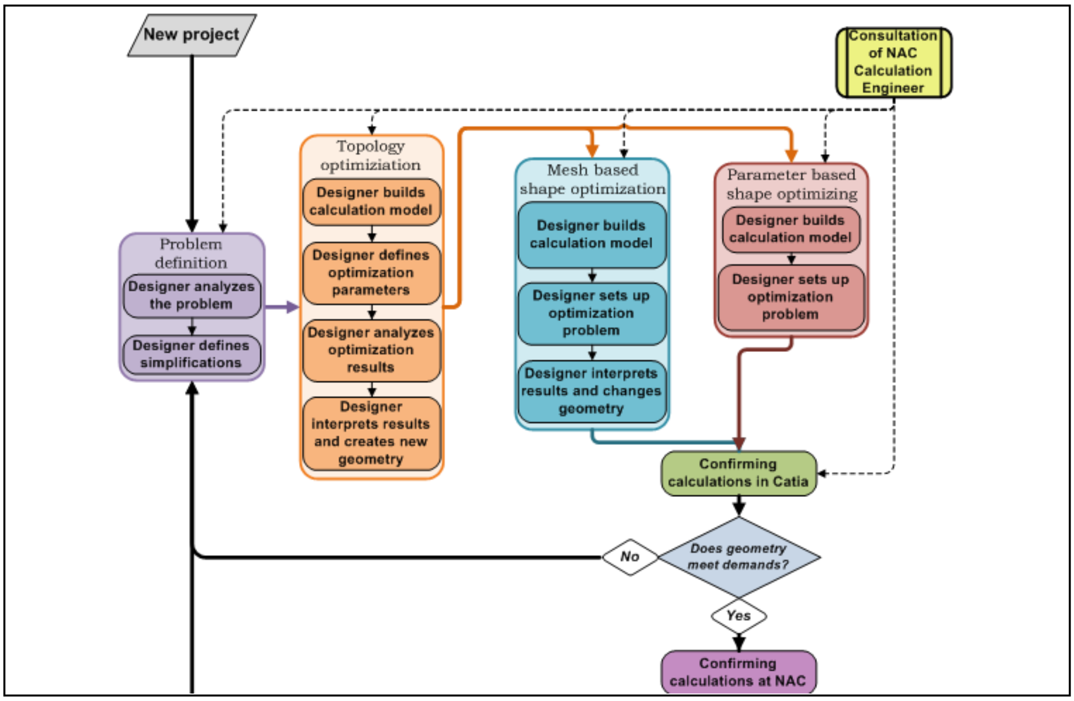

Development of Methodology for Simulation Driven Design

- Evaluation of calculation and optimization tools integrated in Catia and development of methodology.

Master's thesis at Product development

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Abstract

Scania is a Swedish manufacturer of trucks, buses and diesel engines. The department NA is responsible for the development of axles and related components. Within NA, there is a calculation group that uses FE-based tools, NAC, and a design group responsible for a set of components, NAA. A product development process takes the form of an iterative process between the calculation group and the design group. Even though less expensive than physical prototype testing, this process crossing group borders is regarded as time consuming. One of the components that follow this iterative product development process is the front axle beam.

The objective of this project has been to investigate the possibilities of reducing the lead time by letting the designer at NAA perform FE based calculations and optimizations using tools integrated in the designers CAD-application, Catia.

Method/Approach

A case study was made in order to gain an understanding of the current design process. An evaluation was made regarding different FE-based calculation and optimization tools integrated in Catia, and results ware compared to previous results from fully dedicated tools used by NAC. Also, the possibilities to automate parts of the process using macros in Catia were investigated.

Results

The results showed that the outcome from FE-based calculation tool integrated in Catia and the outcome from Abaqus, used by NAC was very similar. A manual regarding the tool, aimed for the designers, was made. One of the optimization tools showed results very close to the results from OptiStruct used by NAC, and was easy to use. The results from the other optimization tool differed from the ones of Catia, required an experienced user and did not guarantee an optimal solution. It did, however, have a few other advantages. Also, an overall methodology was proposed, involving the integrated tools.

Discussion and conclusion

It quickly became apparent that the capacity of desktop computers did not hold the capacity necessary to use these calculation and optimization tools for a component so complex as the front axle beams. If, however, these tools were used with a batch server handling the actual calculations, they could form a foundation for a powerful product development process. With this new process, products fulfilling customer needs could be developed fast and cheap.

Recommendations

For future investigations and evaluations, it is recommended to do a pilot project: Using the proposed methodology and tools for the development of a new component. The experiences from the pilot project would form a basis for future development of the methodology. Before performing this pilot project, the tools must be integrated in Scania’s PDM system and a solution for batch server calculations must exist.

Preface

This report is the outcome of a project conducted at Scania CV AB in Södertälje, Sweden. The project was performed as a master's thesis of 30p at Chalmers University of Technology in Göteborg, Sweden. The report aims to reflect the progress, results and conclusions of the project.

First off, I would like to thank my supervisor at Scania, Sandra Thorén, for motivation, inspiration, support, valuable insight and feedback, as well as a great number of smiles and laughs.

I would like to thank my supervisor at Chalmers, Samuel C. Lorin, as well as my examiner Andreas Dagman, for great feedback and support, and contribution to the outline of the project.

I would also like to thank Mikael Thellner and Magnus Bergman at Scania for invaluable discussions and insights.

Finally, I would like to thank anyone else who in any way has contributed to this project throughout the last 20 weeks.

Södertälje, February 2012

Robin Loman Strinnholm
Soon to become M.Sc.

Nomenclature

Throughout the report, different terms, names and acronyms are used. Even though explained in the report, the most important are listed and described here:

- **FE**
  Finite Element. Used to acknowledge that a method with finite elements is used. Examples: *FE calculations, FE based tools*
  - **FEM**
    Finite element method. A mathematical method for obtaining approximate solutions for partial differential equations.
  - **FEA**
    Finite Element Analysis. The practical engineering application of FEM. Used for e.g. stress calculations and heat transfer calculations.
- **NA**
  The department at Scania that is responsible for the development of axles and related components. It is a part of the N department, which is responsible for the drivetrain.
  - **NAC**
    The calculation group at NA. Uses FE-based tools for calculations and optimizations.
  - **NAA**
    The design group that designs front axle beams, among other components.
- **SDD**
  Simulation Driven Design. A concept in which simulations and calculations are used to aid the designer from the beginning of a design process.
- **DBT-cycles**
  Design-Build-Test cycles. An iterative approach to product development.
- **FMEA**
  Failure Mode and Effects Analysis. A tool for identifying, evaluating and preventing failures in a product or process.
- **QFD**
  Quality Function Deployment. A tool for identifying customer requirements and translating those requirements to product or process characteristics.
- **VM stresses**
  Von Mises stress. An equivalent stress that can be calculated from the principle and shear stresses.
- **Catia PEO**
  Product Engineering Optimizer. Part of Catia V5. Performs parameter based shape optimization.
- **HyperShape/CATIA**
  Software from Altair Engineering Inc., integrated in Catia. Performs mesh based shape optimization as well as topology optimization.

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1 Introduction

In a more and more competitive and global market, manufacturers must continually improve their products as well as the organisation in order to survive. Despite colourful business descriptions or stated core values, a company’s survival depends on its economics: roughly said how much money the company earns and how much it spends. Its income and expenses. A well-functioning organisation with efficient Research and Development (R&D) does not only have great chances of satisfying customers and bringing income to the company, but it does so with a small consumption of resources. However, developing products that satisfies the customer and keeping expenses to a minimum often contradicts each other, as developing products can be expensive in both time and resources (Ulrich & Eppinger, 2000).

From the Toyota Production Systems, the concept of *Muda*, or waste, is derived (Burenius & Lindstedt, 2003). Waste is defined as activities that do not add value to the customer. Since all activities consume resources, it is of great importance to reduce waste. Since waste does not add value to the customer, reducing it will not affect the customer negatively. In R&D, one great source of resource consumption is development of solution proposals that, perhaps after development and refinement, is found not feasible or not meeting the demands.

1.1 Background

In a design process, it is often suitable to apply an iterative approach, where different concepts continually are developed, refined and improved. The solutions of each iteration will eventually converge to a final design. Long iteration times, low convergence speed and the initial design being far from the final design are factors that can increase the total lead time.

These iterations often take the form of Design-Build-Test (DBT) cycles (Wheelright & Clark, 1992). A DBT cycle consists of three phases:

- *The design phase*
  The problem is framed and defined.
- *The build phase*
  Working models of the current design are created.
- *The test phase*
  The prototypes or models are tested. The results from these tests will provide information to the next iteration.

Throughout the design process testing is used, starting with a low level then gradually using higher levels. A test at low level includes several simplifications. It has the drawback of not representing all the aspects of the scenario it is built to represent, but the advantage of being simple, cheap and fast to calculate. A test of higher levels might not include any simplifications and can even be a field test of the final design. The higher test level has the advantage of better reflecting the scenario, but the drawback of being slow and expensive. Trade-off curves representing this dilemma can be found in figure 1.

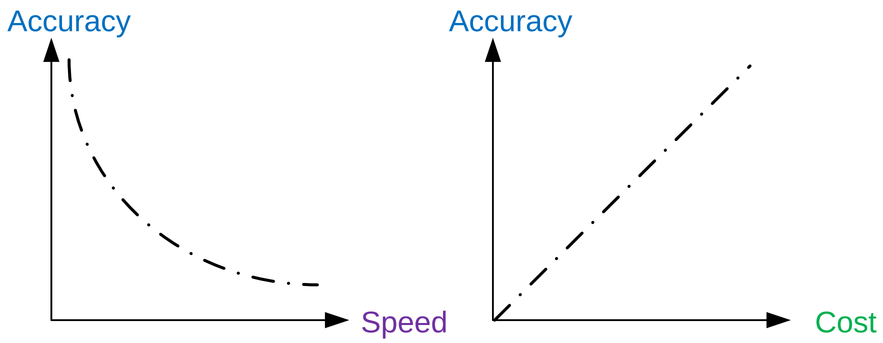


Figure 1 – Principal trade-off curves of the test phase in DBT cycles

With FE calculations, detailed analyses of components and systems can be made without the need of physical prototypes. A virtual model is rather quickly built and analyzed, and can be used for a range of low test levels. For these virtual tests, cost and time consumption is much lower than for a physical prototype test. These virtual models can also be used for different types of optimizations.

Although faster than physical prototype tests, FE based tools are so complicated that calculation engineers are fully dedicated on these tasks. This means that the designer of the component seldom is involved in the calculations. Rather, a time consuming iterative process between the designer and the calculation engineer takes place. Apart from being expensive, this process might hinder the designer from fully understand the connection between design alterations and results of the calculations.

Traditionally, simulations and physical testing has been used only as verification of refined solutions and designs. However, simulations and numerical modelling can also be used as a support when generating innovative solutions. Simulation Driven Design (SDD) is a concept in which simulations and calculations are used to aid the designer from the beginning of a DBT-cycle (Sellgren, 1999). SDD does not necessarily reduce the time of each DBT cycle, but might help the designer to achieve more for each cycle and let the product design converge faster.

According to a benchmark made by the Aberdeen Group, manufacturers rated as "Best in class" not only provides simulation tools for their designers early in the product development in order to reduce time to market and improve product performance, but are also more likely to choose tools that are integrated with their CAD application (The Aberdeen Group, 2006). The best in class category is a selection of survey respondents, based on measurements regarding revenue, cost and development cost targets for products as well as product launch dates and quality expectations. Best in class manufacturers had shorter time to market, lower development cost, and fewer prototypes. In other words: a correlation was found between applying SDD and reducing development cost and development time.

Scania is a Swedish manufacturer of heavy trucks, buses and engines for miscellaneous applications. The head office, R&D office and the main production plant of Scania is located in Södertälje, Sweden. Its product development process heavily depends on physical testing, an approach which is expensive in both time and resources (Bergsjö, Almefelt, & Malmqvist, 2010). Scania's products are heavily modularised, lifting it as one of the main reasons for their commercial success. This heavy modularization is shown in the structure of the R&D department. The different modules of the trucks and buses have its own R&D department, which in much work independently of each other. Each department is divided into groups depending on their areas of responsibility or engineering discipline.

The department responsible for the development of axles, including hubs, brakes, shafts and gears is called Axle Development, NA. NA is divided into several groups, including a group for calculation and analyses, NAC, and a group for designing several components including front axle beams, NAA. When developing products, an iterative process between the groups take place, where NAA forms design proposals that are calculated by NAC.

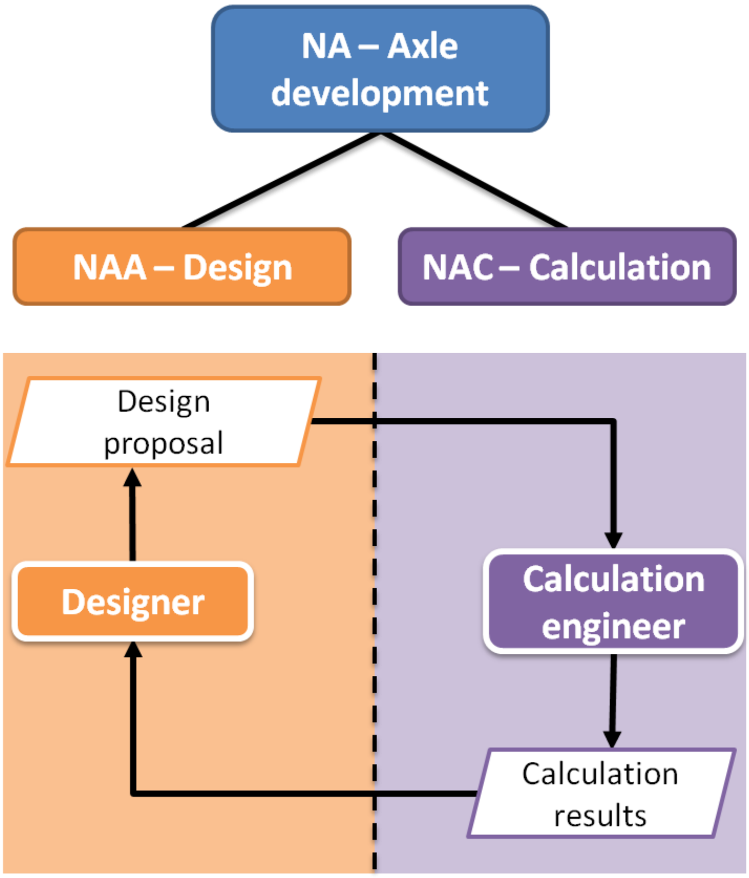


Figure 2 - Examples of products from Scania

The department NA is experiencing dilemmas regarding long lead times for calculations and optimizations. The poor feedback resulting from long iteration times does not provide a basis for good understanding regarding calculations and strength of materials. The calculation engineers are handling routine tasks that are not challenging. This is a poor use of resources and competence locked in these individuals. Physical testing is a expensive and time consuming task, and can be the source of much frustration as the same component must be tested again and again due to several design changes. This can have an impact on the whole R&D organization in terms of long total lead times and an expensive development process due to many redesigns. The organization as a whole is then faced with low quality, customer complaints and lost goodwill, see figure 3.

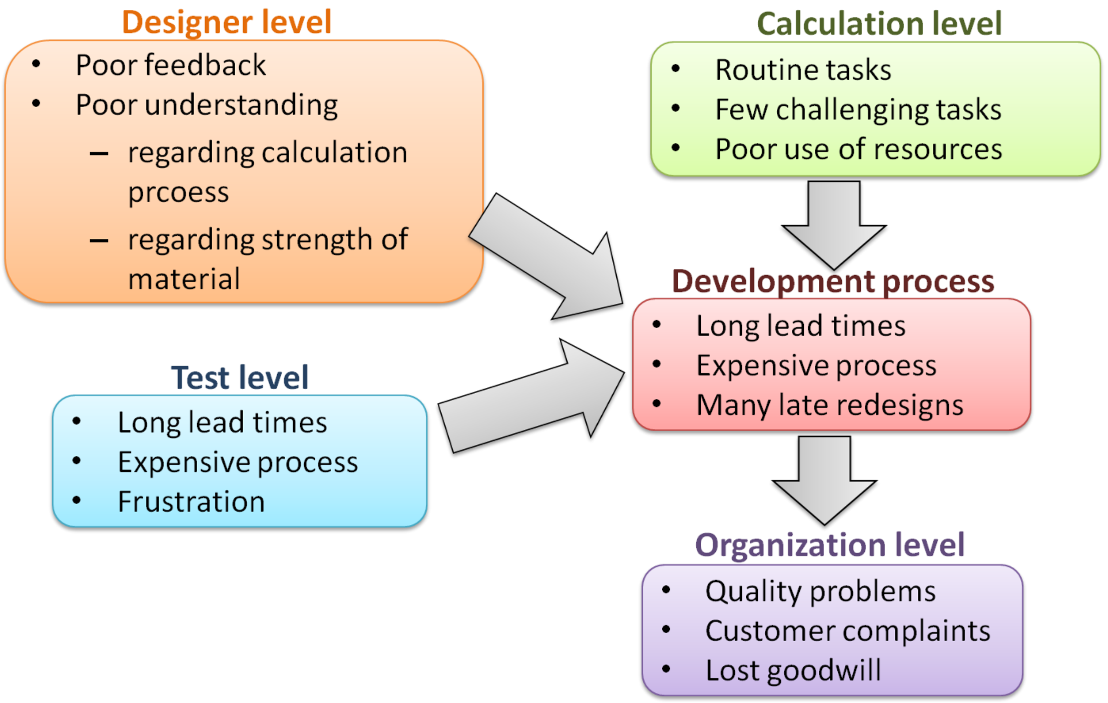


Figure 3 - What problems in the PD process can lead to

There is a desire for the designer group, NAA, to be able to perform FE calculations and optimizations with tools integrated in their CAD application, CATIA V5. This could make for a possible solution, and would allow the designer to make an iterative process by herself and sending an already improved design to calculation by NAC and physical testing, see figure 4.

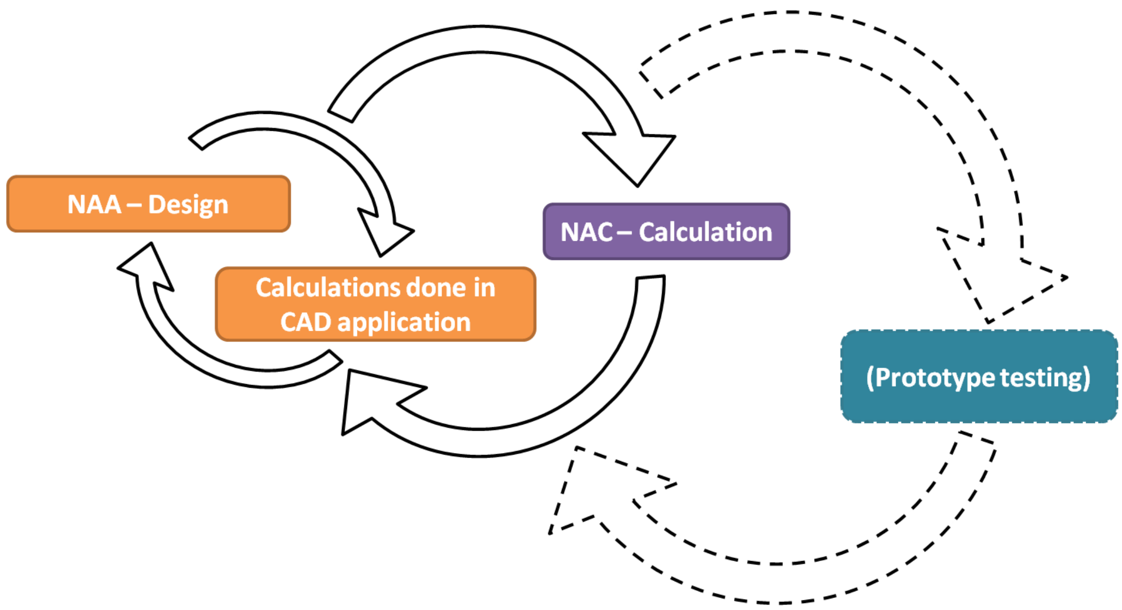


Figure 4 - How the designers calculations could be used in the design process

1.2 Purpose of the thesis

The purpose is to investigate the possibilities to reduce lead times for the design process at NA. This by letting the designer at NA, who uses CATIA V5, to perform FE based calculations and optimizations using tools integrated in Catia. The thesis aims to answer the following questions:

- Can calculations be done using Catia V5?
  - *Are they reliable*
  - *What calculation models would be used?*
  - *Can the calculations be done locally?*
- Can optimizations be done in Catia?
  - *Are they reliable*
  - *Can the optimizations be done locally?*
- If calculations and optimizations can be done in Catia, HOW would they be used?
  - *Can a methodology be constructed?*

1.3 Objectives

A framework methodology is to be development from the findings of the investigation, which should define when and how different calculation and optimization tools are to be used. The method should:

- Employ factors that are identified to reduce lead time, either by reducing the time of each DBT cycle, or reducing the needed amount of cycles.
- Fit in to the established procedures used by designers and calculation engineers at NA today
- Be easy to use, so that the designer does not feel reluctant to use it
- Be efficient enough to be considered worth its while
- Let the designer gain deeper understanding of the simulation process
- Be approved by the stakeholders.

A manual aimed for the designer is to be development. The manual will be a guide for building calculation models with and without the use of macros, and analyzing results. The working procedure included in the guide should be easy to follow and be approved by the stakeholders.

1.4 Delimitations

In order to make some depth in the investigation, only the development of front axle beams will be considered when making calculation models. For the evaluation of optimization tools, a set of calculation examples will be used.

Only the development process and working procedures of the designers and calculation engineers at NA, and the design issues that arise there, is considered. Alternative design processes will not be investigated. Only Catia V5 and integrated tools will be considered.

1.5 The layout of the report

The following report is structured in six main parts:

- **Theory**
  The first part of the report lays a theoretical framework on which the rest of the report is built. Different concepts and product development methods and tools are covered.
- **Case Description**
  The case which lays as an example for this thesis is described, as well as the information gathering methods used. This chapter covers the existing design process as well as the main design of the front axle beams.
- **Method/Approach**
  Here the approach for the thesis will be presented: when and how different methods and tools are used.
- **Results**
  Results of the tools and methods previously presented will be presented here.
- **Discussion and conclusion**
  The results are discussed and analyzed. What do these results mean? What sort of conclusion can be drawn from this? Is this reasonable? What could have been done differently?
- **Recommendations**
  In the final part of the report recommendations for continued investigation and analysis will be presented. It is based on the discussion in the previous section.

Please note that some of the information and results are considered to be part of Scania's intellectual property, and are therefore left out. Such information includes specific stress levels and parameters defining the loading cases. It also includes macros that automatically generate calculation models, which has parameters and forces included in them. Because of that, much of the results and case description may seem incomplete and vague.

2 Theory

In this chapter, used and needed product development methodologies will be explained, and the theoretical basics of FE methods and structural optimizing will briefly be covered.

2.1 Product development methodologies

Product development, the process of bringing new products to the market, deals with the challenge of creating products that fulfil the needs of the user as good as possible while keeping cost at a minimum (Ulrich & Eppinger, 2000). It is a multidisciplinary process which encompasses a wide range of both engineering and business skills.

2.1.1 Design-Build-Test cycles

All product development projects include some sort of Design-Build-Test (DBT) cycles (Wheelright & Clark, 1992). A visualization of the DBT cycles can be seen in figure 5. As the name implies, the cycle consists of three phases:

- *The design phase*
  Goals for the problem solving process are established, and the problem is identified. Once the problem has been identified, a set of solution alternatives are generated.
- *The build phase*
  Working models or prototypes of the generated ideas are created.
- *The test phase*
  The prototypes or models are tested. Depending on the problem, the type of tests may vary. The results of these tests are then evaluated: either the solution meets the goals, or the results will serve as input for the generated alternatives in a new DBT cycle.

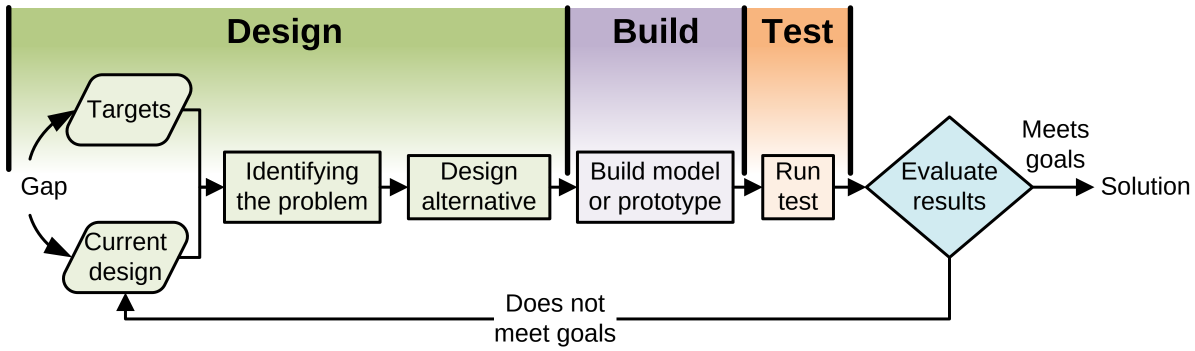


Figure 5 - The Design-Build-Test Cycle in Problem Solving. Inspired by (Wheelright & Clark, 1992)

2.1.2 Failure Mode and Effects Analysis

The Failure Mode and Effects Analysis, or FMEA, is a tool for identifying and evaluating risks or flaws in a product or process (Burenius & Lindstedt, 2003). There are several different approaches and takes on the FMEA, but in this project the FMEA was carried out in the following set of tasks:

- Identifying steps in a process
- Identifying possible failures
- Evaluating factor 1: the possibility of each failure, on a scale from one to nine.
- Identifying the consequence of each failure mode.

- Evaluating factor 2: the severity of each consequence, on a scale from one to nine.
- Identifying the manner in which each failure can be detected.
- Evaluating factor 3: the possibility of each failure to go unnoticed, on a scale from one to nine.
- Calculate the risk number of each failure mode, by taking the product of the factors evaluated.
- A decision is made on what failure modes to regard for product/process improvement, based on the risk number and the individual factors. The improvement can be regarding the failure probability, the effect severity or the control efficiency.

The results of each step can be documented in a FMEA table, see table 1.

Failure mode	Prob.	Effect	Severity	Control	Prob.	Risk number	Action taken

Table 1 - The outline of the FMEA table

2.1.3 Quality Function Deployment

Quality Function Deployment, or QFD, is a methodology which identifies customer requirements and translates these into product or process characteristics. The QFD procedure consists of four stages (Bergman & Klefsjö, 2010):

- Performing a market analysis, identifying customer needs and expectations
- Examining the competitors regarding their fulfilment of identified customer needs and expectations
- Identifying key factors for success based on the identified needs and expectations
- Translating the key factors into product and process characteristics.

The result of the QFD is presented in the House of Quality, as can be seen in figure 6. QFD can be used to represent every level of the product development process, by letting the product characteristics of one level be the customer needs of the next level.

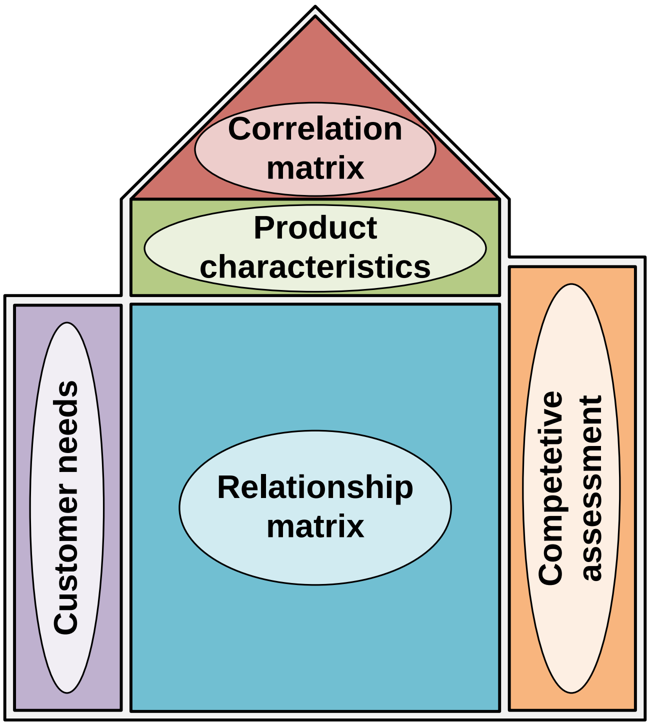


Figure 6 - The House of Quality. Inspired by (Bergman & Klefsjö, 2010)

2.2 Finite Element Method

Many products and components have geometries in which e.g. the heat transfer or mechanical strength is difficult to calculate. The problem can be defined as a Partial Differential Equation (PDE) (Hutton, 2004). A PDE is a function of several independent variables, and can be solved approximately by using numerical methods like the Finite Element Method (FEM). The practical application of FEM is referred to as Finite Element Analysis (FEA).The main concept behind FEM is dividing a complex geometry into a finite number of elements which each can be calculated easily. An element is defined by external nodes, and can take many forms. Often beam elements, triangular elements and quadratic elements are used, see figure 7.

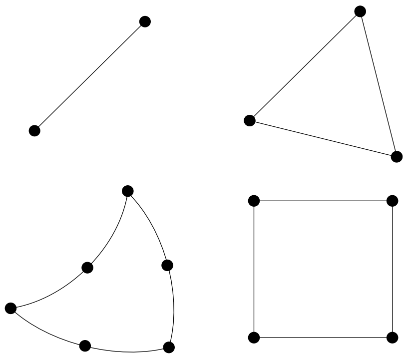


Figure 7 - Different types of elements. Beam element defined by two nodes (upper left), triangular element defined by three nodes (upper right), triangular element defined by six nodes (lower left) and an quadratic element defined by four nodes (lower right).

When dividing a geometry into elements, *meshing*, the size of the elements is an important parameter. The element size decides the number of elements needed, and how well the mesh represents the geometry. It also affects how close to the analytic solution the approximate solution will be. The mesh size can also be defined locally: a finer mesh can be used in a certain area of interest, see figure 8.

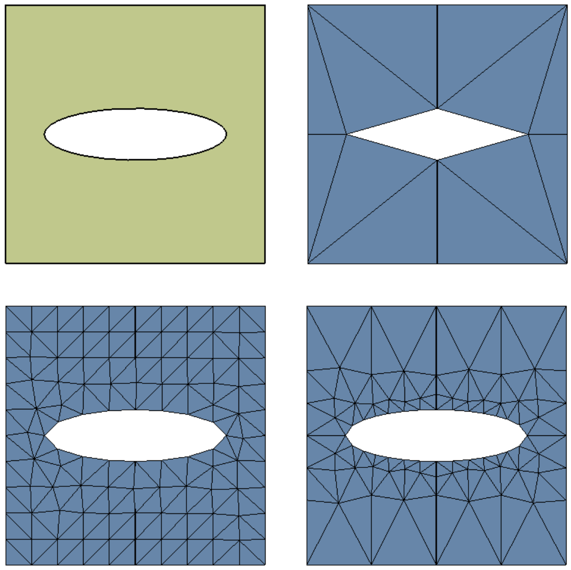


Figure 8 –An example of a geometry divided up into elements. Upper left: Original geometry. Upper right: Course mesh representing geometry. Lower left: Fine mesh representing geometry. Lower right: Course mesh with local small mesh size around the ellipse. Notice how the meshes follow the ellipse.

When deciding upon a suitable element size, a convergence study can be made. The convergence study aims to find the most optimal size of the mesh. On one hand, a course mesh means fast calculation times, but involves the risk of inaccurate results. On the other hand, a fine mesh means more accurate results, but with calculation times increasing exponentially with the number of elements. It is a trade-off, and an assessment has to be made, see figure 9.

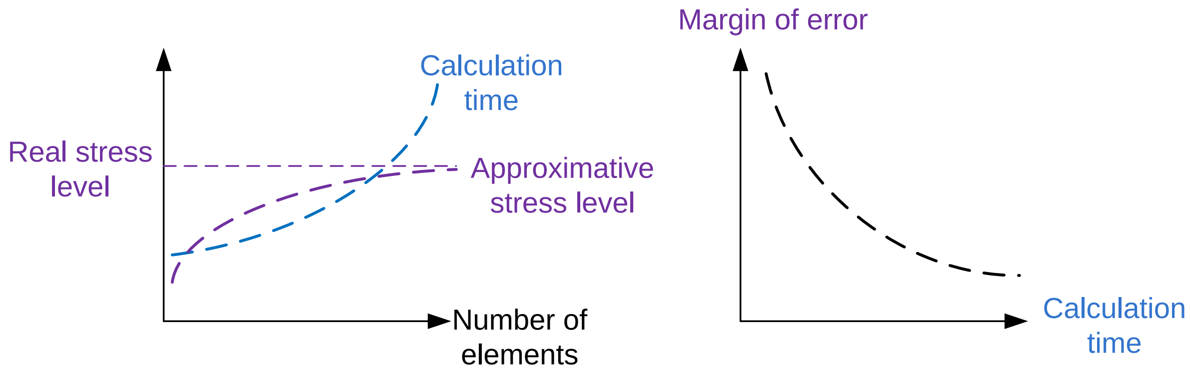


Figure 9 – The trade-off curves of mesh size

2.2.1 Structural optimization

Structural optimization is a set of methods for finding an optimal design for a given structure. The new design can either be based on an existing design which is altered, *Shape Optimization*, or be a new design generated from a design space, *Topology optimizing*.

Topology optimization is a mathematical method for finding the optimal geometry in a limited design space for a given problem (Sigmund & Bendsøe, 2003). The design space consists of a mesh, and can be either 2D or 3D. The problem can have one or more loading cases, with applied loads and boundary conditions. The optimization problem is solved iteratively, generating an optimal distribution of material using a limited fraction of volume.

Shape optimization is a method for altering a pre-existing design for a given problem (Christensen & Klarbring, 2009). The problem is defined by an objective, constraints and one or more loading cases. The objective can typically be of mass, stress or displacement. The constraints can be regarding mass, stress levels, displacement or certain parameters. The optimization is solved iteratively. Shape optimization can either be mesh based or parameter based. In the mesh based shape optimizing, the nodes of the mesh are moved in each iteration. In the parameter based shape optimization, a set of geometrical parameters are allowed to change. For each iteration, a new geometry is generated which is then remeshed.

2.2.2 FEA software

There are several different applications that support FE calculations and structural optimizations. Without going deep in the different types of tools, here is a brief description of the tools that are covered in this project.

- Catia V5
  A software suite for CAD, computer aided manufacturing (CAM) and computer aided engineering (CAE). It is developed by Dassault Systemes.
- *Catia Generative Structural Analysis (GSA)*
  A part of Catia V5. It supports different types of FEM calculations.
- *Catia Product Engineering Optimizer (PEO)*
  Another part of Catia V5. Uses calculation models from GSA, for parameter based shape optimization.
- *HyperShape/CATIA*
  A tool integrated in Catia V5, from Altair Engineering Inc. Uses calculation models from Catia GSA, for mesh based shape optimization and topology optimization. HyperShape/CATIA is based on OptiStruct, only the user interface is different.
- *Abaqus/Standard*
  FEM software from the Dassault Systemes brand Simulia. Used by NAC to perform FEM calculations.
- *OptiStruct*
  Optimization software from Altair Engineering Inc. Used by NAC. Can perform mesh based shape optimization as well as topology optimization.

3 Method/Approach

The project consisted of five major parts:

- Defining the case
- Building calculation models in Catia
- Writing a manual for calculation models in Catia
- Evaluation of optimization tools in Catia
- Construction of new design methodology

In this chapter, the approach for the projects five parts will be covered.

3.1 Method for defining case

In order to understand the design process employed at NA; interviews, field studies and literature studies were conducted.

The interviews were semi-structured in order to let the interviewee speak freely, not be constrained by the questions, and maybe lead the conversation into an important area not considered when planning the interview. The interviewees were designers and calculation engineers at NA, and a “judgement sampling” was made. A judgement sampling means that the selection of interviewees was the ones who were considered to be able to contribute the most (McQuarrie, 2006). Three calculations engineers and four designers were interviewed. The chosen interviewees were also considered to be affected by the new methodology the most. The interviews were conducted at the workplace of the interviewees, and aimed to answer at least the following questions:

- What is your role in the product development process?
- What aspect of the product development process do you find work well?
- What aspects of the product development process do you find troublesome?
- What do you think can be accomplished by letting designers perform calculations and optimizations on their own?
- What risks do you think are involved in letting designers perform calculations and optimizations on their own?

The field studies consisted of several visits to the testing laboratory, where components are tested with respect to fatigue and strength. The purpose was to gain an understanding regarding how the components were tested, and also to understand the organization as a whole. Literature studies covered reports from affected actors at NA.

3.2 Building calculation models in Catia

When building the calculation models, they were constantly compared to the results from NAC calculations, performed with tools dedicated solely to FEM calculations. An iterative approach was used; where the calculation model for each loading case was refined and altered until an accepted trade-off regarding complexity of the model was reached. First the iterations was regarding simplifications of the model, and then regarding the mesh size. Then, a similar approach was used in order to construct a manual for the designers to use. The manual was refined and altered until representatives from both NAC and NAA were satisfied. This approach is visualized in figure 10.

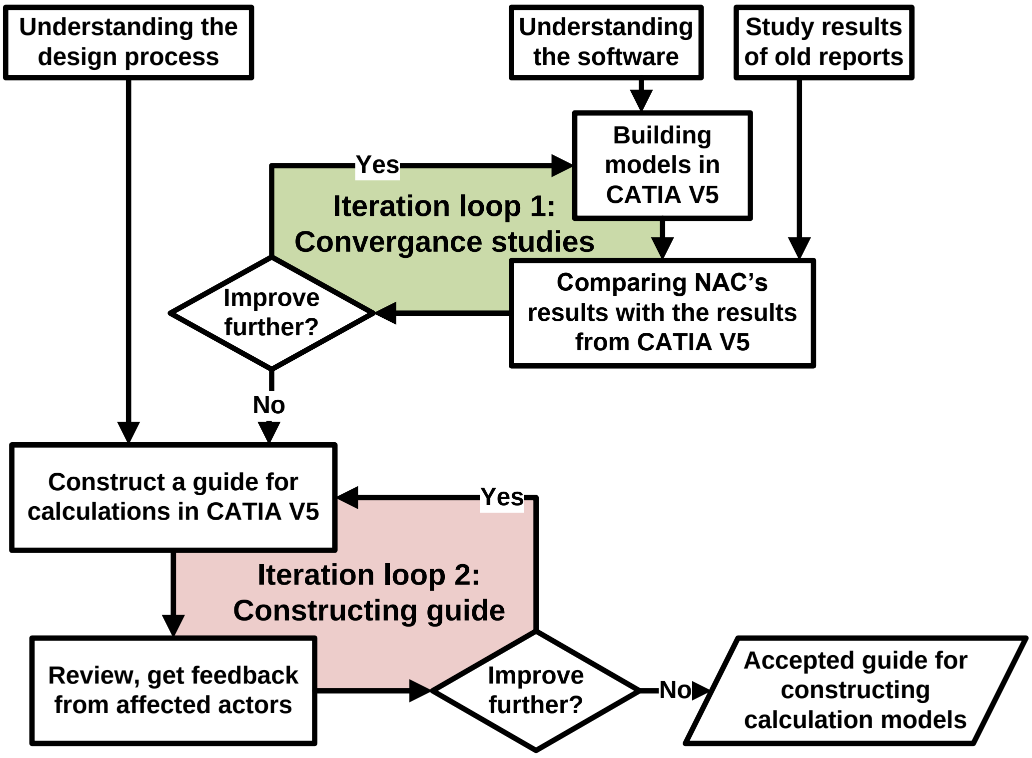


Figure 10 – Method used for this thesis to construct calculation models and guide

To test the loading cases, calculations were done to an already thoroughly tested and calculated front axle beam. Throughout the process of creating calculation models comparisons were made to the results from the calculations made by NAC. The comparisons included analyses of stress plots and stress levels of critical areas. Both the Von Mises stress and the principle stress were regarded.

3.2.1 Defining calculation models to be used in Catia

Models for each loading case was first built with extreme simplifications. It was then step by step made more complex. It was in that sense a convergence study. This convergence study resulted in three or four different models of each loading case, with names corresponding to the degree of complexity, from "Very simple" to "Very complicated". First, a "Very simple" model was made and evaluated. It would contain many simplifications and very few components. Then, more advanced models, with less simplifications and added components, where built until the results converged with the results from NAC. The model was wanted to be as simple as possible, yet giving accurate results, in order to reduce the work load of the designer as well as the computation time.

3.2.2 Convergence study of the mesh

For each loading case a convergence study was made, aimed to find the most optimal fineness of the mesh. The mesh size could be divided into two categories: global mesh size and local mesh size. The global mesh size sets the general element size of a component, while a finer, local mesh size can be defined at certain areas of interest.

For all the loading cases, several areas of importance were found, thus resulting in several areas where the size of the mesh was essential. The method was to start off with a course mesh, and step by step decreasing the size of the elements, and plotting the calculation time and the maximum stresses of crucial areas.

Each step would take a certain amount of time, which would increase for each step. To save time, a one-factor-at-a-time-approach was initially employed; only changing the mesh of one area, until an accepted trade-off of that area was found. It was assumed that the calculations would be done locally on a desktop computer just as this convergence study was. Later, the findings of the trade-off of the different areas were used to find the initial values of a multiple-factor-experiment.

3.2.3 Constructing method with automation

Catia supports the use of macros: pre-programmed set of instructions for the software to interpret. These macros could be made to, e.g. assemble a predefined assembly or build a calculation model.

By using macros different levels of automation could be obtained. A high level of automation would mean fast results, at the cost of lost understanding of the process, and a low ability to adapt the model to new conditions, see figure 11. Several scenarios were created, and discussions with affected actors were held in order to find the optimal solution.

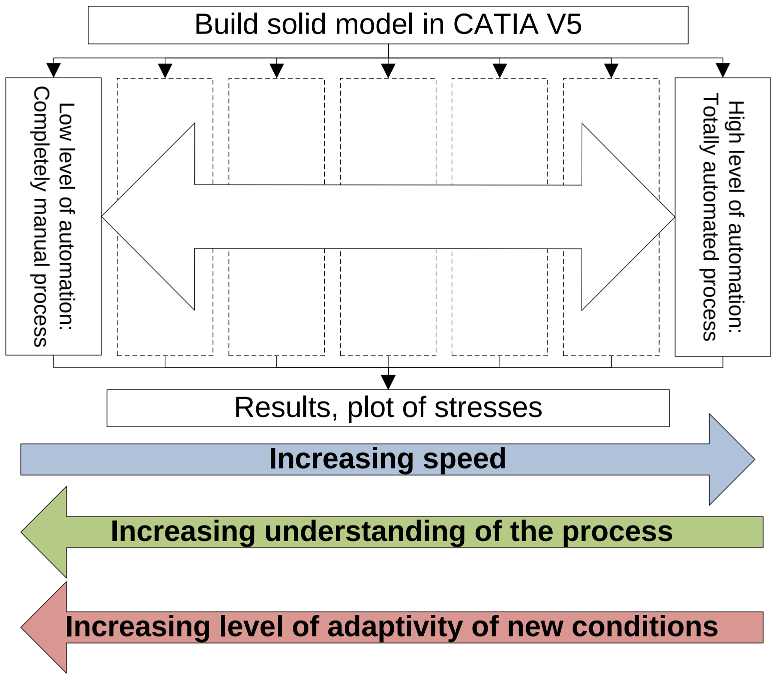


Figure 11 - Different levels of automation

3.2.4 Writing manual regarding calculation models

Based on the experience of building models and the results of the convergence study, calculation results and discussions regarding automation, a manual was written. The manual was to be a support for designers building calculation models. With it, a designer should with ease be able to build calculation models with or without the support of macros. An iterative process was used, where the manual was refined based on opinions and suggestions from calculation engineers as well as designers.

3.3 How to compare and evaluate optimization tools

Two tools were evaluated, Catia PEO and HyperShape/CATIA. In order to evaluate the different tools for structural optimizing two calculation examples were used. The two calculation examples were called “the bridge” and “the bracket”. A convergence study was to be done, analyzing how the results and calculation times would change with different element sizes. As a reference, the problems were solved by NAC with a small element size, using OptiStruct.

The reason for not using a front axle beam as an example is that optimization tools are far more performance demanding than FEM calculations. The experiments were done on a desktop computer so running large optimization models was not an option. Instead, these examples were used in order to gain an understanding regarding limitations and advantages of the two calculation tools.

The bridge

The bridge is a 2D example, as seen in figure 12. To reduce calculation time, the symmetry of the geometry was used and only half of the bridge was modelled. For the shape optimization the objective was to minimize the weight of the component, with a constraint being that the maximum Von Mises stress could not exceed the maximum Von Mises stresses of the initial design. For the topology optimization another calculation model was used, also shown in figure 12. Here, the goal was to maximize the stiffness, given a limited amount of material. Again, this was a 2D mesh representing half of the bridge.

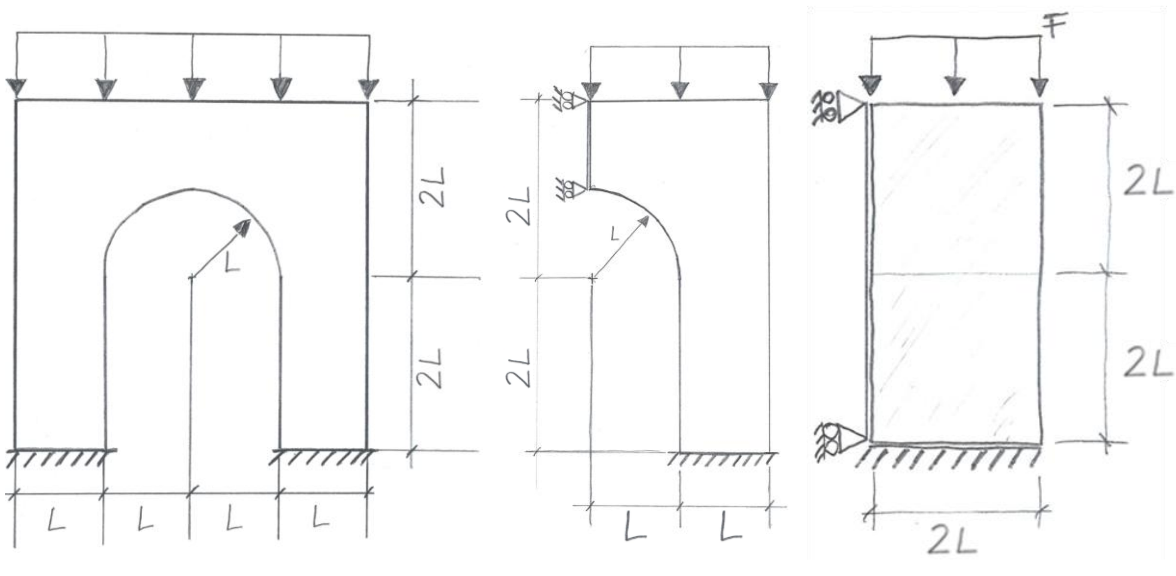


Figure 12 - The loading case of the bridge (left), the corresponding calculation model (middle) and the model for topology optimization (right)

The bracket

The bracket example consists of a T-shaped bracket, as can be seen in figure 13. A load of 10 kN is being applied at the far end of the bracket. The calculation model representing the bracket was a 3D mesh, and no simplifications were done.

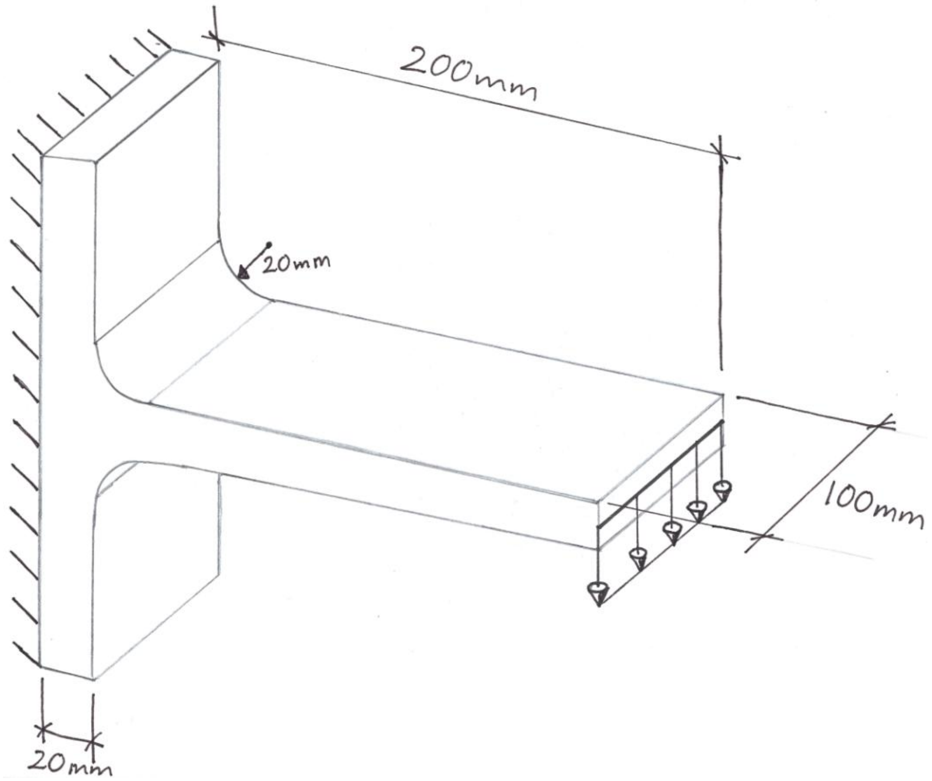


Figure 13 - The bracket loading case

For the shape optimizing, the objective was to minimize the weight of the component, with a constraint on the displacement at the far end of the bracket. It was not to exceed 1 mm. The topology optimization model was a solid 3D rectangular box, as can be seen in figure 14. Once again, the goal was to maximize stiffness with a limited amount of material.

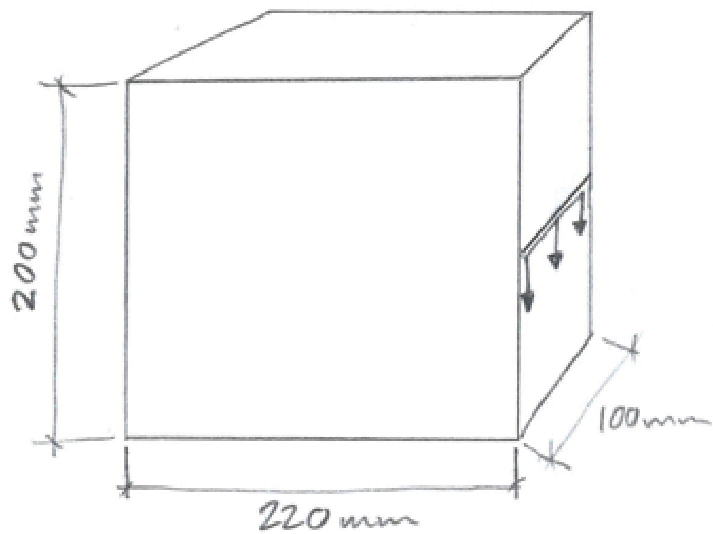


Figure 14 - The topology optimization model for the bracket loading case

3.4 How to create overall methodology for design process

A methodology for using the different tools was to be constructed. It was to start with the need for a new product, and end with a geometric model being sent to NAC for verifying calculations. These calculations would contain more complex models, and also take in to account the fatigue strength of the material. The aim of the methodology was that an optimal solution would be found and that the evaluation of the verifying calculation would not result in a redesign. An optimal design was said to be the design using the least amount of material, but still meeting the demands in material strength.

Brainstorming, discussions with designers and calculation engineers as well as a questionnaire sent out to affected actors, resulted in a collection of needs, wishes, expectations and potential risks. This list made a foundation for a QFD. Later it was also considered in a FMEA. The questionnaire contained the following questions, here translated into English:

- What are the problems with today’s design process? What isn’t working as it should?
- What are the advantages with today’s design process? What is going well?
  What do you want the designers to accomplish by doing calculations and optimizations themselves? What do you expect them to accomplish?
- What problems do you see in the designers performing calculations and simulations by their own? What could go wrong?
- How do you expect the designers’ role in the design process would look like, if they did calculations and optimizations by their own?
- How do you expect the calculation engineers’ role in the design process would look like, if the designers did calculations and optimizations by their own?

A QFD was done in order to meet the wishes and needs of the user and customer of the method. From the QFD and the results from the comparison of optimization tools, an initial method was constructed. An FMEA was made in order to analyze the initial method and eliminate or reduce the consequences of potential failures. This resulted in a slightly altered method.

4 Case description

In order to make a more narrow analysis of the tools and gain some depth, the development of front axle beams at NA served as an example for calculations and simulations. It was also the subject of the development of the manual as well as the new methodology. By doing so, the objective of the project was not how the tools could be used generally, but rather how they could be used for the development of front axle beams.

The department NA is responsible for axle development. Axle development includes hubs, brakes, propeller shafts and axle gears. NA is a part of the department N, which handles all the drivetrain development. Within NA there are several groups, including NAA and NAC. NAA designs front axle beams, among other components. NAC performs calculations and optimization for the NA department. See figure 15 for a structure tree of the different departments and groups.

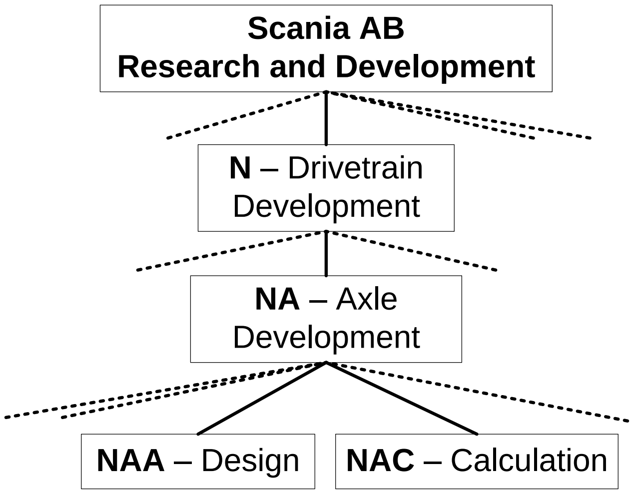


Figure 15 - Extract of the orginazational structure at Scania AB

4.1 NA design process

The design process at NA is built upon DBT cycles. The first tests are FE-based calculations and optimizations done by NAC. Later in the design process, physical prototypes are used in test rigs and for field testing. The lead time for standard FE calculations averages about a week, the lead time for a prototype in a test rig can be several months. When it comes to field tests, it is not unusual that lead times are measured in years. If the need for redesign is discovered after the field testing, it can mean that the design process is set back several years.

4.2 Scania's front axle beams

The shape of the front axle beam is based on an I-beam. As it is forged, it is practical to stay with the I-beam shape, as only two tools are needed. The two forging tools would press upon the I-beam from one side each. Holes for interfaces are thereafter created by machining. An example of this design can be seen on the AM900 beam, see figure 16.

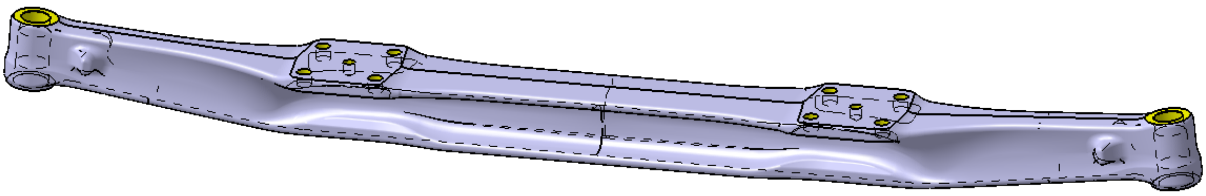


Figure 16 - The AM900 beam

As with all of Scania's components, the front axle beam has defined interfaces in order to support a high level of modularization. There are two main interfaces covered in this project: the kingpin interface and the spring seat. Both can be seen in figure 17. The kingpin interface connects the beam to the spindle, and consists of two contact surfaces for tapered roller bearing raceways. The spring seat consists of a contact surface and four holes to connect two hooks which hold the leaf spring in place.

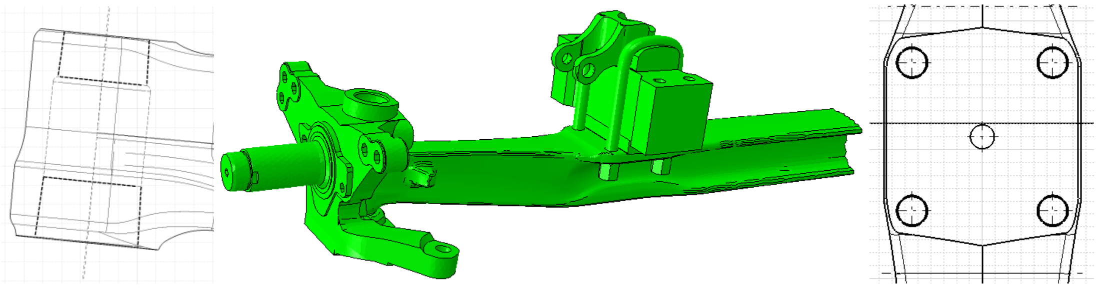


Figure 17 - Standard beam interfaces at Scania. Left: Kingpin interface. Middle: FE model of beam, spindle and suspension package. Right: Spring seat.

4.2.1 The loading cases

Regarded in this project are three loading cases used by NA. They are used to dimension front axle beams regarding fatigue strength and are called: the *braking load case*, the *side force load case* and the *pulsating wheel force loading case*. Of course, the beams are tested in more scenarios, but the initial FE calculations are done according to these three specific loading cases. When FE calculations has been done, and the front axle beam has been verified, physical prototypes are tested in the same loading cases. The physical loading cases can be seen in table 2.

The braking load case is designed to represent the scenario in which the brakes are applied. This is accomplished by using a lever with a length corresponding to the wheel radius. The results show that high stresses are located in the area around the spring seat. The side load case is designed to represent the forces that occur when the truck is turning. The pulsating wheel force load case represents a high force from one of the wheels through the front axle beam. The results show that high stresses are located in the area around the spring seat, as well as at the bottom of the beam, directly below the spring seat.

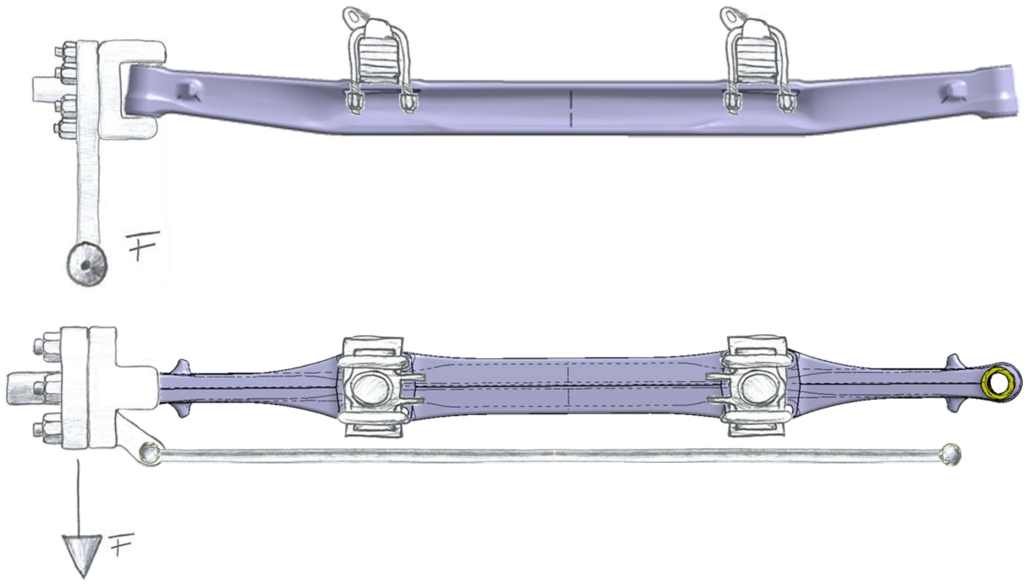
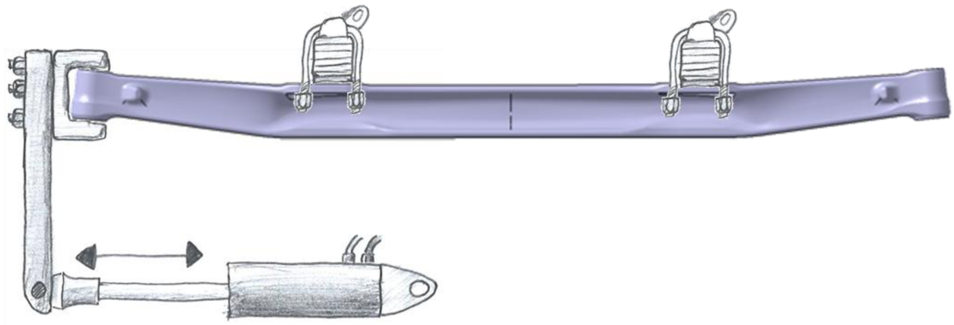
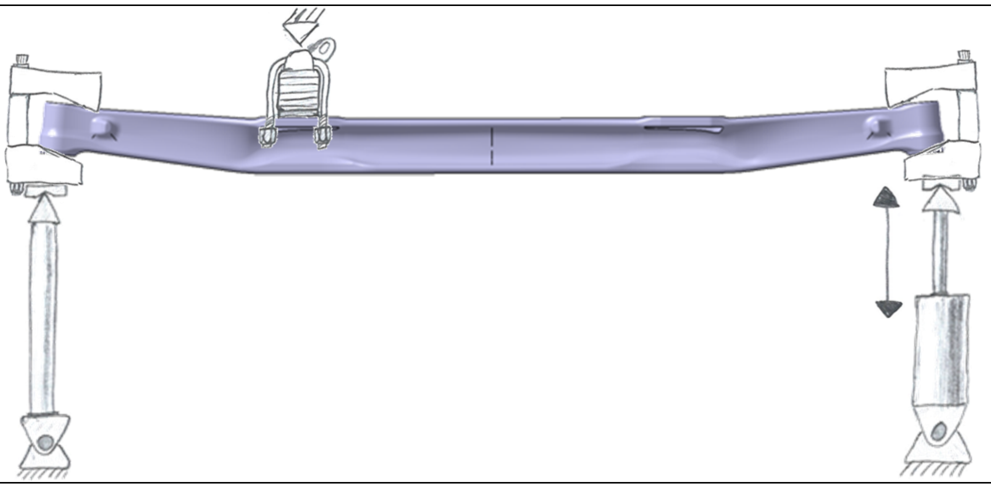
Name	Loading case as tested for physical prototypes
Braking load	
Side force	
Pulsating wheel force	

Table 2 – Schematic representations of the physical loading cases

4.2.2 Calculation models used by NAC for FE calculations

The calculation loading cases used by NAC are based on the loading cases for the physical prototype testing, but do include some simplifications. The calculation model rig components are replicates of the real rig components. Some physical levers are replaced by virtual beams, and long drop arms with revolute joints are replaced by components with limited degrees of freedom. The calculations do not only consider the static yield strength, but rather the fatigue strength of the component.

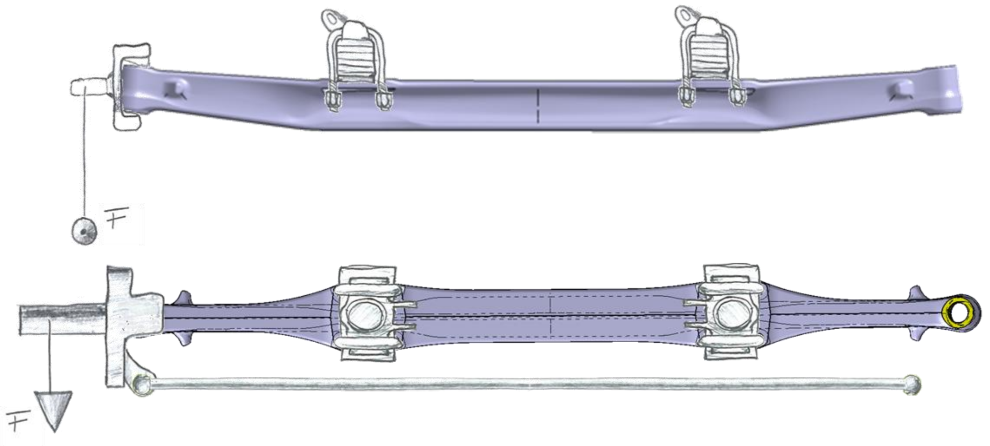
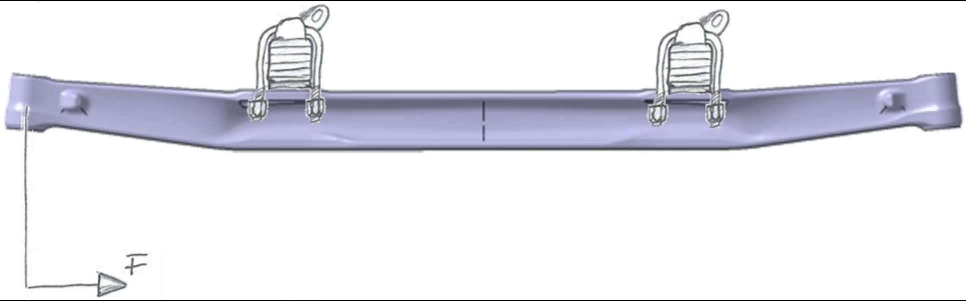
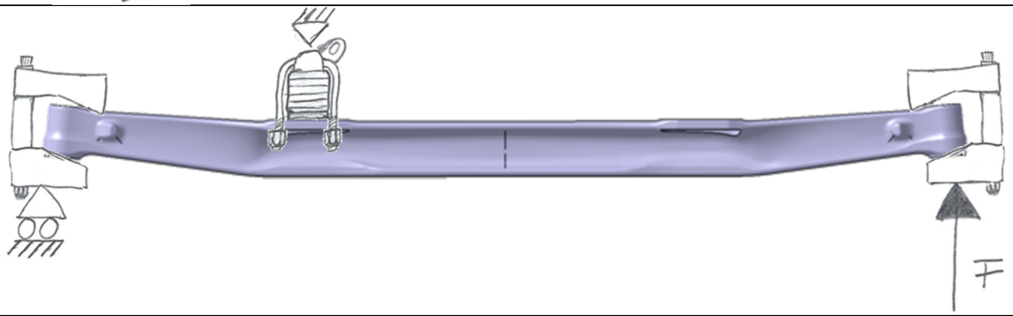
Name	Calculation loading case
Braking load	
Side force	
Pulsating wheel force	

Table 3 - Schematic representations of calculation loading cases used by NAC

5 Results

Here, the results from the methods described in the previous chapter will be shown. Only a summary of the results will be shown here, the rest can be found in appendices referenced in this chapter.

5.1 Built calculation models in Catia

Here the constructed calculation models for Catia will be presented. Also, the constructed macros for automation will be covered.

5.1.1 Defined calculation models to be used in Catia

Several models were made for each loading case. For a detailed description of the different models, see Appendix: Calculation models for loading cases.

Generally, the components of the test rig were somewhat simplified, partly in order to reduce complexity of the calculation model, but also to ease the assembly of the test rig. For example, the revolution joints and degrees of freedom could be applied to geometrical features of the components, which is much easier than applying them to virtual parts, as it were done by NAC. The simplifications were deemed necessary in order to reduce lead time and ease the construction of the models. The simplification only affected the calculation results marginally.

Braking load

The braking load case where simplified in several ways, apart from using the simplified rig components. One of the suspension packages was removed and the steering rod was removed. Further simplifications could not be done without compromising the accuracy of the results. For the final calculation model used for the braking load case, see figure 18.

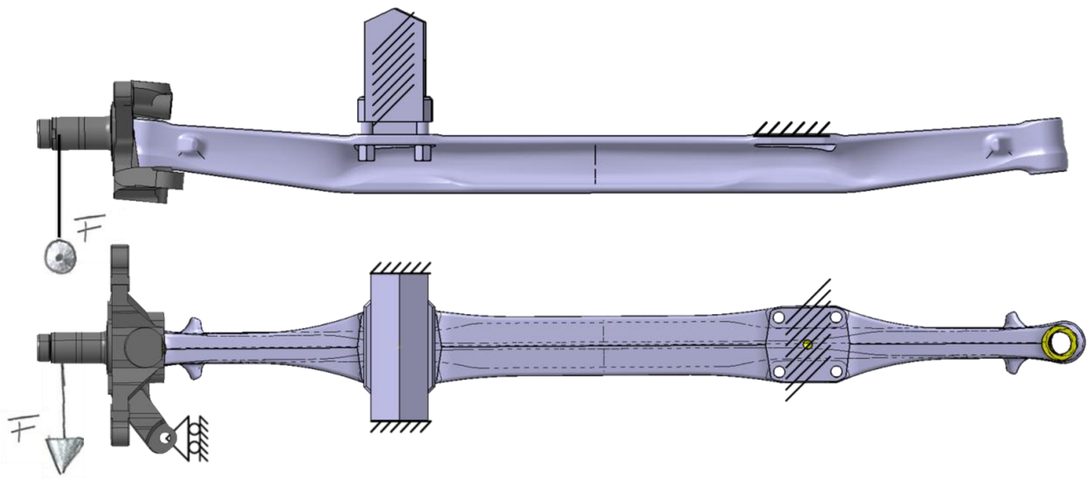


Figure 18 - Calculation model used in Catia representing the brake load case

Side load

For the side load case, there was one major simplification: both the suspension packages were removed. This had no effect on the stress levels at the areas of interest. For the final calculation model used for the side load case, see figure 19.

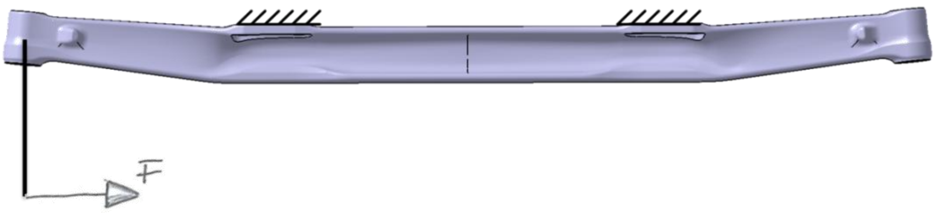


Figure 19 - Calculation model used in Catia representing the side load case

Pulsating wheel force

For the pulsating wheel force load case no further simplifications apart from the use of simplified rig components could be used without compromising the accuracy of the results. For an illustration of the final calculation model representing the pulsating wheel force load case, see figure 20.

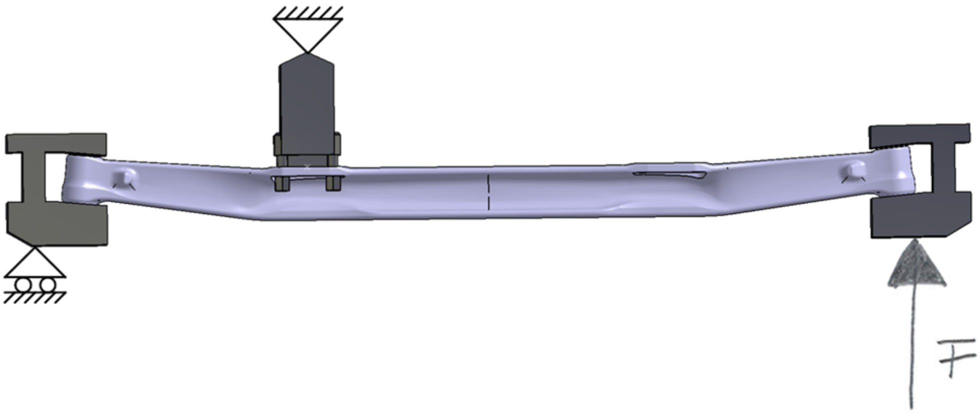


Figure 20 - Calculation model used in Catia representing the pulsating wheel force load case

5.1.2 Performed convergence study

The results of the convergence study were discussed with calculation engineers, and the size of the elements was decided upon. The calculation times for the recommended models decided upon ranged from 10 to 20 minutes. When analyzing results of the study, experience from previous calculations and field tests were used as a comparison. Models with smaller elements than the recommended ones was calculated, with results closer to the ones from NAC, but the calculation times was considered too long.

Braking load

For the braking load case, the area around the spring seat was considered critical. The element size was set to 7 mm. Also, the radius between the front outer spring seat hole and the web of the beam was considered. There, the element size was set to 1mm.

Side force

The areas of interest were the bottom and top of the beam in the direct vicinity of the holder. Since the side force varied between positive and negative values, both the top and bottom surfaces were deemed equally important. Therefore, the element size of both surfaces was changed together. The element size was finally set to 5 mm.

Pulsating wheel force

For the pulsating wheel force load case, two areas of interest were identified:

- The surface on the bottom of the beam, below spring seat. Element size set to 10mm.
- The surfaces around the spring seat. Element size set to 7mm.

5.1.3 Comparison between Catia and NAC calculations

When comparing the results of the Catia calculation models with the ones form NAC, the critical areas showed some differences regarding stress levels, and a negligible difference regarding the stress plots and stress concentrations. These differences became smaller if the element size was further decreased, but the calculation times would peak. The final comparison was made using specific loads that testing had shown gave the beam a given probability of failure when running a given amount of load cycles. The given values are part of the standard procedure of component testing at Scania.

Braking load

For the NAC calculations of the braking load case, stress concentrations were located around holes of the spring seat as well as the radius between the front outer spring seat hole and the web of the beam. These stress concentrations were located on the same place when running the calculations in Catia, see figure 21. However, for the hole, the maximum Von Mises stress level was 6.7% lower, and the principle stress was 0.5% lower. For the radius, the Von Mises stress was 2,2% lower, and the principle stress 3,2% lower.

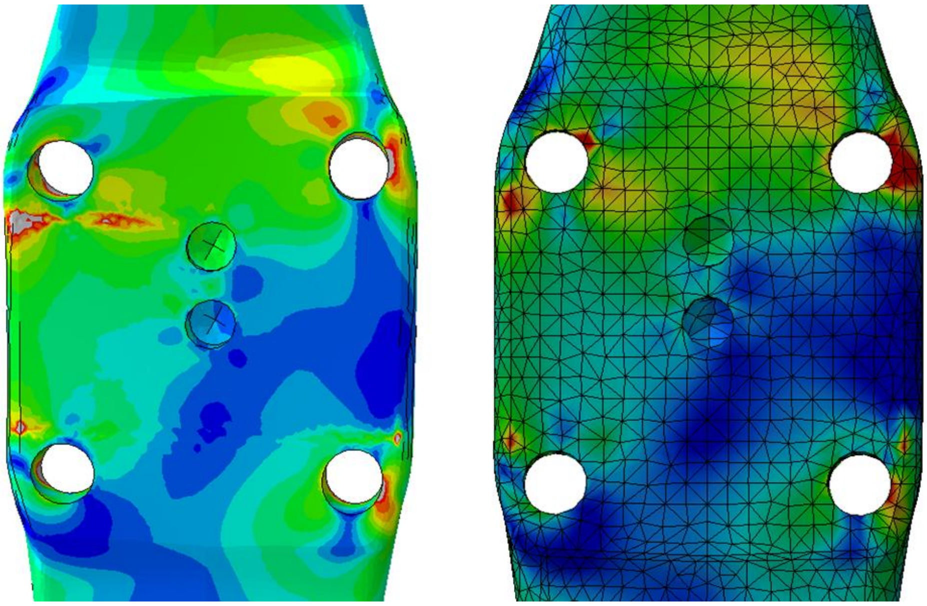


Figure 21 - Comparison between calculation models of the braking load case. Showing the Von Mises stresses of the spring seat. Left: NAC calculations. Right: Catia calculations.

Side load case

For the NAC calculations of the side load case, concentrations of stresses were located near the holder, at the top and the bottom of the beam. The areas of concentration were the same on the new calculation models in Catia, see figure 22. For both directions of the side force, the Von Mises and the tensile stress levels were approximately 3% lower.

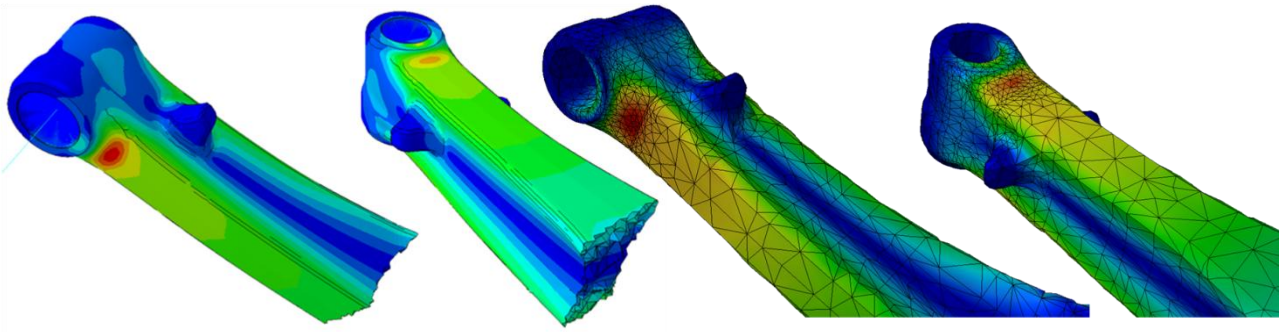


Figure 22 - Comparison between Von Mises stresses of the calculation models of the side load case. Left: NAC calculations. Right: Catia calculations.

Pulsating wheel force

Two critical areas were identified in the NAC calculations of the pulsating wheel force load case: the spring seat and the bottom of the beam, right below the interface. The plot of the Von Mises stresses of the spring seat formed what internally was called “a butterfly”, and the Catia calculations also showed this butterfly, see figure 23. The stress plots at the bottom of the beam were similar using both calculation models. Differences occurred around the holes of the spring seat. This could be because the calculation models done by NAC includes radial clearance, and the ones done in Catia does not.

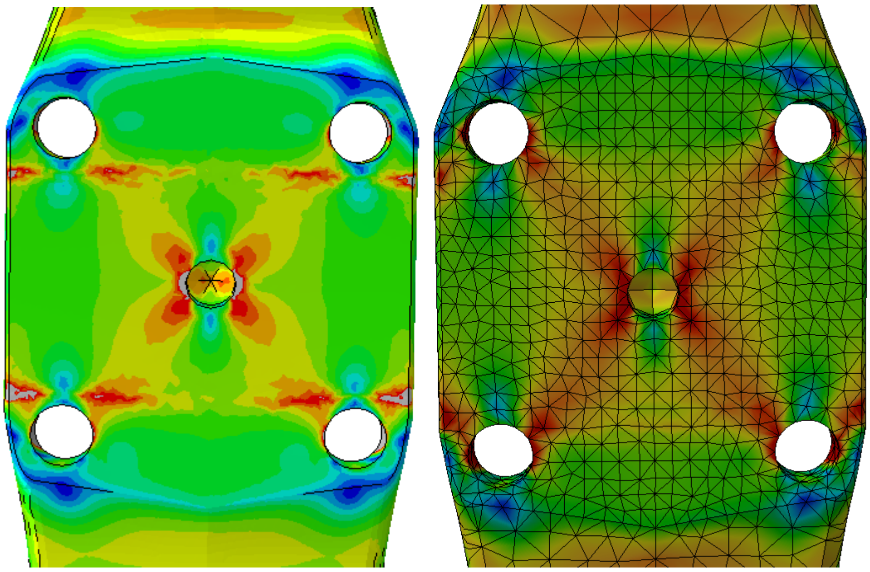


Figure 23 - Comparison between Von Mises stresses of the calculation models of the pulsating wheel force load case. Left: NAC calculations. Right: Catia calculations. Please note that differences in colour are partly due to the pictures being created in different tools.

As with the other load cases, the actual stress levels differed somewhat from the NAC calculations. At the holes in the spring seat, the maximum Von Mises stress was 22.2% lower, and the maximum principle stress was 3.1% lower. At the bottom of the beam the Von Mises stress was 5.1% higher, and the maximum principle stress was 4.6% higher. This was the only area in the comparison study that showed higher levels of stress than NAC's calculation.

5.1.4 Constructed method with automation

In order for the macro to assemble the different parts correctly, a tool was needed to identify certain surfaces, edges and points of the beam of importance. Catia has such a tool already: Publications. It is simply a list of selected features, which can be given names for easy identification. A list of what features to select, and what names to give these was made, and can be found in Appendix: Publications.

Of several different levels of automation, the following four levels were considered:

- *Completely manual*
  The calculation model was built completely manually, without the use of macros.
- *Mostly automated I*
  Publications are created and defined. A macro is used for creating a calculation model. The calculation model could then be altered to the designer's desire. Then, another macro was used to calculate the model and present the results.
- *Mostly automated II*
  Certain parameters, like forces and element sizes, are defined in a document. Publications are created and defined. Then a macro is used, which reads the document and builds a calculation model according to the data in the document.
- *Completely automated*
  One macro is used which builds the calculation model and runs the calculation, after the publications are created and defined. There is no room for altering the calculation model.

After discussions with designers, the level "Mostly automated I" was selected on the basis that it would be the best trade-off regarding speed, understanding and ability to perform changes. It included five steps between a solid model and results of a FE calculation:

- Run macro for creating and naming publications
- Connect publications according to given specifications.
- Run macro 1 for chosen loading case.
    - The macro creates an assembly, imports front axle beam and components, and places them correctly
    - The assembly is converted into a calculation model. Material, mesh, connections, constraints and loads are defined
- With the calculation model built according to standards, make changes if needed.
- Run macro 2 for the chosen loading case.
    - Sensors for locating maximum stresses are defined, and the calculation is run.

Each loading case has two macros: one that builds a calculation model according to standards, and one that runs the calculation and identifies the maximum stresses of critical areas, see figure 24. The point of having two separated macros is the ability to make changes to the model before the calculation is run, and thereby adapt it to any changed conditions. Defining publications took less than three minutes for a novice, and thereafter letting a macro create the calculation model would be done in a matter of seconds.

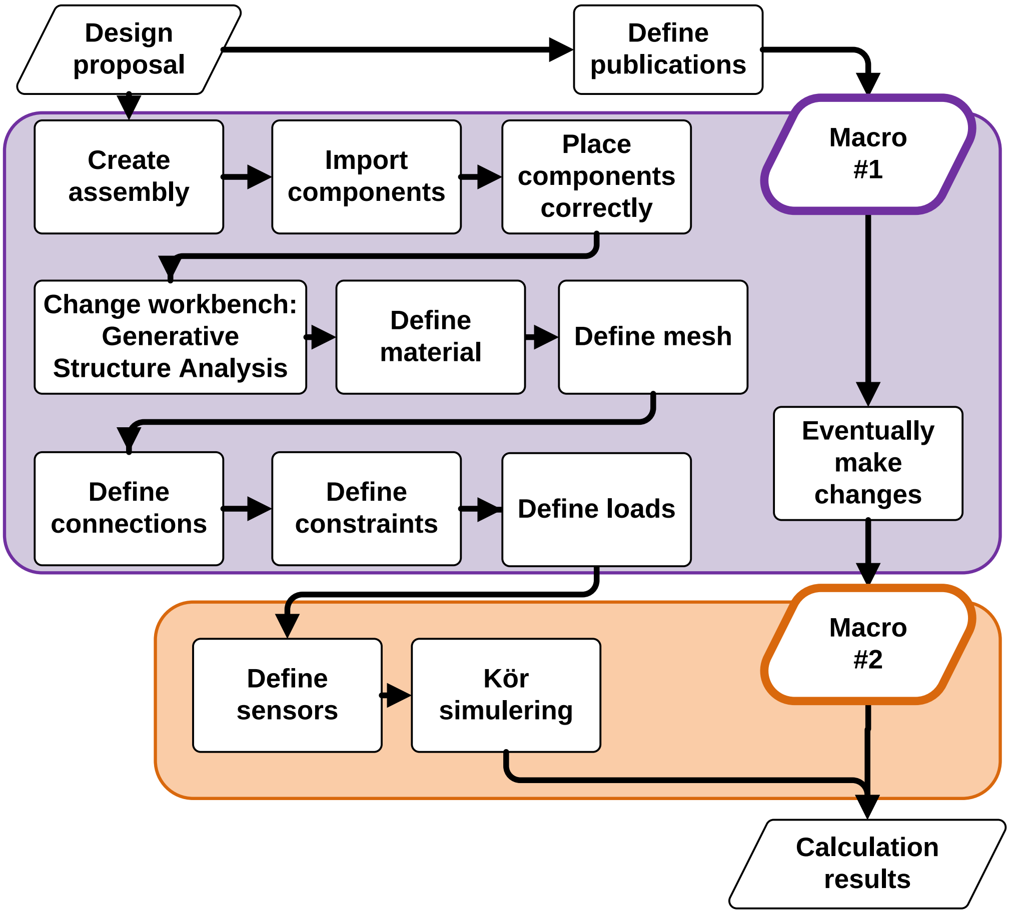


Figure 24 – The chosen level of automation

5.1.5 Written manual regarding calculation models

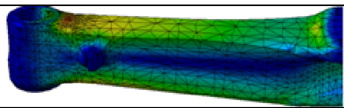
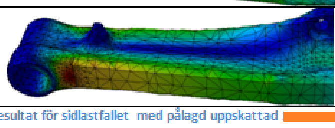
A written report was made and was eventually approved by both calculation engineers as well as designers. It encompassed the overall method of constructing a calculation model, the construction of the specific models for the different loading cases, a description on how to use macros as well as a guide regarding analysis of results. Of confidentiality reasons, it has been decided not to release the manual, since it is regarded as part of Scania's intellectual property. An extract of the manual can be seen in figure 25. The outline of the manual is as follows:

- Overall structure
  The structure of the document is explained, as well as the purpose of each chapter.
- Nomenclature
  The names of the different parts of the front axle beam is explained.

- Manually building calculation models
  Here the reader is taught how to construct a calculation model with mesh, restraints, connections and loads.
- Using Macros
  Here the reader is taught how to use macros, and how to prepare the front axle beam for the use of macros.
- Interpreting results
  Interpreting calculation results is not a straight forward task. In this chapter, guidelines for interpreting results for calculations of the front axle beam are presented.
- To keep in mind
  Here the importance of analyzing the results critically is stressed. This to avoid the risk of basing design alterations on faulty calculation results.
- Appendixes
  The appendixes contain detailed calculation results.

5.1 Sidlast

För sidlastfallet finns det två områden som får höga påkänningar: ovansidan och undersidan av balken, i anslutning till näven. I och med att lasten är växlande, räcker det med att göra en beräkning när lasten går åt ena hållet: de dragspänningarna som uppstår blir tryckspänningar när lasten växlar. För finns ingen Wöhler-kurva, istället bygger acceptenskriterium på en uppskattad Spänningsplotter och maximala spänningar för och uppskattad finns i Tabell 5.

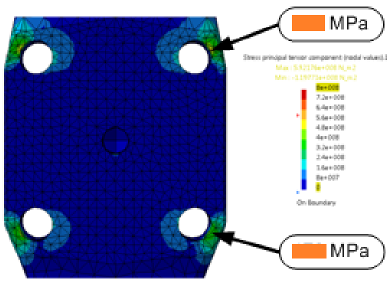
Lastfall	*Område*	*Bild*	*Nivåer*
Sidlast	Ovansida av balk, nära näven		Von mises: MPa Tryck/Drag: Mpa
Sidlast	Undersida av balk, nära näven		Von mises: MPa Tryck/Drag: MPa

Tabell 5 - Catiaresultat för sidlastfallet med pålagd uppskattad

5.2 Pulserande hjultryck

För lastfallet pulserande hjultryck finns två områden som bör studeras närmare. Dels är det områden kring hålen i fjädersätet. Det uppstår lätt sprickor vid hålen, ut mot fjädersätets ytterkant. Det är värt att notera att godstjockleken vid bygelhålen utåt är i tunnaste laget och att det finns fall då sprickor uppstår i fält. Det är alltså önskvärt att uppnå lägre spänningsnivåer här än vad referensen ger.

Vid provning sker sprickstart vid övre kanten av bygelhålens mantelyta. Även om just dessa sprickor inte leder till funktionsbortfall är det ändå ett problemområde. När ingen last är pålagd och endast förspänningen verkar på balken uppstår dragspänningar vid mantelytans övre kant. När lasten sedan läggs på uppstår istället tryckspänningar på samma punkt. När det växlar mellan drag- och tryckspänning uppstår sprickor mycket lätt. Vid utvärdering av hålens mantelyta bör alltså balken beaktas både med och utan pålagd last. Plot över dragspänningen i balken med endast förspänning pålagd finns i Tabell 6.

Lastfall	Område	Bild	Nivåer
Endast förspänning	Ovansida av fjädersäte		Runt hålen Ov: Dragspänning: MPa Ne: Dragspänning: MPa

Tabell 6 - Catiaresultat med endast förspänning pålagd

Figure 25 - Extract from the manual

5.2 Evaluation of structural optimization tools

The comparison of the optimization tools resulted in several geometries being created. The resulting shapes and topologies were compared to solutions from NAC using OptiStruct. These were assumed to be the optimal solutions of the different examples, therefore the designs were compared rather than stress levels or amount of material used.

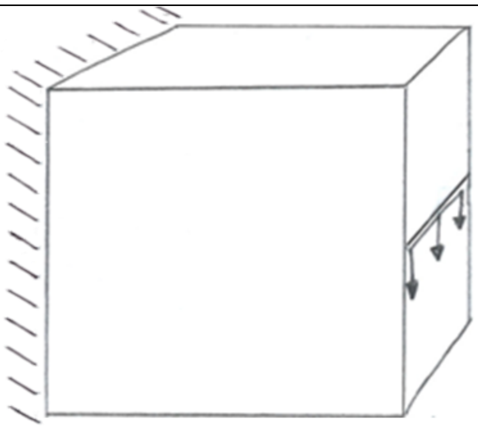
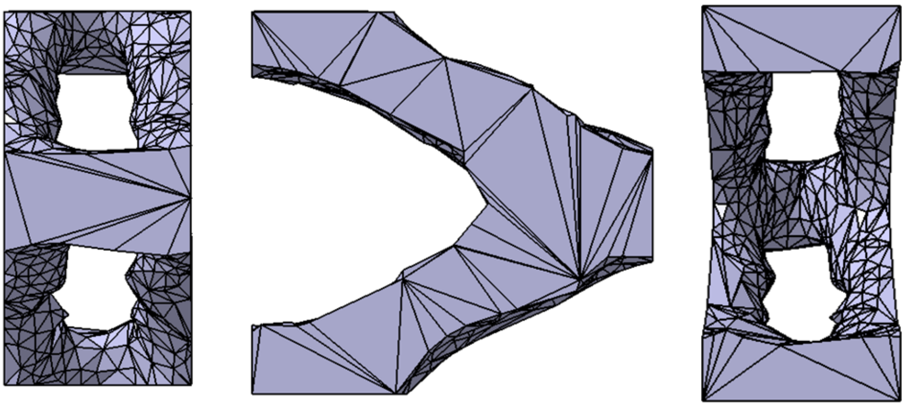
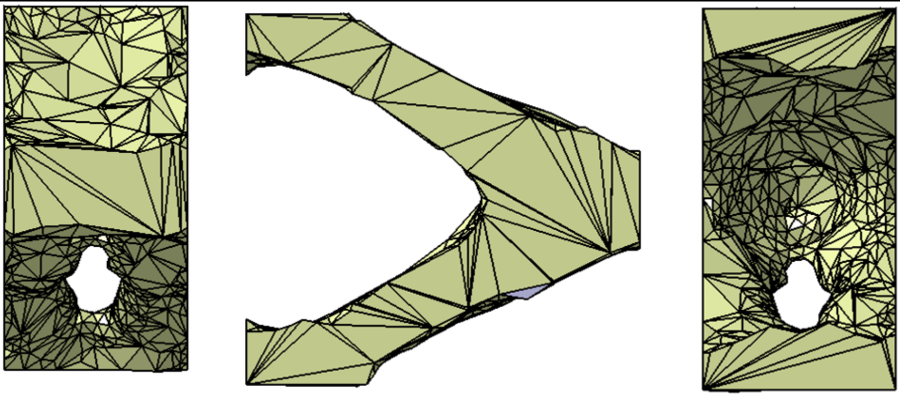
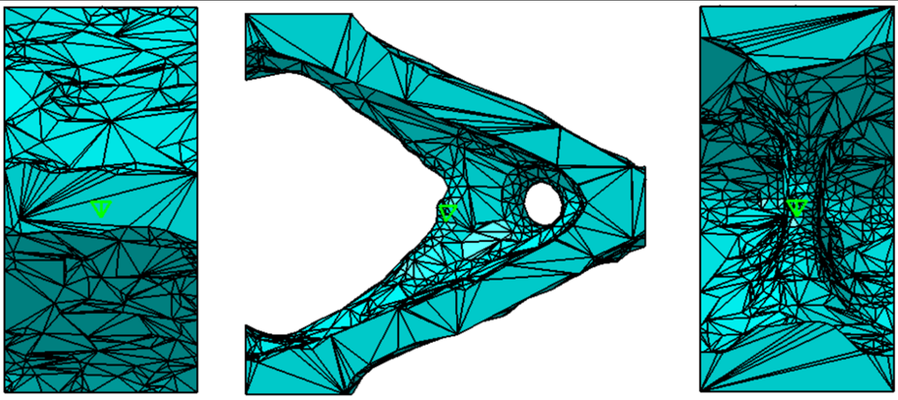
5.2.1 Topology optimization comparison

Only the tool HyperShape/CATIA can perform topology optimisation. Hence, the only comparison to the topology optimization was an optimization done in OptiStruct. Since HyperShape/CATIA is based on OptiStruct, the only difference in the results should be due to differences the element size.

The maximum volume fraction was set to 0.3, meaning that a maximum of 30% of the volume of the design domain is allowed to be used. As the objective is to maximize the stiffness of the design, all of the allowed material will be used.

Topology optimization results for the bracket loading case

The convergence study regarding the topology optimization of the bracket resulted in several geometries. Even though it was similar to the results from the optimization done in OptiStruct, there was several differences, see table 4. The resulting geometry from OptiStruct contains a cavity which cannot be found in the results from HyperShape/CATIA due to the larger element size, see figure 26. The convergence study was carried out until the calculation times reached two hours.

Mesh size	Tool	Topology results
Design space		
20 mm	HSC	
15 mm	HSC	
10 mm	HSC	

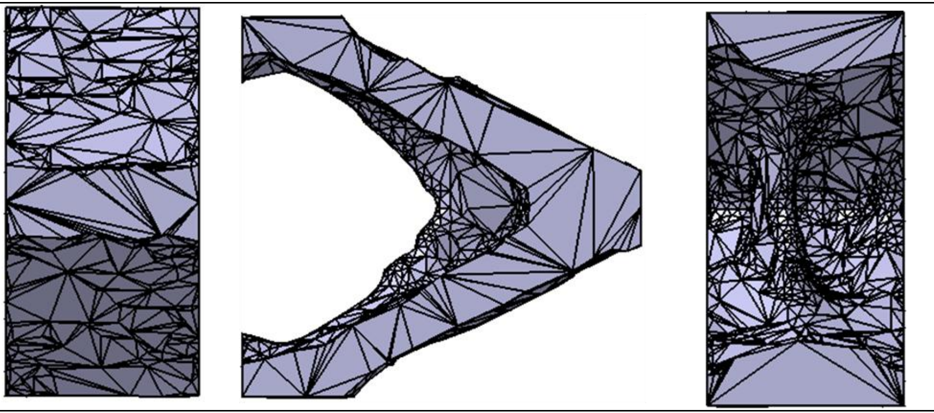
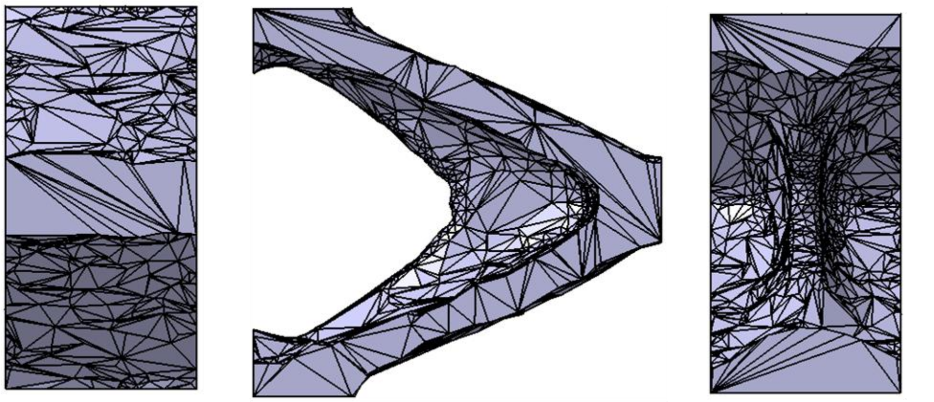
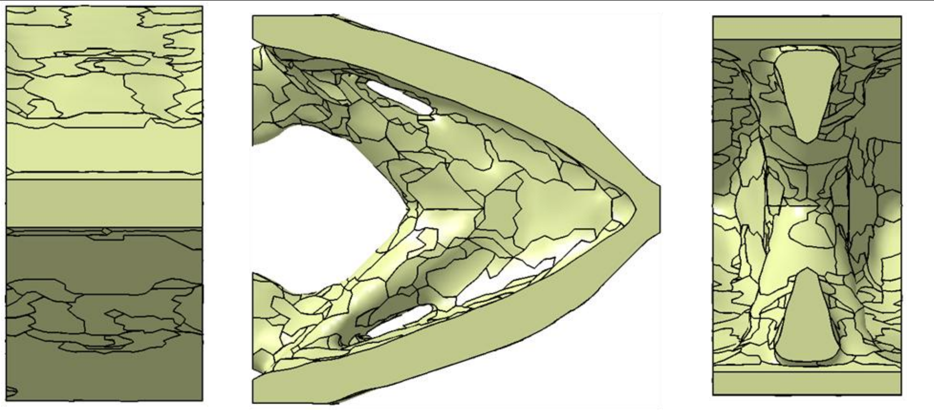
9 mm	HSC	
8 mm	HSC	
5 mm	Opti-Struct (Done by NAC)	

Table 4 - The results of the convergence study of the bracket loading case

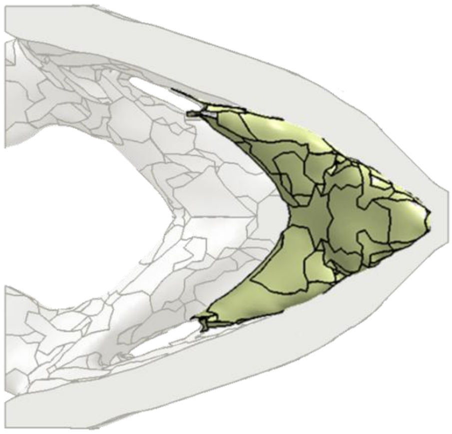


Figure 26 - Cavity in the topology optimization results of the bracket loading case from OptiStruct

Topology optimization results for the bridge loading case

The convergence study regarding the topology optimization of the bridge loading case resulted in several geometries, see table 5. The results quickly converged to a design that was identical to the results from OptiStruct. Also here the convergence study was carried out until calculation times reached two hours.

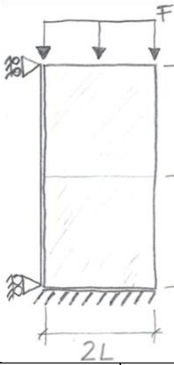
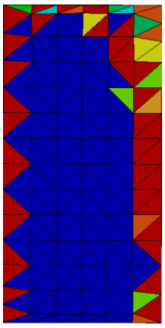
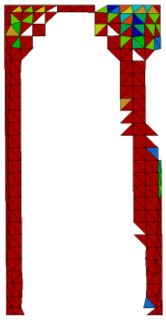
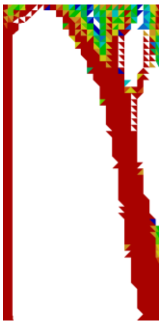
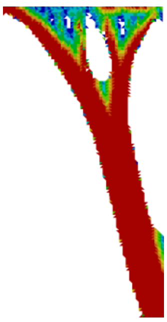
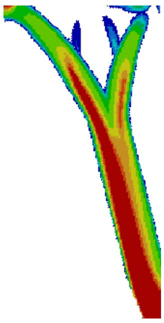
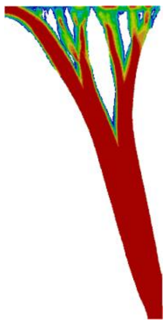
Element size	Design space		32 mm	16 mm
Topology results				
Element size	8 mm	4 mm	2 mm	1 mm (Identical to OptiStruct results)
Topology results				

Table 5 - The results of the convergence study of the bridge loading case

5.2.2 Shape optimization evaluation

Both the evaluated tools, HyperShape/CATIA and Catia PEO, were able to perform shape optimization. HyperShape/CATIA performs mesh based shape optimization, and Catia PEO performs geometry based mesh optimization. In HyperShape/CATIA the optimization is solved using a first order algorithm, guaranteeing the solution is the optimal solution. In Catia PEO the optimization can be done using different algorithms, either a first order algorithm or a zero order algorithm. A zero order algorithm as used in this evaluation does not guarantee an optimal solution. The algorithm decides how the next design alteration will be done.

Therefore it was not only a comparison between the different tools, but also a comparison between the different methods.

Mesh based shape optimization results

The mesh based shape optimization method has the drawback that it is hard to perform large shape changes, as the mesh may then become distorted. The optimization is aborted if the mesh becomes too distorted. For the mesh based shape optimization several mesh sizes was tested; not in order to make a convergence study, but rather to see when the mesh easily would become distorted.

Optimizations of the bracket example always resulted in a distorted mesh after a few iterations, regardless of element size. However, the geometry generated before the mesh became distorted were similar to the results from NAC, see table 6.

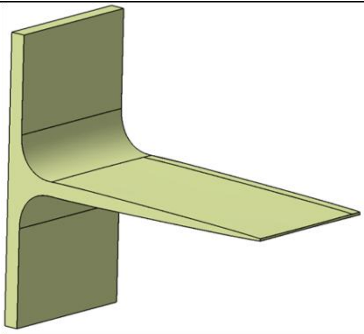
Results			
Element size	20 mm global, 4mm local at the radius	10mm global, 4mm local at the radius	2 mm (Done by NAC)
Comments	Distorted mesh	Distorted mesh	Distorted mesh

Table 6 - Results of the mesh based shape optimization of the bracket loading case

The mesh based shape optimization of the bridge loading case brought about many geometries, see table 7. It quickly took the shape of the benchmark results from NAC, even though the mesh became distorted at some of the element sizes.

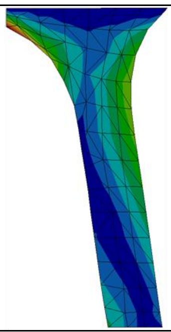
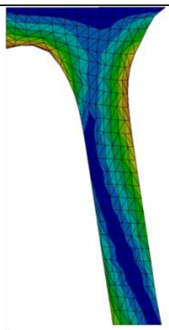
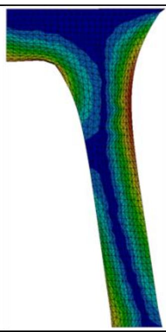
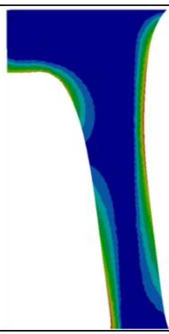
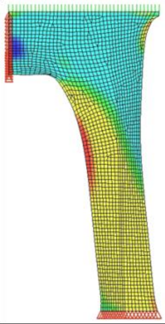
Results					No geometry was being returned	
Mesh size	32 mm	16 mm	8 mm	4 mm	2 mm	2,5 mm (done by NAC)
Comments	Converged	Converged	Distorted mesh	Converged	Distorted mesh	Converged

Table 7 - Results of the mesh based shape optimization of the bridge loading case

Parameter based shape optimization results

For the parameter based shape optimization the analysis was not regarding different element sizes, as the geometry was remeshed for each iteration. Rather an analysis regarding free geometric parameters was performed. Since the tool alters the different parameters, the solution becomes dependant on the definition of the original geometry. A predefined zero order algorithm was used. This had the drawback of not guaranteeing an optimal solution, but of the predefined algorithms, it was the one that was the most easy to use and worked the fastest.

In the bracket optimization model, four free parameters was defined and a solution was quickly found, see figure 27. Other optimizations with several more free parameters were done with similar results.

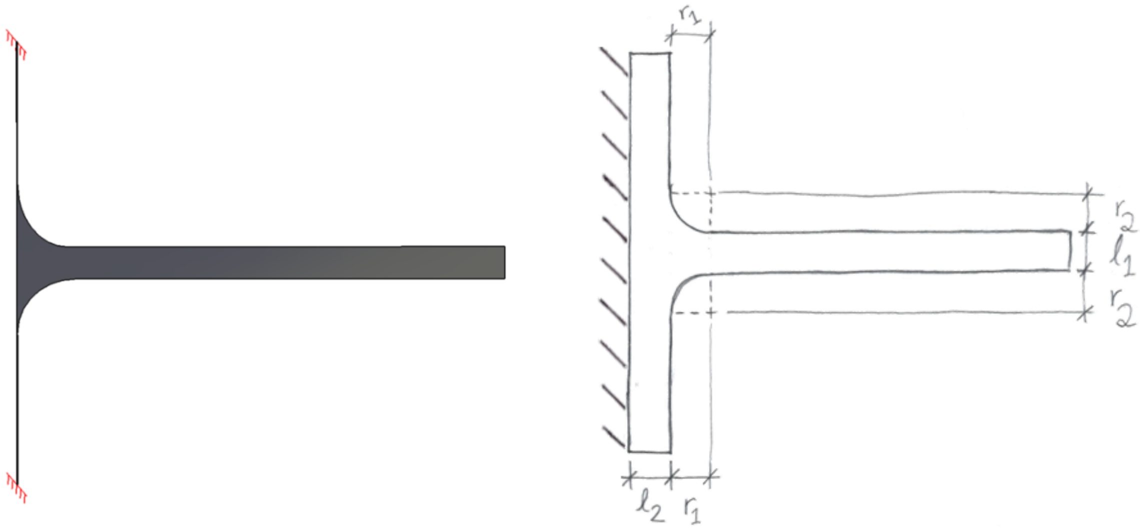


Figure 27 – Left: Results from parameter based shape optimization of the bracket loading case. Right: Free parameters in the shape optimization model Please not that the entire left side of the bracket is clamped and therefore locked regarding all degrees of freedom.

For the bridge loading case several different ways of defining the geometry was tested, and two of them are presented here, see table 8. The first of them was defined by three parameters. The second was built up using splines defined by five points each, and the model had a total of eleven free parameters. In theory, the model with eleven free parameters could converge to the same results as the mesh based shape optimization, see table 7, but in practice it is hard to obtain.

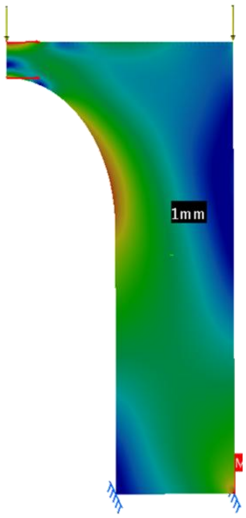
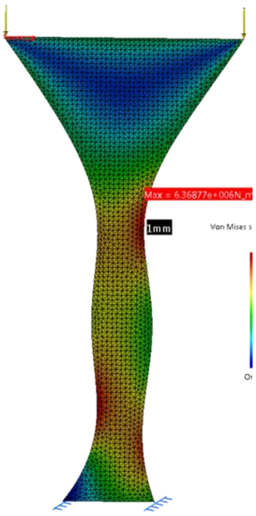
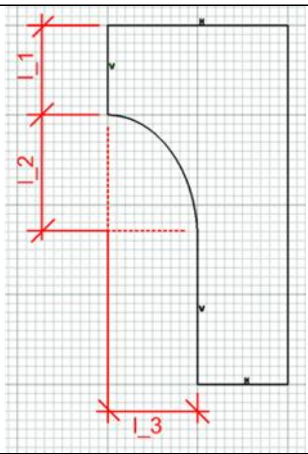
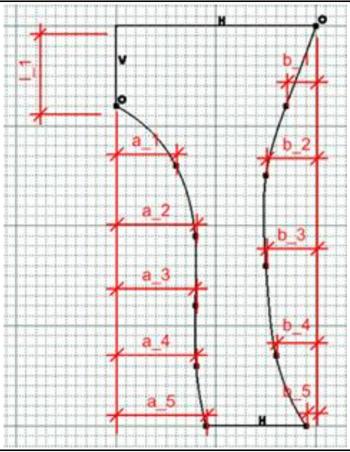
Result		
Free parameters		

Table 8 - Results from parameter based shape optimization of the bridge loading case

5.3 Overall methodology for design process

In order to have a scientific ground to build the method upon, a QFD and a FMEA was done. Responses of a questionnaire sent out and discussions with affected actors served as input for the methods. The results from the two methods, together with discussions with affected actors, led up to a proposal regarding a future design process involving SDD. The questionnaire sent out contained the following questions (Note that the questions and answers originally was in Swedish):

- What are the problems with today's design process? What isn't working as it should?
  Answers:
  - *NAC must handle even the simplest calculations, which takes more time than necessary.*
  - *Lots of administrative work has to be done be writing reports for each handover.*
  - *The iteration loops can grow long.*
  - *The designer does not reach his/her full potential.*
- What are the advantages with today's design process? What is going well?
  Answers:

- *The calculation engineers gain a great experience and expertise by only doing calculations.*
- *The calculations that are done, are done very well.*
- *Not every calculation is so simple that anyone can do them.*
- *The designer does not have to make decisions he/she is not capable of making.*

- What do you want the designers to accomplish by doing calculations and optimizations themselves? What do you expect them to accomplish?
  Answers:
  - *Make valuable calculations from the start.*
  - *Quickly understand the problem areas of different designs.*
  - *Achieve a greater quality of the geometries sent to NAC.*
  - *Reduce the time for each iteration.*
  - *Perhaps even perform calculations at level that makes NAC calculations redundant.*
- What problems do you see in the designers performing calculations and simulations by their own? What could go wrong?
  Answers:
  - *The designer makes mistakes in the calculations, and builds the design on inaccurate results.*
  - *The designer becomes overconfident, and deems NAC calculations redundant even though they might not be.*
- How do you expect the designers' role in the design process would look like, if they did calculations and optimizations by their own?
  Answers:
  - *The models sent to NAC would be optimized solutions for evaluation and fine tuning, as opposed to raw models for optimization.*
  - *Their role would encompass more fields of work. However, the designer would be able create geometries with higher quality faster.*
- How do you expect the calculation engineers' role in the design process would look like, if the designers did calculations and optimizations by their own?
  Answers:
  - *By focusing on more complex and challenging tasks, the calculation engineer would develop and increase their knowledge and experience.*
  - *They would become a support for designers running into problems.*
  - *NAC would handle only calculations and tasks so complex that the designers tools or knowledge are not enough.*

5.3.1 Results of QFD regarding overall methodology

A set of customer requirements was listed and based on their importance and how well they were filled today, a rating of each requirement was made. The requirements that scored a high rating were classed as prioritized areas and were deemed most important to solve. The requirements were:

- *Speed*
  The main purpose of the method is to reduce lead time. This was considered to be a prioritized area.
- *Precision*
  The results gained from the calculations must be accurate enough to make the calculations worth its while. This was not considered to be a prioritized area, as NAC already had high precision tools.
- *Ease of use*
  The methodology and tools involved must be easy enough to use in order for the user to feel motivated to use it. This was considered to be a prioritized area.
- *Understanding of strength of materials*
  By using the methodology, the user should be able to gain an understanding regarding strength of materials. The idea is that this understanding should help the designer in later projects. This was considered to be a prioritized area.
- *Understanding of the calculation process*
  The user should understand what he/she is doing, and thereby not running and analyzing calculations containing errors. This was considered to be a prioritized area.
- *Being able to perform estimations of fatigue*
  The ideal would be that the user could be able to perform calculations and estimations of fatigue, even though it requires complex calculations. This was not considered to be a prioritized area.
- *Integration with Catia V5*
  By only using tools integrated in Catia, the user would not as easily feel alienated by using them. This was considered to be a prioritized area.

Six characteristics was identified, these were:

- *Automation*
  The use of macros to automate parts of the process.
- *Designer performing FE calculations*
  Building calculation models and performing strength calculations.
- *Designer performing parameter based shape optimization*
  Using the built calculation model to perform parameter based shape optimization in Catia PEO.
- *Designer performing mesh based shape optimization*
  Using the built calculation model to perform mesh based shape optimization in HyperShape/Catia.
- *Designer performing topology optimization*
  Building a calculation model for topology optimization.
- *Designer using batch server for calculation*
  By sending the calculations to a batch server, more complex calculations are done faster and does not use performance of the designers work station.

All this was added to a House of Quality, see figure 28.

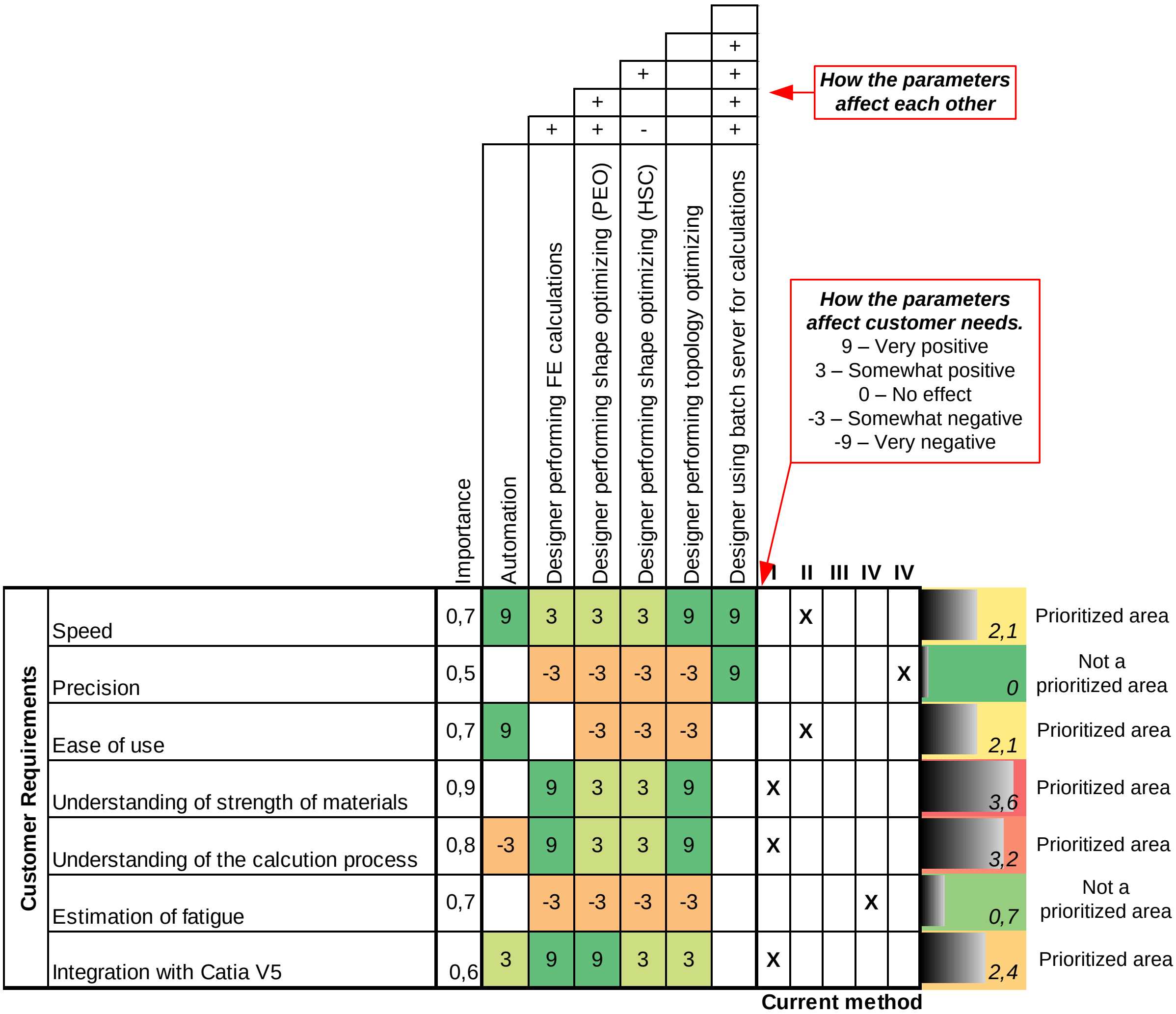


Figure 28 – House of quality regarding overall methodology

The last characteristic, *Designer using batch server for calculation*, only had positive effects. All other had a positive effect on one or more of the requirements, and a negative effect on at least one other. Not one of the characteristics could therefore be ruled out. Instead, the initial overall methodology would contain elements of all these characteristics.

5.3.2 Initial overall methodology

Based on the QFD and the findings of the evaluation of the different tools, an initial methodology was made, see figure 29.

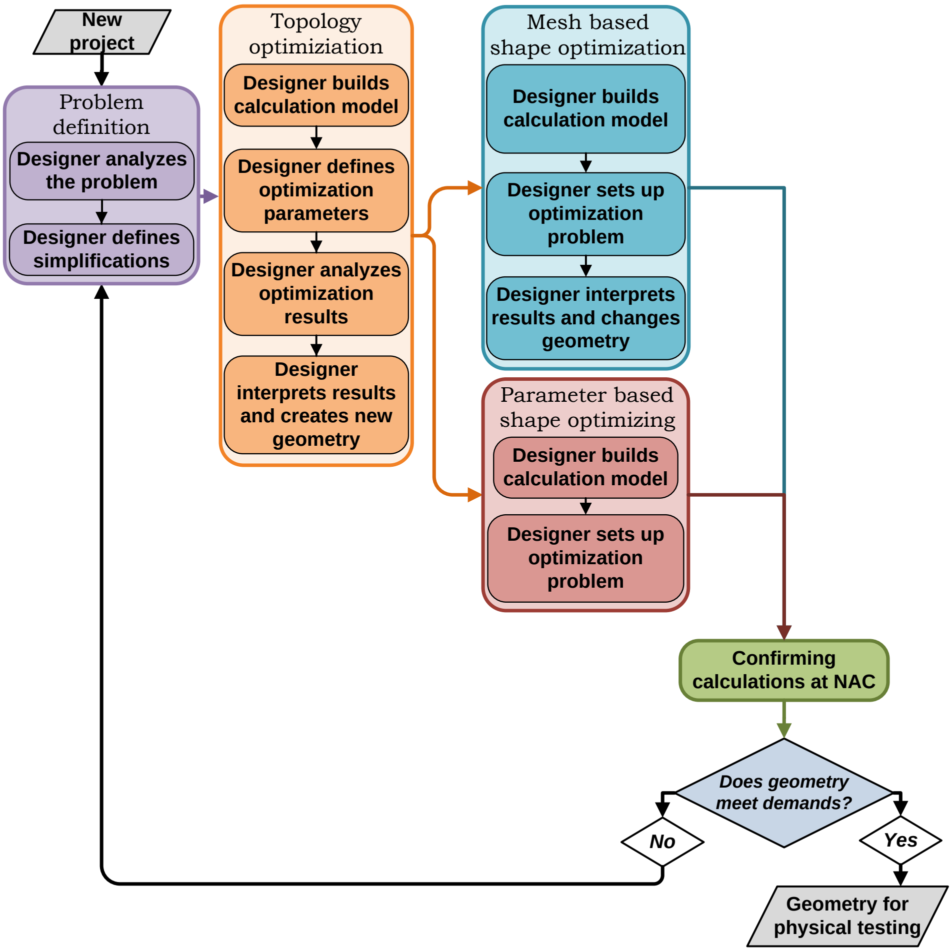


Figure 29 - Initial proposal of overall methodology

The methodology was divided into the following set of points:

- *Problem definition*
  The designer analyzes the problem and decides upon simplifications.
- *Topology optimization*
  The designer would build a calculation model according to the defined problem, define the optimization parameters, analyze results and interpret them into a new geometry.
- *Shape optimization*
  Even though the geometry is interpreted from a topology optimization result, it does not mean that it is optimal. A shape optimization can further improve the design. Based on the problem and geometry, the designer must decide between a mesh based and a parameter based shape optimization.
  - *Mesh based shape optimization*
    The designer builds the calculation model, sets up the optimization problem, runs optimization and interprets results into a new geometry.
  - *Parameter based shape optimization*
    The designer builds the calculation model, sets up the optimization problem and runs the optimization. The optimal geometry is automatically returned.

- *Confirming calculations at NAC*
  NAC performs confirming calculations and evaluates if the geometry meets the demands and also to evaluate if the geometry is optimal or if more mass can be reduced. If it meets the demands it is sent to physical prototype testing. If not, it is to be redesigned.

5.3.3 Results of FMEA regarding overall methodology

The FMEA was performed, see figure 30, and several possible failures was detected. These included making incorrect calculation models, failure to detect errors in the calculation model or misinterpreting results. As recommended actions there was only two actions repeated for several failure modes:

- Designer and NAC calculation engineer together receiving and reviewing the problems.
- Train designers to carefully review results.

Discussions with calculation engineers led to the conclusions that the NAC calculation engineer would also be consulted during the review of calculation results, and also that a confirming calculation in Catia would be made. The FMEA can also be found in Appendix: FMEA regarding overall method.

Process step	Failure Mode	Probability of failure	Effect	Severity	Control	Probability of detection	*Linear Risk Number*	Recommended action taken
Designer receives, interprets and analyzes information regarding the problem	Designer misinterprets problem	2	Design process becomes based on inaccurate information	9	Comparison to NAC calculations	3	*54,00*	Designer and NAC calculation engineer together receives and reviews a new problem
	Designer misses information	2	Design process becomes based on inaccurate information	9	Comparison to NAC calculations	3	*54,00*	Designer and NAC calculation engineer together receives and reviews a new problem
	Designer is misinformed	2	Design process becomes based on inaccurate information	9	Comparison to NAC calculations	3	*54,00*	Designer and NAC calculation engineer together receives and reviews a new problem
Designer decides upon suitable simplifications	Designer makes unsuitable simplifications	4	Calculation model does not reflect reality	9	Analyses of results; Comparison to NAC calculations	3	*108,00*	Designer and NAC calculation engineer discusses different simplifications
	Designer does not make enough simplifications	4	Calculation model too complex, long calculation times	7	None until prototype and field testing	9	*252,00*	Designer and NAC calculation engineer discusses different simplifications
Designer builds calculation model	Designer makes mistake in building calculation model	5	Calculation model does not reflect reality	9	Analyses of results; Comparison to NAC calculations	2	*90,00*	Train designers to critically review calculation results.
Designer defines topology optimization goal and limitations	Designer makes mistake in building optimization model	3	Calculation model does not reflect reality	9	Analyses of results; Comparison to NAC calculations	2	*54,00*	Train designers to critically review calculation results.
Designer analyzes the topology optimization results	Designer misinterprets the optimization results	1	Rest of design process is not based on optimal design	7	Analyses of results; Comparison to NAC calculations	3	*21,00*	
Designer interprets topology optimization results and creates geometry	Designer misinterprets the optimization results	1	Geometry does not entirely reflect optimization results, greater gap for shape optimization to fill	4	Not being able to perform shape optimization	1	*4,00*	
Designer rebuilds calculation model based on topology optimization results	Designer makes mistake in building calculation model	3	Calculation model does not reflect reality	9	Analyses of results; Comparison to NAC calculations	2	*54,00*	Train designers to critically review calculation results.
Designer sets up mesh based shape optimization problem	Designer makes mistake in building optimization model	3	Optimization of geometry does not reach it's full potential	5	Analyses of results; Comparison to NAC calculations	4	*60,00*	Train designers to critically review calculation results.
Designer interprets mesh based shape optimization results and changes geometry	Designer misinterprets the optimization results	3	Geometry does not entirely reflect optimization results, greater gap for parameter based shape optimization to	4	Comparison to NAC calculations	3	*36,00*	
Designer rebuilds calculation model based on mesh based shape optimization results	Designer makes mistake in building calculation model	2	Calculation model does not reflect reality	9	Analyses of results; Comparison to NAC calculations	2	*36,00*	Train designers to critically review calculation results.
Designer sets up parameter based shape optimization problem	Designer makes mistake in defining parameters	3	Calculation results may not converge to an optimum	7	Analyses of results; Comparison to NAC calculations; Model might crash	1	*21,00*	
Designer sends geometry to NAC for confirmation calculations	Designer misses to inform NAC of the entire problem	2	The calculation process at NAC becomes based on inaccurate or inadequate information	9	None until prototype and field testing	9	*162,00*	Designer and NAC calculation engineer together receives and reviews a new problem
	NAC misinterprets the designer	2	The calculation process at NAC becomes based on inaccurate information	9	None until prototype and field testing	9	*162,00*	Designer and NAC calculation engineer together receives and reviews a new problem

Figure 30 - FMEA regarding overall methodology

5.3.4 Refined overall methodology

After the FMEA a new, refined, overall methodology proposal was constructed, see figure 31. It consists of the following points:

- *Problem definition*
  The designer analyzes the problem and decides upon simplifications, with the aid of a consulting calculation engineer.
- *Topology optimization*
  The designer would build a calculation model according to the defined problem, define the optimization parameters, analyze results and interpret them into a new geometry, with the help of a calculation engineer.
- *Shape optimization*
  Even though the geometry is interpreted from a topology optimization result, it does not mean that it is optimal. A shape optimization improves the design further. Based on the problem and geometry, the designer must decide between a mesh based and a parameter based shape optimization.
  - *Mesh based shape optimization*
    The designer builds the calculation model, sets up the optimization problem, runs optimization and interprets results into a new geometry, with the help of a calculation engineer.
  - *Parameter based shape optimization*
    The designer builds the calculation model, sets up the optimization problem and runs the optimization, with the help of a calculation engineer.
- *Confirming calculations in Catia*
  The designer performs a strength calculation in order to evaluate the geometry, with the help of a calculation engineer. Together, they evaluate if the geometry meets the set demands and also to evaluate if the geometry is optimal or if more mass can be reduced. If it meets the demands it is sent to NAC. If not, it is to be redesigned.
- *Confirming calculations at NAC*
  NAC performs final confirming calculations and evaluate if the geometry meets the demands and also to evaluate if the geometry is optimal or if more mass can be reduced. If it meets the demands it is to physical prototype testing. If not, it is to be redesigned.

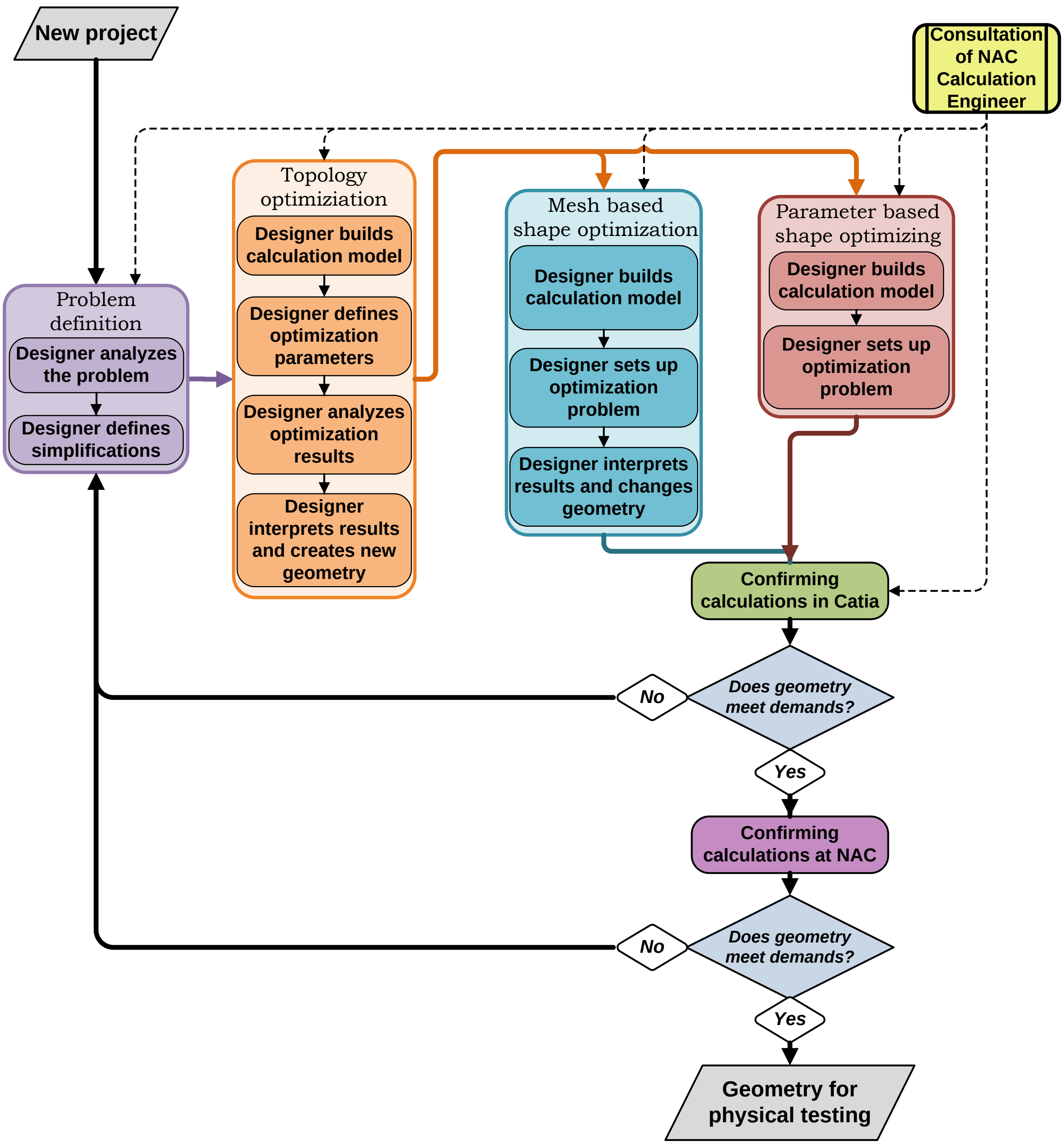


Figure 31 - Refined overall methodology proposal

Automation in the overall methodology

The macros created can be used for more than just strength calculations. The calculation models made by the macros can also be used in the optimization tools. The use of macros in the proposed overall methodology would be to quickly build models that later would be used in an optimization problem, see Figure 32.

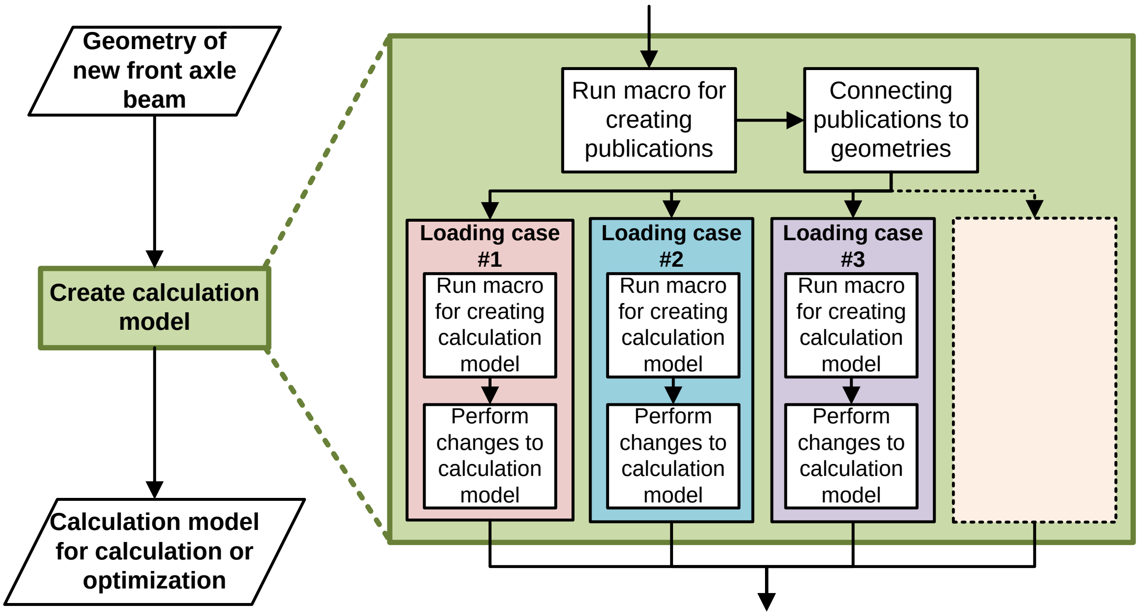


Figure 32 - The use of macros in the proposed overall methodology

6 Discussion and Conclusion

Here, the methods used and results are discussed and compared. Also, conclusions of the discussions are presented.

6.1 Regarding the methods used

The interviews were held with people that were most likely to adapt the new methodology and the people who showed the most interest. A questionnaire was sent out to all the affected actors, but only a handful of responses were received. The people responding were more or less the same people that were interviewed. Even though it resulted in a great amount of information, some information may still have been missed, by not getting information from every single one. With that being said, it was still concluded that the information gathered was sufficient to build a study upon, as a great many of both advantages and drawbacks was identified.

Just as with the interviews and questionnaires, the QFD and the FMEA was discussed and performed with a selection of the affected people. Even if the participants was considered sufficient for the information gathering, the outcome of the QFD and FMEA might have been slightly affected by the narrow selection. Especially people more skeptic to the new tools might have had a different input that would have changed the outcomes.

It was considered that more information only would change the conclusions and results from the performed QFD and FMEA marginally, and that the information gathered was sufficient for this project. However, for future evaluation and development of the methodology it would be appropriate to perform a more extensive information gathering, with focus groups and maybe employ tools such as the SWOT analysis.

6.2 Regarding calculation model and convergence study

The results was very similar to the ones from NAC, and the margin of error became smaller when the element sizes decreased. The convergence study was performed with one condition being that the calculations would be done locally. If, however, it would be done on a more powerful batch server, and a new convergence study would be done, the results would be better. Much smaller element sizes could be set, and the calculations would be much more reliable and closer to the ones made by NAC. That would make FEM calculations as a much more obvious choice for the designers, and might persuade even the most sceptic ones.

The conclusion is simple: The results of the convergence study was the best that could be obtained at the given situation. If a batch server solution would be used, better results would be had, and the designer would be more likely to perform the calculations.

6.3 Regarding optimization results

When the optimization models first was calculated, it became obvious that the if the desktop computers performance was limiting for simple FEM calculations, it was nowhere near the performance needed for optimization. Therefore very simple optimization examples were used, as a batch server solution could not be used. However, if the optimizations had been done using a server solution, different results may have been had and different conclusions may had been drawn.

Topology optimization in HyperShape/Catia

For the bridge, the results quickly converged to the ones from NAC. Even though some differences was shown for the bracket loading case, the differences decreased with the element size. It showed that the tool would bring satisfactory results, if the model was detailed enough. Hence, the limitations identified was regarding the specific computer's performance and not the tool or the method. The HyperShape/Catia tool was very easy to use, and should not be an obstacle for the designer.

Mesh based shape optimization in HyperShape/Catia

For the bridge, the results quickly converged to the ones from NAC. Some problems were had regarding distorted mesh due to the big geometrical change from the original geometry. The issue is due to the method rather than the actual tool. The same goes for the bracket example. Both the optimizations from HyperShape and the one from NAC resulted in a distorted mesh, due to the big geometrical change. The conclusion was drawn that the HyperShape/CATIA is a reliable tool, and that the limitations regarding big geometrical changes was a problem with the method itself, and not the tools.

Parameter based shape optimization in Catia PEO

The parameter based shape optimizations did not have problems regarding big geometrical changes. The problems were rather regarding what parameters that would be changed, i.e. the problem definition. For the bridge example, it was difficult to identify what parameters were to be set as variables. Either there was hardly any mass change, or the results did not make any sense, see table 8.

However, the parameter based shape optimization was the only method that made a significant reduction of material for the bracket example. No mesh could be distorted, but there was still a limitation in how much the geometry could change: the parameterization of the geometry. This has an advantage and a drawback. The advantage is that the parameterization could be set so interfaces are not affected and manufacturing constraints are considered. The drawback is that the truly optimal solution can be very hard to find. This is the reason that the results from PEO differed so much form the ones from HyperShape/Catia and OptiStruct.

Hence, parameter based shape optimization in Catia PEO also is a powerful tool, if the problem is set up correctly. It gives the user the ability to better control what parameters to change, and how the geometry can change. However, the choices regarding the parameters can also restrain the tool, and blocking the path to an even more optimal solution. Also, instead of one optimal solution being generated, the user is presented with a list of different design proposals. One of these proposals must be chosen. It therefore requires a lot of the user. Therefore it cannot be considered as easy to use, and that may become discouraged not use the tool.

6.4 Regarding overall methodology

Since all of the structural optimization methods and tools were found to have specific advantages and drawbacks, not one of them could be ruled out. The QFD showed this as well. All of them should in one way or the other be included in the final methodology.

When the overall methodology proposal was constructed it was assumed that a batch server solution would be used, allowing the user to employ all of the tools without restraints.

The methodology has only been constructed and refined using a theoretical basis, with tools as QFD and FMEA. When actually testing the methodology, it will probably be refined and developed further. The methodology proposed is therefore not a suggestion for how to conduct product development, but rather a first step in a longer development process.

6.5 Connecting to the purpose of the thesis

The purpose of was to investigate how simulation driven design could reduce the lead time of the design process. It can be argued that the proposed methodology makes a foundation for reducing the lead time, but without actually testing the methodology we cannot know. As mentioned in chapter 1.1 Background, the Aberdeen group has found a correlation between implementing simulation driven design and and reducing development cost and development time, but whether it is true for this methodology and Scania, we cannot say.

Apart from the reduction of lead time, the thesis also aimed to find the answer of the following set of questions:

- Can calculations be done using Catia V5?
    - *Are they reliable*
    - *What calculation models would be used?*
    - *Can the calculations be done locally?*

      Answer: Yes, calculations can be done, and suitable calculation models were found. Calculations are somewhat reliable if they are done locally, but if they were to be done using a batch server solution, the calculations could be made even more reliable.
- Can optimizations be done in Catia?
    - *Are they reliable*
    - *Can the optimizations be done locally?*

      Answer: Yes, optimizations can be done in Catia. However, it requires an experienced user to determine what tool to use, and an even more experienced user to use the Catia PEO tool. The optimizations cannot be done locally, if reliable results are to be returned.
- If calculations and optimizations can be done in Catia, HOW would they be used?
    - *Can a methodology be constructed?*

      Answer: A methodology has been constructed, that in theory utilise the tools and method in such a way that the lead time of the design process is reduced. However, evaluation and further development is needed, see chapter 7 Recommendations.

It was argued in chapter 1.1 Background, that the problems at NA had affects throughout the organization. As discussed, it cannot be said that the proposed methodology actually solves these problems, but conclusions can be drawn on the assumption that it would.

If the designer do calculations and optimizations, she would get better and faster feedback and gain an understanding regarding the calculation process and strength of materials. The calculation engineers could focus on more challenging tasks and develop their competence. It would be a better utilization of the competence locked in the engineers. The testing of components would be unaffected, but the need for physical testing would decrease as fewer design solutions are tested. Therefore, the problems at the testing level would not affect the organization as much.

This would decrease the total lead time of the R&D process, and make it more efficient as fewer redesigns are needed. The organization as a whole would produce products with higher quality, have more satisfied customers and gain goodwill, see figure 33.

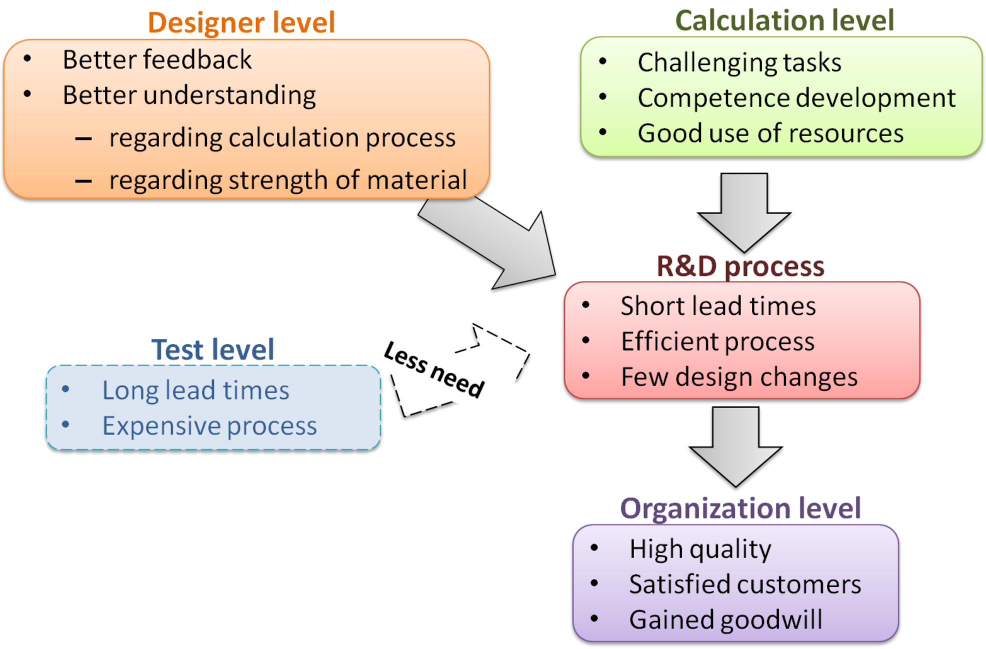


Figure 33 - The solved problem throughout the organization

7 Recommendations

Here follows recommendations for further evaluation and investigations. It includes areas deliberately delimitated from this project as well as predicted areas of interest.

As the proposed methodology needs further refinement, it is recommended to use it for a pilot project for future investigations and evaluations. During this pilot project, the proposed methodology and tools are to be used for the development of a new component. The experiences from the pilot project would form a basis for future development of the methodology.

During the evaluation, the tools and methods have been used on a desktop computer. This means that all files were saved locally, and all calculations and optimizations have been done locally.

During a product development project at Scania, a PDM system is used. Thus, for a pilot project to be made and a correct evaluation to be possible, the tools must be integrated with Scania’s PDM system. The macros designed are made to work locally, and they have to be adapted in order to work with the PDM system.

Even though already part of the Catia portfolio, Scania does not have a batch server solution for PEO. Neither does one exist at Scania for HyperShape/CATIA. This must exist in order for a pilot project to take place.

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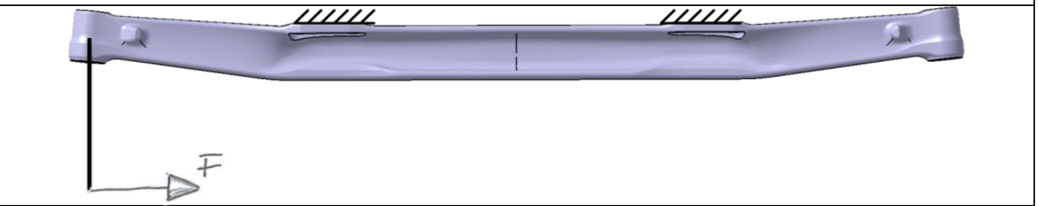
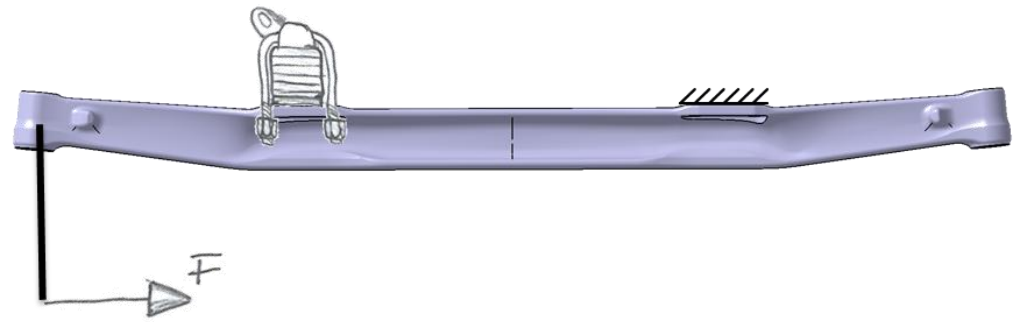
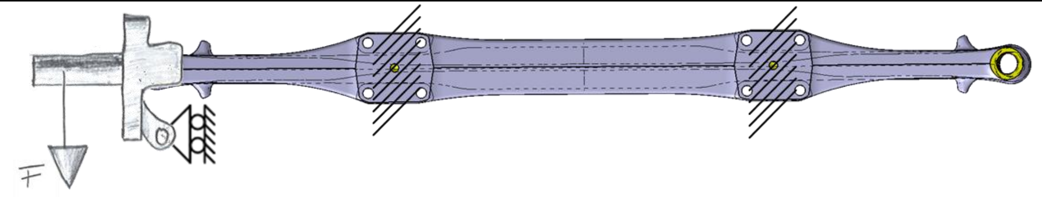
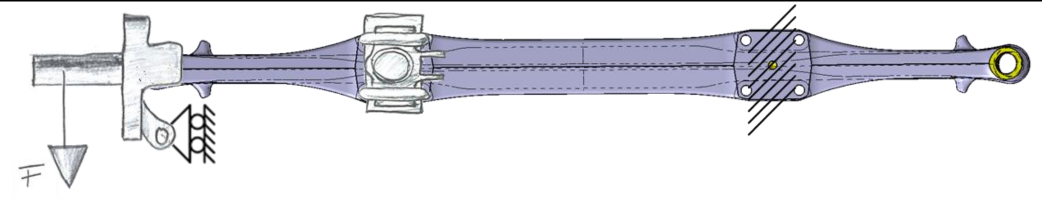
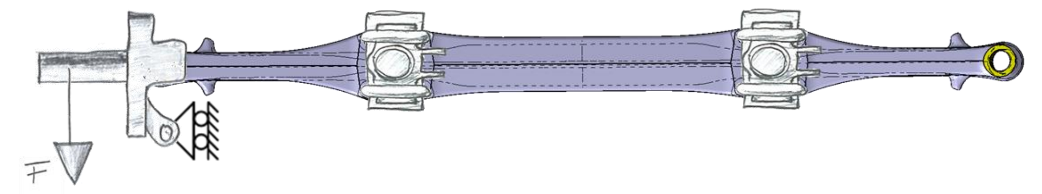
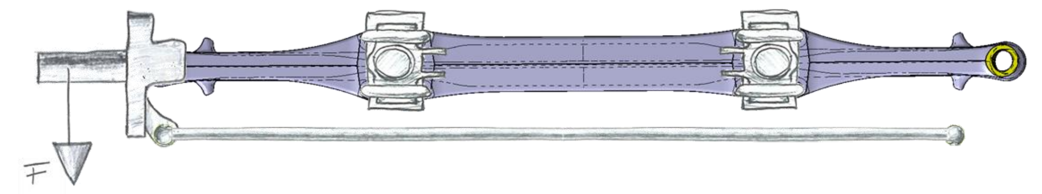
Appendix: Calculation models for loading cases

Here follow representations of the different calculation models that was made.

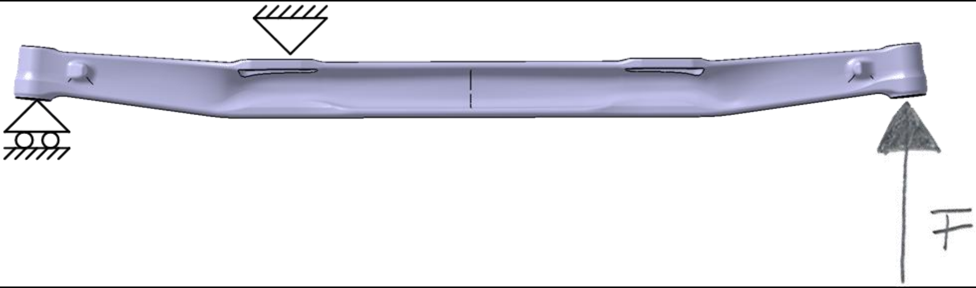
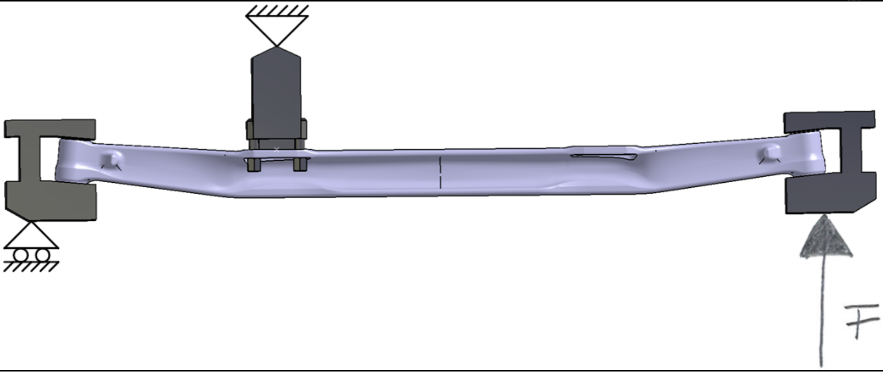
For the side loading case, two models where made:

Complexity	*Model*
Very simple (Chosen)	
Somewhat simple	

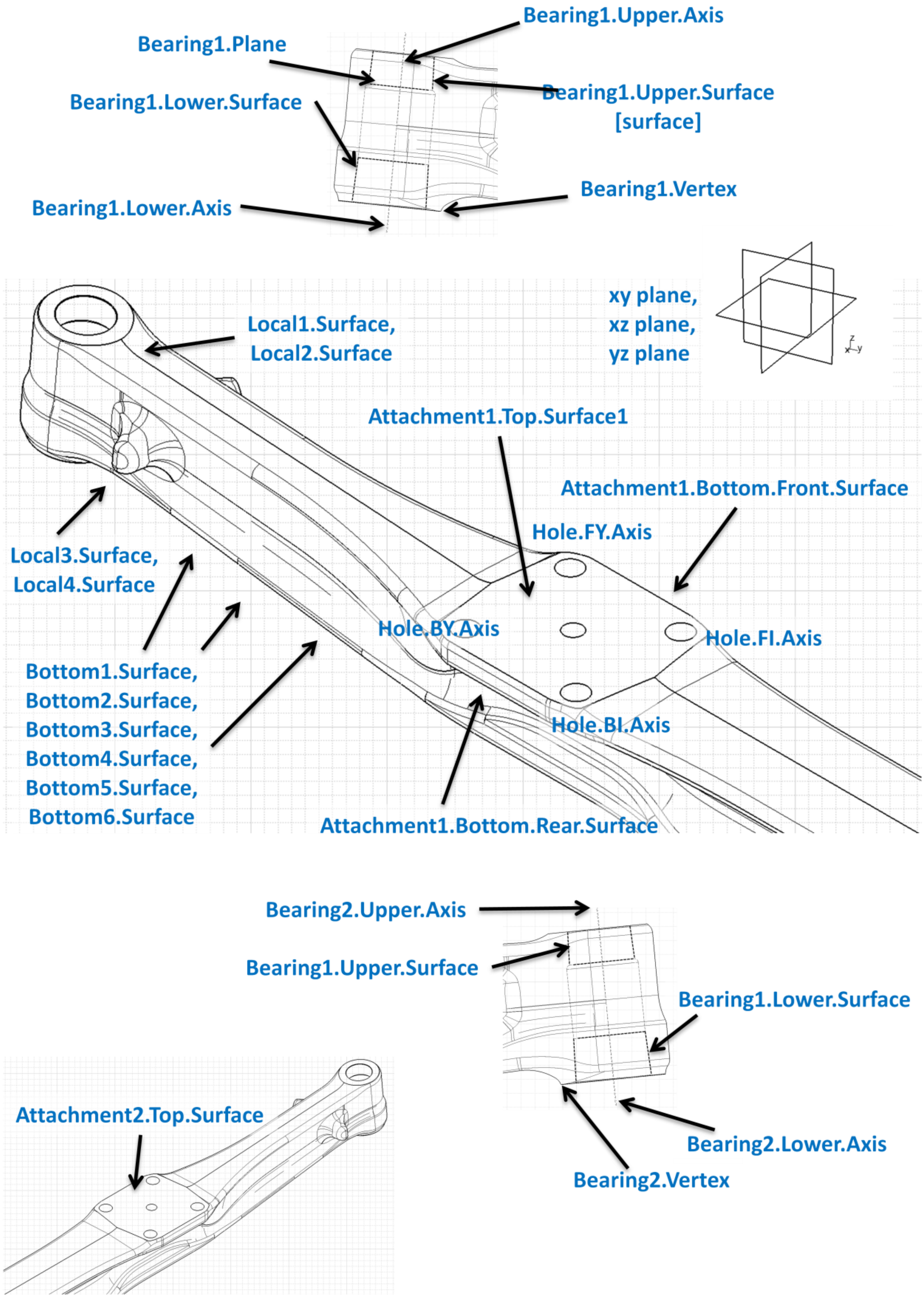
For the braking load case, four models was made

Complexity	*Model*
Very simple	
Somewhat simple (Chosen)	
Somewhat complex	
Very complex	

For the pulsating wheel force load case, two models were made

Complexity	***Model***
Very simple	
Somewhat simple (Chosen)	

Appendix: Publications



Appendix: FMEA regarding overall method

	Process step	Failure Mode	Probability of failure	Effect	Severity	Control	Probability of detection	*Linear Risk Number*	Recommended action taken
1	**Designer receives, interprets and analyzes information regarding the problem**	Designer misinterprets problem	2	Design process becomes based on inaccurate information	9	Comparison to NAC calculations	3	*54,00*	Designer and NAC calculation engineer together receives and reviews a new problem
		Designer misses information	2	Design process becomes based on inaccurate information	9	Comparison to NAC calculations	3	*54,00*	Designer and NAC calculation engineer together receives and reviews a new problem
		Designer is misinformed	2	Design process becomes based on inaccurate information	9	Comparison to NAC calculations	3	*54,00*	Designer and NAC calculation engineer together receives and reviews a new problem
2	**Designer decides upon suitable simplifications**	Designer makes unsuitable simplifications	4	Calculation model does not reflect reality	9	Analyses of results; Comparison to NAC calculations	3	*108,00*	Designer and NAC calculation engineer discusses different simplifications
		Designer does not make enough simplifications	4	Calculation model too complex, long calculation times	7	None until prototype and field testing	9	*252,00*	Designer and NAC calculation engineer discusses different simplifications
3	**Designer builds calculation model**	Designer makes mistake in building calculation model	5	Calculation model does not reflect reality	9	Analyses of results; Comparison to NAC calculations	2	*90,00*	Train designers to critically review calculation results.
4	**Designer defines topology optimization goal and limitations**	Designer makes mistake in building optimization model	3	Calculation model does not reflect reality	9	Analyses of results; Comparison to NAC calculations	2	*54,00*	Train designers to critically review calculation results.
5	**Designer analyzes the topology optimization results**	Designer misinterprets the optimization results	1	Rest of design process is not based on optimal design	7	Analyses of results; Comparison to NAC calculations	3	*21,00*	
6	**Designer interprets topology optimization results and creates geometry**	Designer misinterprets the optimization results	1	Geometry does not entirely reflect optimization results, greater gap for shape optimization to fill	4	Not being able to perform shape optimization	1	*4,00*	
7	**Designer rebuilds calculation model based on topology optimization results**	Designer makes mistake in building calculation model	3	Calculation model does not reflect reality	9	Analyses of results; Comparison to NAC calculations	2	*54,00*	Train designers to critically review calculation results.
8	**Designer sets up mesh based shape optimization problem**	Designer makes mistake in building optimization model	3	Optimization of geometry does not reach it's full potential	5	Analyses of results; Comparison to NAC calculations	4	*60,00*	Train designers to critically review calculation results.
9	**Designer interprets mesh based shape optimization results and changes geometry**	Designer misinterprets the optimization results	3	Geometry does not entirely reflect optimization results, greater gap for parameter based shape optimization to	4	Comparison to NAC calculations	3	*36,00*	
10	**Designer rebuilds calculation model based on mesh based shape optimization results**	Designer makes mistake in building calculation model	2	Calculation model does not reflect reality	9	Analyses of results; Comparison to NAC calculations	2	*36,00*	Train designers to critically review calculation results.
11	**Designer sets up parameter based shape optimization problem**	Designer makes mistake in defining parameters	3	Calculation results may not converge to an optimum	7	Analyses of results; Comparison to NAC calculations; Model might crash	1	*21,00*	
12	**Designer sends geometry to NAC for confirmation calculations**	Designer misses to inform NAC of the entire problem	2	The calculation process at NAC becomes based on inaccurate or inadequate information	9	None until prototype and field testing	9	*162,00*	Designer and NAC calculation engineer together receives and reviews a new problem
		NAC misinterprets the designer	2	The calculation process at NAC becomes based on inaccurate information	9	None until prototype and field testing	9	*162,00*	Designer and NAC calculation engineer together receives and reviews a new problem