case study results, using spaces in the lines over problem areas, with mesh size of 1 mm, 2 mm and 5 mm.

<table>
<thead>
<tr>
<th>Weld type</th>
<th>1 mm mesh</th>
<th>2 mm mesh</th>
<th>5 mm mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Connector created</td>
<td>Successful pitch remesh</td>
<td>Connector realized</td>
</tr>
<tr>
<td>Intermittent</td>
<td>22</td>
<td>22</td>
<td>22</td>
</tr>
<tr>
<td>Circular</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Adjacent to corner</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Containing corner</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Crossing welds</td>
<td>6</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td>41</td>
<td>38</td>
<td>38</td>
</tr>
</tbody>
</table>

**Success rate # welds**
- Intermittent: 100%
- Circular: 93%
- Adjacent to corner: 93%
- Containing corner: 100%
- Crossing welds: 97%

**Success rate weld length**
- Intermittent: 97%
- Circular: 72%
- Adjacent to corner: 72%
- Containing corner: 97%
- Crossing welds: 87%

5.3.3 Time Profits and Benefits
There are both temporal benefits and drawbacks concerning the developed methodology. While the CAD phase requires more time to make the necessary weld arrangements, the meshing phase saves a lot of time for the CAE department. In the headings below, the extra or less time needed for each step is stated. The calculations are based on data from the development of after-treatment systems at Scania, where one iteration is four weeks long and therefore include 20 days of working. After half the time, approximately, the CAD model is delivered from the design department to the CAE engineers.

**CAD**
The foundation of the developed methodology is the design engineer’s work inserting weld lines in the CAD model and naming them correctly. Without these lines, the pre-processor cannot identify where to mesh the welds. However, adding this task to the design engineer’s work affects the total time spent on developing the CAD model. From discussions with the design engineer team when presenting the developed methodology to them, their prediction is that one additional day would be necessary for them to implement the weld lines in CATIA before delivering the model to the CAE engineers.

**Delivery**
In the methodology developed, all the weld lines are already created before export of the CAD model. This means that the communicational error between the departments that are present today will be eliminated. At the point of delivery, the CAE engineer will have all the information necessary to perform the remaining work before exporting the model to Abaqus for verifying FEM simulations. This will result in less time spent on trying to retrieve the correct information and more time invested in value-adding work. This is concurrent with the results from the interviews, where the delivery was identified to be non-standardized and sometimes difficult to retrieve the correct information of weld positions, more presented in Chapter 4.2.2 and 4.2.3.
**Meshing**

As mentioned above in Chapter 5.3.2, intermittent and circular welds demonstrate a high robustness level, while welds close to edges and welds crossing each other are less stable. This results in a robustness of at least 54% for the methodology when applied on the case study model. For similar models with resembling weld configurations, it means the CAE department will cut their development time with up to five days per iteration.

However, if the designer when implementing the weld-representing lines excludes the error areas, the percentage of realized weld meshes can amount to at least a 72% success rate concerning weld length (see Table 5.3). This would result in one additional day saved.

**Total profit**

Since the design engineer have to spend about one extra day to insert all the weld lines needed and the CAE engineer save around five days of development time, the total days saved amounts to four. Considering one whole iteration takes four weeks, or 20 days, a four-day decrease corresponds to 20% less required development time. If ignoring the critical weld areas, approximately one more day of repetitive work needed could be eliminated. This would result in a total time profit of 25%, or for the CAE engineers a profit corresponding to 60%.

![Figure 5.16 – An illustration of the time profits to gain if using the methodology developed.](image)

As can be seen in Figure 5.16 above, apart from the CAD phase being more time consuming, the delivery of the model to the calculation department, the automatic meshing of the components and welds as well as the manual mesh cleanup all together result in a substantial decrease in developing time. This is in accordance with the theories concerning KBE, which can be read in Chapter 2.6.
6 Final Methodology

Below, in Figure 6.1, the final methodology is represented as a flowchart.

![Figure 6.1 – The final methodology represented in a flowchart.]

The first step in the methodology is to prepare the CAD model and insert lines, which will represent the welds and later be used to create connectors in HyperMesh and that way create meshed welds. When preparing the CATIA model, the design engineer inserts lines where the welds are intended to be. These lines are created between the components designed to be welded together. Here, it is important that critical areas (see Chapter 5.3.2) such as regions where welds lay on top of each other or welds that are in connection with sharp edges, are excluded. This, since these types of welds fail when automatically trying to generate in HyperMesh, leading to longer remeshing time for the CAE engineers.

Now, the CAD Excel GUI is launched, and the engineer checks that all the weld lines are named as stated by the methodology and then chooses to show all weld lines in CATIA before exporting the files in order to make them available for the CAE engineer. In this step, the design engineer also exports thickness parameters to a text file with the help of the GUI.

Here, the calculation department takes over and launches the CAE Excel GUI, selects the CAD parts that should be meshed and prepared for FEM simulation and then makes the necessary remaining inputs, including choosing mesh size, criteria and parameter files and thickness data file, before initiating the mesh procedure by the click of a button. Through the use of VBA code, batch files and Tcl scripts the sheet metal components are batch meshed, HyperMesh is launched automatically, the batch meshed components are imported, and welds are meshed. A finished HyperMesh model has now been generated, corresponding to earlier CAE Excel GUI inputs. If desired, a manual element cleanup is possible before exporting the mesh to analysis. To see if this is necessary, the automatically generated quality report can be reviewed. Seeing the methodology
is not 100% robust, the failed connectors are manually remeshed until all welds are realized. After this, the model is exported to Abaqus.
7 Discussion
In this chapter, this thesis project and its results are discussed.

7.1 Thesis Methodology Discussion
The thesis methodology was based on theory concerning product development according to Ulrich & Eppinger (2011), where the main developing phase was an iterative design process beginning with a broad perspective which is narrowed down until the final product is completed. Due to the time limit of the thesis work, it was decided to perform the case study on a simplified model of an after-treatment system rather than a fully developed model. Doing this meant a smaller scale of an actual model could be tested to verify that the final methodology has potential to work in an industrial setting, but actual verification in an industrial project could not fit within the scope of the project. The benefits of this was that the evaluation of the methodology could be performed within a shorter time frame, resulting in a decreased iteration time and more time for improvements. Before industrializing this methodology, more thorough evaluation on more complex CAD models should however be executed.

7.1.1 Data Collection
Starting the project with a data collection and interviewing phase proved to be most beneficial. The past three years, master’s thesis works within DA has been conducted at Scania with mostly positive results. Taking part of the previous work helped to narrow down the thesis’ scope and establish what the natural next step was. This also gave an understanding of the bigger picture and how this thesis could contribute to the whole product development process. The data collection phase and literature study were conducted in accordance with the theories presented by Ulrich & Eppinger (2011). The authors say to collect relevant data before starting the actual project. Not only to find its niche, but also to allow for different thesis scopes. Applying this method was considered helpful since it contributed to a larger understanding concerning relevant theories which proved to be useful throughout the project.

Concerning the interviews, a semi-structured approach was chosen. This, according to Hancock, et al. (2009) is a good approach if the interviewee provides the interviewer with limited answers. In this case, the answers could be more than limited and sometimes gravitate to an unstructured interview. However, even though preparing the correct questions sometimes was difficult due to lack of pre-knowledge, having a template to follow proved to be useful and resulted in new and important insights, laying the foundation to the project.

7.1.2 Case study
To develop a methodology based on accepted theories, KNOMAD (see Chapter 2.6) was considered during the development phases of the thesis. The stages of KNOMAD applicable to this methodology are mainly normalization and organization. Where the definition of weld lines in CATIA is part of normalization, to standardize a delivery of weld positions. This is suitable for two reasons, firstly that the weld positions are clearly set in the actual model, reducing the risk of confusion and misinterpretations in the delivery between the design engineer and the CAE engineer. Secondly, reducing the extra work for CAE engineers of preparing the models when they are received, since the delivery is defined, and the models already come prepared.
7.2 Results Discussion
Below, the results concerning the interviews, the case study and the final methodology is discussed.

7.2.1 Interview Results
The interview results made it clear that engineers working in different departments are very keen on perfecting their specific task, and all their focus is on what their department is working on. Even if this of course is valuable for the company, and that departments need their own goals to work towards concretizing the challenge of designing and delivering state of the art technology, one equally important part is to get all departments to work towards one, common goal. All departments can perfect their own work, but without collaboration the final product will not be able to maintain its position among world leading companies. The bigger the company is, the more difficult collaboration between departments is, but by using simple standards and methodologies, the cooperation can be improved. By simply analyzing what the different departments do and need, deliveries between departments can be defined more clearly. This can save large amounts of unnecessary work caused by departments receiving unfinished models, or models missing information needed for day-to-day work tasks. This is backed up by Lindahl & Tingström (2006), who talks about the so-called "over the wall problem", which means that there is no explicit methodology for transferring information between work groups and departments. The authors argue this might lead to prolonged lead times and a less effective iteration process since time is unnecessarily spent on understanding the task received, instead of concentrating on developing the product further.

Moreover, further tasks can be reduced by identifying and reducing repetitive work, clearly present in many stages of the development process. By using design automation, the engineers can focus on more value-adding tasks, and while doing so contributing to the company with increased productivity due to the reduction of repetitive, tiring work. This will also allow for a more challenging and dynamic work flow. Stimulated employees can lead to multiple advantages, such as increased productivity, improved employer reputation and an overall more prosperous company.

7.2.2 Case Study Results
The case study results show great potential of reducing large parts of repetitive tasks for the CAE engineer. The CAD model and welds used were modeled to represent those of a real after-treatment system as well as possible with different kinds of welds that could appear (see Chapter 5.3.2). However, the robustness results are only valid for the specific CAD model tested in the case study. By doing more extensive evaluation on further developed CAD models in real development situations, more accurate results of the robustness could be achieved. This could also help the identification of problem areas, and result in even more explicit instructions to the design engineer on how to implement the weld lines in CATIA, to achieve a high level of robustness of the methodology. Still, the results show great potential of the methodology, capable of cutting time but more importantly, reducing repetitive work for the CAE engineers in the FEM meshing process.
7.2.3 Final Methodology

The main reason for developing the methodology has been to shorten lead times and rationalize the iteration process. While these are straightforward objectives, there are many aspects to consider when estimating the results. In Chapter 5.3.3, it is declared the CAE engineers will save up to 60% of development time, if implementing the methodology, removing the main identified bottleneck during the interviews in Chapter 4.2.1. These numbers are based on the engineer’s professional, but still subjective estimates. However, the total time profit per iteration cycle corresponds to 25%. This is in accordance with the KBE theories in Chapter 2.5. In Figure 2.7, which is inspired by the work of Skrakra (2007), it is said that “KBE changes the development process radically, shortening the overall time, as well as drastically increases the time for innovation”. This is also consistent with the argument that inserting weld lines in an early stage of the modeling process takes more time, but results in a more thought-through CAD model, which in turn will result in more innovative work, both for the design and the CAE engineers.

The main goal with automation is to eliminate repetitive tasks and instead focus on more value-adding assignments. In a larger perspective, this is most beneficial since focusing on innovative work could, for example, lead to better and more environmentally friendly after-treatment systems, which will benefit not only the organization, but also the society and the environment. In a few years Euro VII (also known as Euro 7) might be legislated, implying even tougher emission demands. As can be seen in Figure 2.6, the laws concerning this are already strict. Adjusting to even stricter environmental laws will require better and more innovative products. So, the saved time acquired through automation could instead be used to develop products further or to start new projects aiming to advance even more on the market.

For Scania, it is recommended to investigate how the developed methodology could be implemented in their product development process. The authors believe the methodology can be used both in the Concept Development phase and the Product Development phase, since as described in Chapter 2.1.2, it is in these stages that the iterative process is performed. In the Concept Development phase, quicker design iterations allow the engineers to explore more concepts and develop them to a higher degree. This would lead to more well-established choices and better concepts being delivered to later development stages. In the Product Development phase, quicker iteration would benefit the quality of the final product, since this stage involves the detailed design. By allowing the engineers more iterations here, more parts of the product can be analyzed and optimized, resulting in the high-quality products that Scania is known for.

The developed methodology in this thesis is mainly based on CATIA, HyperMesh and Excel VBA. Other software was not investigated due to the time limit and the scope of this thesis, however, the flowchart presented in Figure 5.1 is developed to be suitable for other software as well. The main subject to investigate is how other pre-processors handle the lines defined in the CAD software to identify the weld positions. With that starting point, implementing the developed methodology with other software is believed to be possible. More software should therefore be investigated, possibly enabling a higher robustness level if other pre-processors handle the identified problem areas in a more robust fashion. The CAD software and GUI do not interfere with the results on the same level.
Furthermore, for MDO to work, it is, as mentioned in Chapter 2.8.1, mandatory to have a fully automated process. Seeing that the developed method fulfills this requirement, it is possible to include automatic FEM meshing in an MDO framework in the future. As mentioned above in Chapter 7.2.1, a problem ascertained during the interviews is that most departments tend to focus fully on their own assignments, while not seeing the big picture and realizing other department’s needs. By promoting MDO in a company, this problem could be eliminated, which is also supported by the claims by Tarkian (2012). Not only would the understanding for other department’s work increase but the workflow would be more efficient and additional time could be spent on more creative product development. Instead of optimizing, for example, FEM, CFD and acoustic processes individually, an MDO framework would mean the collaborative optimal product, which is beneficial according to Amadori (2012). Seeing it all must work together in the final product, enabling the collaboration in an early stage would result in a product most satisfying.

Lastly, the methodology developed is fulfilling its purpose to the extent possible within the timeframe. Still, there are room for improvement. As it is today, the robustness is not 100 %, resulting in the CAE engineer still having to manually edit a few meshes after running the program. Some of these errors are due to flaws in the software used, while a few can be managed by spending more time on investigating the problem. The methodology is limited to 2D meshes and seam welds, excluding for example 3D meshes and spot welds. Also, not fitted within the scope is the managemental approach, investigating how to implement the methodology on a larger scale and if doing so, how to customize the developed software for this purpose. More about potential future work can be found in Chapter 8.
8 Future Work

This thesis project is based on earlier work about parametrization and design automation in the design phase of the development process, this contribution adds to later stages of the development process. By combining earlier work with the developed methodology in this thesis, many stages of the development process can be made more efficient and automated, especially concerning the iteration process between the design and CAE engineer. Yet, there are still some areas to explore before this methodology can be implemented fully in the industry.

First of all, the developed software, including scripts, Excel GUIs et cetera, should be further developed to increase robustness and to include more features, such as 3D mesh and bolts before it is ready to be launched. This would increase the usability of the software, making it more flexible and easier to implement in different areas and on different products. It would be a part of securing the stability of the software, something very important if it should be implemented in the industry. The software is supposed to be used as a tool to make the development process more efficient, and therefore it needs to be reliable at all times.

Some further improvements of the software could be to investigate the possibility to automate more parts of the entire process. The naming of the weld lines is for example still very manual, repetitive and therefore suitable for automation. By automating this process in CATIA, by for example developing a script identifying all weld lines and naming them after what components the line is in contact with, these repetitive tasks could be eliminated. Potentially, this could be solved in HyperMesh as well, by for example creating a weld mesh with the components in the vicinity of the weld line, not by the name of the line. This would further increase the robustness of the methodology, eliminating the human errors that could appear in the line naming convention.

Another thing increasing robustness would be to further investigate the parameter and criteria files used to determine the mesh quality and settings. During the case study, it was observed that the definition of these files played a large role in how robust the generation of weld meshes was. Making standardized criteria and parameter files that allow for weld mesh creation at a large scale while creating high quality meshes would be very valuable, increasing both robustness of the methodology in question and the mesh quality, and in the future yielding more reliable analysis results. Because of the time limit and the project’s scope, this was not further investigated during this thesis.

Furthermore, how to include spot welds in the methodology should be investigated. Also, there is an error in HyperMesh which means that sometimes the connector is realized, but without actually remeshing the sheet metal components or implementing the throat thickness. This is unfortunate since a weld marked as realized, even though it is not, can lead to increased troubleshooting time when trying to find the failed connector. This problem has been passed on to the developers at Altair and a follow-up on this matter will be required in the future. Also, connectors in HyperMesh cannot handle welds crossing each other. The developers at Altair is working on this flaw and a follow-up concerning this matter would also be beneficial in the future.
Concerning the throat thickness, a potential development might be to divide the element pitch into three separate elements, seeing it would benefit the current way of working at the CAE department.

Further investigation of how this methodology could be implemented in an MDO framework with, for example, CFD and acoustic simulations would add value to the project. Showing how an MDO framework can be set up in an industrial constellation as well as investigate if lead times can be decreased is an interesting scope and could potentially result in a better product development process in the future. If results indicate that optimal solutions can be found within a shorter time frame than today’s developing time, it could possibly make a favorable imprint in the mechanical engineering industry, showing that engineers only should focus on creative and value-adding tasks.

The developed methodology, with automation of weld meshes together with the earlier work performed in parametric modelling and design automation shows potential, but further investigations about implementation need to be performed. It has so far been discovered that time can be saved in multiple phases of the development process, including the meshing stage. To implement the methodology fully, the benefits and drawbacks at the full scale also needs to be investigated. Do the profits of saved time exceed the costs of required licenses, training-courses and software development? If not, implementing the methodology would be difficult to motivate. However, if the conclusion is that implementation of said methodologies are beneficial for the company, another area that should be explored is how to implement design automation and all that comes with it on a larger scale in a heavy-duty vehicle company.
9 Conclusions

Below, the conclusions drawn from the project performed are stated.

9.1 Research Question 1

*How could FEM pre-processes of welded sheet metal components be automated?*

It is concluded that FEM pre-processes contain many steps with characteristics suitable for automation. However, to achieve automation of these steps, other phases in the development process might have to be investigated as well. This thesis recommends that the CAD models are further developed to include lines describing the weld positions and parameters with the thickness of the sheet metal and the material. This enables the pre-processor to automatically mesh the sheet metal details and identify where to add weld mesh using scripts calling existing features in the pre-processor.

This methodology is however not fully robust, and will need some manual meshing, mainly in three identified problem areas: crossing welds, welds adjacent to a sharp corner and welds containing a sharp corner. By excluding these areas in the line definition in CATIA, the robustness level increases and the CAE engineer can focus solely on the areas where the pre-processor fails in meshing the welds.

To improve the usability of the software, it is recommended to develop a GUI which allows the user to interact with the scripts in an intuitive manner.

9.2 Research Question 2

*How could the design development process be improved by implementing automated FEM pre-processes at an after-treatment systems department?*

By implementing automated FEM pre-processes, lead times can be shortened, and the iteration process become more efficient. Even though it will take more time for the design engineer to construct the CAD model in a way suited for automated FEM pre-processes, by adding weld lines, the overall developing time will be decreased due to larger time profits in the CAE department. The definition of the weld positions in the CAD model reduces communication problems between the design and CAE departments, resulting in even faster and more reliable iterations and verifications. On a larger scale, more thorough CAD models can be developed with this methodology, since it forces the design engineer to consider the weld positions in an earlier stage of the development process. This together with the time savings, means that repetitive work could be reduced and more focus on value-adding tasks can be achieved.

Ultimately, implementation of an automated FEM pre-processes methodology could result in a higher product quality and larger profits for the company. Automated processes are also needed to enable MDO frameworks in the development process. Utilizing MDO could potentially decrease lead times even more and result in an optimal product being developed, enhancing the concept of simulation-driven design even further.
Bibliography


Appendix
Appendix A – Interview Questionnaire

Questions to the Design Engineer

1. Tell us about your background concerning education and work experience.
   (*Education, previous employments, number of years at Scania, number of years at current group*).
2. What is your main work tasks?
3. In short, tell us about what the development process, concerning a CAD model, look like from the moment you get your assignment till the moment you pass the model over to the different calculation groups.
4. Are there any guidelines for what type of approach you should adopt when you develop a CAD model or do you apply any method of your own?
   (*Specifically for the group/the department/Scania?*)
5. If so, what does these guidelines contain?
6. What is your estimation of the time distribution during the development process, concerning modelling, administration, analyses, etcetera?
7. As you know, before simulations there is need for multiple modifications of the CAD model so it can be analyzed. How do you work with these preparations before handing over the model to the calculation department?
8. Are there any explicit guidelines for how the model should be prepared at the time of delivery to the CAE engineering department?
9. If so, what does these guidelines contain?
10. What does the information exchange look like when the CAD model is delivered to and from the calculation department, respectively? What do you deliver and what do you get back after the CAE engineers have done their first analysis?
11. What does the process look like after you have gotten back the results from the calculation department?
12. Do you perceive that there are some problems with the development process that you practice?
13. What would you say is a bottleneck in the development process? Do you perceive it as obvious?
14. What changes do you believe would lead to a more effective overall process?
15. How would you like to modify the process to make your specific work task simpler and more effective?
16. Is there anything else you think we should know or that you would urge us to investigate?
Questions to the Calculation Engineer

1. Tell us about your background concerning education and work experience.
   *(Education, previous employments, number of years at Scania, number of years at current group)*.
2. What is your main work tasks?
3. In short, tell us how you work with a FEM analysis from the moment you receive the CAD model from the design engineer till the moment it is completely finalized.
4. More specifically, what steps do you take to prepare a CAD model for FEM analysis?
5. Are there any guidelines for what type of approach you should adopt when analyzing a model or do you apply any method of your own?
6. If so, what does these guidelines contain?
7. What is your estimation of the time distribution from the moment you receive a model from the design engineer till the moment the analysis is finished?
   *(Cleanup, pre-processing, meshing, etcetera)*
8. Do you provide the design engineer with any specific demands regarding the CAD model’s shape, etcetera, at the time of delivery?
9. If so, what kind of demands?
10. What does the information exchange look like when the CAD model is delivered to and from the design engineering department, respectively? What do you deliver and what do you get back after the design engineer has updated the model?
11. If the designer has modified a CAD model after receiving the results from an analysis you have performed, what does then the task of analyzing the updated CAD model look like? To what extent is it possible for you to re-use previously accomplished work?
12. Do you perceive that there are some problems with the development process that you practice?
13. What would you say is a bottleneck in the development process? Do you perceive it as obvious?
14. What changes do you believe would lead to a more effective overall process?
15. How would you like to modify the process to make your specific work task simpler and more effective?
16. Is there anything else you think we should know or that you would urge us to investigate?
Questions to the Mesh Scripting Engineer at RCCC

1. Tell us about your background concerning education and work experience.
   (*Education, previous employments, number of years at Scania, number of years at current group*).

2. What is your main work tasks? What is the work like at RCCC?
   a. What does the collaboration between the design engineer and the calculation engineer look like?
      (*Information exchange*?).
   b. Are there any guidelines for what type of approach you should adopt when analyzing a model or do you apply any method of your own?

3. As we understand it, you have started to investigate the possibilities of scripting the mesh before FEM analysis. What reasons are there for doing this?
   (*Own initiative? Directives from above*?).

4. How far have you come in your work? Have you investigated different methods? Different software? Different programming languages?
   (*ANSA, HyperMesh, Python, Java, etcetera*).

5. Please explain how you have approached the problem.
   (*Have you looked at the connection between CATIA and ANSA? How do you script the mesh more specifically*?)

6. Have you developed everything by yourself or have you been in contact with someone else?
   (*Within Scania or externally*).

7. What have you gained from your work so far?

8. Have you encountered any problems or difficulties concerning scripted meshing? How have you handled them?

9. What kind of potential do you see in scripted meshing? What is your long-term goals?

10. Have you thought anything about collaboration of work procedures and implementation in HEEDS?

11. What will the development process look like from here and forwards? Is this something you will continue working with and try to implement (further) in your daily work?

12. Do you think you will encounter any problems concerning the implementation of the scripted meshing in your daily work?

13. Is there anything else you think we should know or that you would urge us to investigate?
Questions to calculation engineer at RTLC

1. Tell us about your background concerning education and work experience.  
   (Education, previous employments, number of years at Scania, number of years at current group).
2. What is your main work tasks?
3. As we understand it, you have been active within the SimManager project, please tell us about that.
4. Why did you initiate the project in the first place?
5. What are your main objectives with the project in the near future, as well as in the further future?
6. How far have you come in your work with SimManager?
7. Our project aims to develop a method to fast and simple update meshes when the geometry changes. Probably by using HyperMesh. Have you investigated the possibilities of automatically mesh or update mesh in HyperMesh or other software?
8. Have you encountered any problems or difficulties concerning scripted meshing? How have you handled them?
9. What kind of potential do you see in scripted meshing? What is your long-term goals?
10. What will the development process look like from here and forwards? Is this something you will continue working with and try to implement (further) in your daily work?
11. Do you think you will encounter any problems concerning the implementation of the scripted meshing in your daily work?
12. Is there anything else you think we should know or that you would urge us to investigate?
Other Comments

- Number of iterations
- Total time
- Time per iteration
- Time development concerning the whole iteration process

End of the Interview

- Thank the interviewee for its participation