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Master Thesis

Geometric module library for conceptual product development

Reducing Complexity and Increase Product Understanding in order to enable Geometrical Design Space exploration during early concept development

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Product Development
Chalmers University of Technology
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Abstract

The geometrical design space represents the set of all possible design alternatives for a product. Therefore, when creating new design alternatives for an existing product, a high design freedom within the design space is desired in order to explore as many solutions as possible.

Unfortunately, current practices restrict developers to optimization work due to rigidity in the existing CAD models, uncertainties on the performance and time and resource constraints.

The knowledge gathered during the exploration of the problem is used to identify requirements and create a framework for a Library System that solves the existing issues. The framework is presented through a User Perspective flowchart. The flowchart describes the required actions in both the preparation work (setting up the Library System structure and the CAD-model setup) as well as the activities during usage of the system. As a final part of the project a Proof-Of-Concept is created through a demonstration of the activities in the proposed Library System which are applied on a Case Product.

The resulting Library System solution consists of flexible CAD-models that increases the Design Space Freedom and presents a structured storage for the developers. The presented Library System introduces an approach where complexity is reduced by using a controllable geometrical design space exploration through use of hybrid modelling techniques during the early concept development process. The created Library System allows the Users to increase the knowledge about the new novel design alternatives (through collecting data using virtual testing on the performance) and in parallel allowing the users to create new design alternatives based on the new knowledge.

Finally, a comparison versus the current state of art and the proposed Library system implies that the potential impact of the created solution, if realized, can result in a higher productivity for developers as well as a platform that allows for reuse.

As a conclusion the created work of this thesis can be seen as a baseline for solving an existing problem in the industry that has not yet been addressed. Further development, in order to realize the Library System is needed, but the initial feedback and results of the demonstration showcases great potential and therefore creating an incentive for continuing the research on this topic.

Key words: Design Space Exploration, Parametric Modelling, Synchronous Modelling, Direct Modelling CAD, CAE, PLM, SBCE, Complexity Management, Early Concept Development.

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Mikael Mousavi

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1. Introduction

The generation of concepts begins with collecting requirements in the form of customer needs and specifications (Ulrich and Eppinger, 2012). These needs and requirements can vary (e.g. minimum length, maximum width etc acting as design parameters) during or after the development process. The reasons for this being e.g. new competitive products that are better have been introduced or new technologies that make a product obsolete have been developed. The first step is to analyse and find the requirements. As explained by Grady (2016), performing a requirement analysis can be very challenging, therefore it is important to break down the requirements to really understand the core for why they exist. The identification of the needs and requirements ultimately creates the boundaries for which the new developed concepts must follow. The aim of the development is to be able to explore as many concepts as possible in order to find the best performing solution (Ulrich and Eppinger, 2012).

This Master's thesis project has been performed at the department of Industrial and Materials Development at Chalmers University of Technology as an exploratory research to explore how a solution, that enables product developers to increase their design freedom when creating new concepts during the early concept development process, could be realized.

1.1. Background

Even though there are many benefits of CAD modelling such as the possibility to virtually illustrate a product and using CAD models for virtual tests, there are some challenges with CAD software regarding the design space exploration when creating concepts. A recognized challenge is that the created CAD models used in today's industry practice are too rigid (Heikkinen et al, 2018). To explain the rigidity of CAD models further imaging the scenario where some time has passed since the development of a product. The new objective is to explore a new design alternative for the same product with the same requirements. Time and resources are of course of importance and therefore naturally the ability to reuse the previous existing CAD model as much as possible is sought for. Unfortunately, the CAD model is too rigid for geometrical change, and in order to actually reuse the existing CAD model and not start completely from scratch (requiring a lot of time and costly operations) the only available alternative is to not derive from the already existing design (Eckert and Jankovic*,* 2016). And even if the development is started from scratch and a lot of time and resources are allocated, there are no guaranties that the new design alternative is going to perform better than the already existing solution.

Therefore, the consequence of this problem is that product developers are restricted to create conservative concepts that resembles the existing solutions design. This due to both a lack of knowledge on how the novel concept would compare against the already working existing design alternative and the limitations of resources and time. This restricts the exploration of novel concepts, and by doing so the possible value gained of new geometrical design alternatives are lost (Eckert and Jankovic*,* 2016).

1.2. Problem Definition and Aim

The problem is that product developers experience a low design space freedom when exploring new concepts. This is partly due to existing CAD models being too rigid, therefore forcing developers to abandon novel concept solutions because of cost and time restraints.

Aim: The aim of this project is to enable the exploration of design alternatives during the early concept development phase within a CAD environment, this through describing a Library System consisting of flexible CAD-models that increases the Design Space Freedom for the product developers.

1.3. Research Question

As a continuation of the determined deliverables and aim of the project, two research questions are formulated in order to both guide the data collection and problem-solving activities.

RQ1:
What are the needs of a product developer during early concept development in order to enable exploration of different geometries in a CAD environment, thereby improving the design freedom?
RQ2:
What is a possible solution for increasing the design freedom for a product developer during early concept development within the CAD environment?

1.4. Delimitations

In order to answer the problem, it is valuable to narrow the scope and to realize that there will be certain areas that will not be explored in this project. It is important to point out that this is an explorative thesis work where the aim is to understand the problems and gather insights that can be used as a basis for further research. The following limitations are set within three areas:

The work effort expected for this master's thesis work is equivalent to 20 weeks full-time studies. Therefore, the result of the thesis is adapted to deliverables that can be reached during this short timeframe.

The method will be limited to research in specifically the concept development processes in the product development process. The data collection will be conducted through literature research and interviews with practitioners within the aircraft engine manufacturing field.

In order to set a realistic outcome of the master's thesis work the result of the project is limited in creating a proof of concept as a demonstration of a library system. The library system will be consisting of flexible CAD models which are used when creating new geometrical design alternative concepts for a product. The proof of concept will act as a demonstrator using a case product for the creation of CAD models and mock-ups for the illustration of the library system.

1.5. Ethical Statement

The master thesis project is aimed as an exploratory research where the rigidness of CAD Models is explored. The project is conducted by collecting data and translating them into requirements for a library system before developing the proposed approach through a demonstration on a case product. Collecting data anonymously can raise ethical concerns about how the opinions from the interviewee translates to the validity of the collected information. The choice of a library system as a solution is made due to the extensive use of database solutions in the industry.

The implementation of a new Library systems affects primarily the users, which are the product developers, and the companies that use the proposed solution.

For product developers an implementation of the solution could potentially create a new working environment that can be unusual and for the company the implementation could result in implementation of new development processes.

The outcome of this master thesis project is a demonstration which illustrates the potential impact of implementing the proposed Library System. The demonstration can be valuable in research aspects but may not present any value for the practitioners and company at the given time. However, if further developed is conducted, a realization of the proposed library system could positively affect the users and the company.

For the user the potential impact of the outcome is increased value adding work as repetitive and unnecessary rework activities are eliminated. This can result in better performances from the product developer as well as it increases the design freedom creativeness during work.

For the company the potential impact is better allocation and distribution of resources such as time, cost and personnel as well as potential increased value of developed products.

If unnecessary rework activities are eliminated the reduced time of the development process, when creating new concepts, results in cost savings. The possibility to develop more valuable concepts in a time and cost-efficient approach can result in an economically beneficial outcome for the company.

One argument for why this project should not be implemented is that it is not directly benefiting the society. As time and resources is of value there are other more urgent problems that can be explored. However, there are a few flaws with this argument.

Another argument is if the owners of the library system misuse it to design hazardous products. However, it is impossible to control how the owner will use the system and therefore the argument is flawed as it is impossible to know the unknowns of the future use of the system.

In order to conduct good applicable research, there is a need that a basic exploratory research has been conducted in order to serve as a guidance for future project.

Another counter argument is that one of the fundamental values of research is that a researcher should be able to explore areas that are of interest for them and where there is a gap of research.

And thirdly, it is difficult to evaluate the impact of a research on the society as the future is unknown.

2. Theoretical Framework

In the following chapter the theories used in this master's Thesis Project are presented. The theories are divided into three sections (see Figure 1): Product Development, CAE Technologies and Product Architecture.

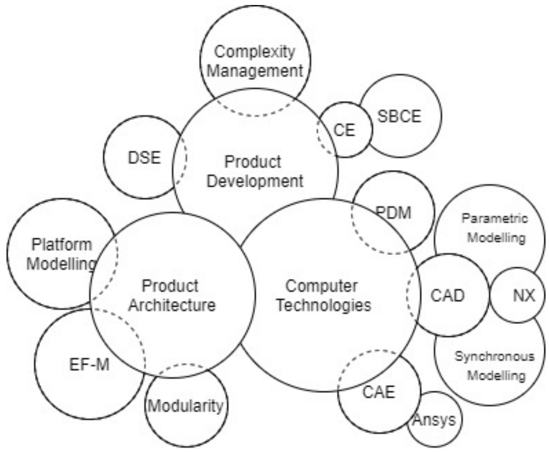

Figure 1 Overview of the theory in the Theoretical Framework

2.1. Product Development

Pahl and Beitz (2007) and Ulrich and Eppinger (2012) share the common perception that the PDP needs to follow a systematic approach in order to develop products. The systematic approaches are presented through frameworks with defined phases and activities that act as a tool to guide the team through the PDP. The framework is referred to as generic product development processes, see Figure 2 for the proposed generic PDP by Ulrich and Eppinger (2012).

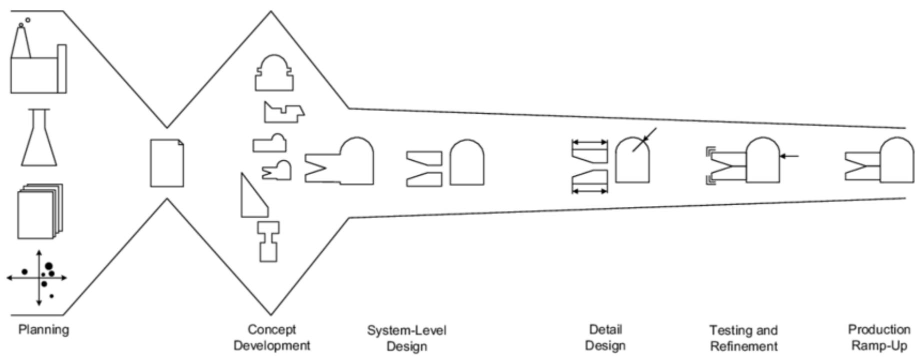

Figure 2 The generic product development process proposed by (Ulrich and Eppinger, 2016)

As can be seen in Figure 2, the proposed PDP consists of six major activities. The first stage is the planning activity where the intended results of the project are clarified, the needs are captured, and the current state of art identified in order to decompose the existing problems.

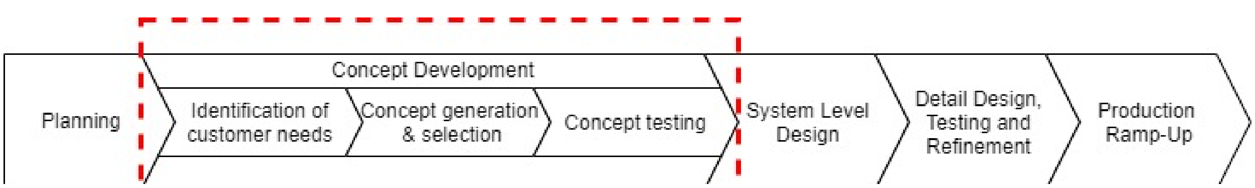

Figure 3 Highlighted concept development phase from the proposed generic framework by (Ulrich and Eppinger, 2016)

Following this, a concept development phase is initialized. The aim is to create a wide variety of candidate concepts, that fulfil the needs and requirements which were identified in the beginning of the project (Ulrich and Eppinger, 2012).

This Master thesis work is primarily revolved around the concept development phase, see Figure 3. The main activities of the concept development phase are identifying critical information such as needs, functions, requirements. As this has been done the goal is to translate these into candidate concepts through various ideas, and create illustrative demonstrators e.g. prototypes. The concepts are then screened, iterated and validated to assure that the strongest candidates can progress to the next stages of the development process (Ulrich and Eppinger, 2012).

2.1.1. Design Space Exploration in early concept development - Design Paradox Graph

The Design Paradox can be seen in Figure 4. Whereas the design freedom is high, the knowledge of the product is low. As time progresses the design freedom is lowered due to activities and processes. This Paradox results in that the early decisions made in the development process tightly constraints the future choices (Fernandez et al, 2002). As can also be seen in Figure 4, even before reaching the Concept Development Process, the design freedom has decreased and at the detailed development stage the room for changing the design is slim.

The design space is defined as all the possible different design alternatives within a system and Design Space Exploration is the exploration of the variants within the Design Space (Saxena and Karsai, 2010). The constraints of a product create the boundaries for the Design Space but even with the boundaries, the possible sets of design alternatives remain nearly infinite (Woodbury and Burrow, 2006).

The actual considered design solutions within the Design Space during the development process is called the Search Space (Woodbury and Burrow, 2006). The Search Space is limited by these early decisions. Therefore, by decreasing the impact of decisions in the early concept development a broader Search Space, increasing the design freedom, can be explored.

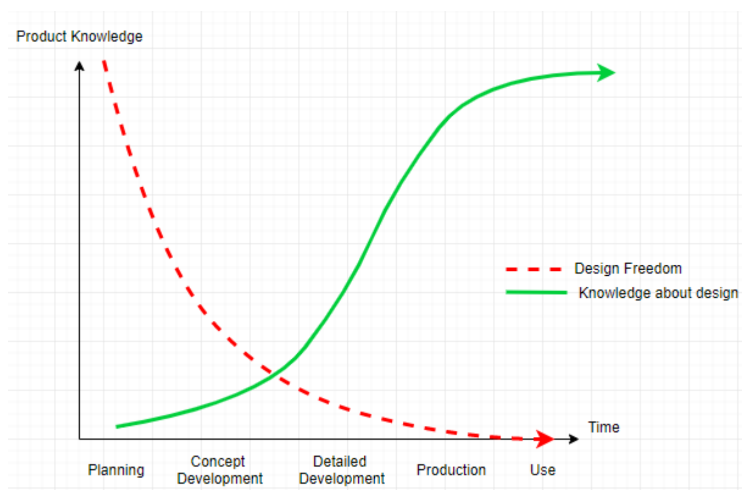

Figure 4 The Design Paradox

2.1.2. SBCE

Set-Based Concurrent Engineering (SBCE) is a descent from the CE approach. The concurrent engineering (CE) approach introduced a parallel product development process (PDP) rather than the sequential (Moustapha, 2003). The major difference between SBCE and other traditional approaches and CE is that a quick determination on a single solution is not made. In the traditional approaches and CE the quickly chosen solution is modified and adapted throughout the development process until it satisfies the set requirements and objectives of the design (Sobek, 1999). Sobek (1999) argues that even though this may seem as an effective approach it may result in not satisfactory results. “All eggs in one basket” is the best metaphor to explain Sobek’s (1999) reasoning behind the argument. If the chosen concept is faulty, there is a need to refine the solution which can be a very time-consuming and costly operation.

The way that the SBCE approach eliminates this risk is by presenting an approach where it early on does not eliminate solutions. The method rather creates a broad variety of solutions that gradually are narrowed down based on new information emerging. By using this funnel thinking it becomes more likely that the best solution will be found (Sobek, 1999). Raudberget (2010) explains the SBCE as a stepwise methodology (see Figure 5) where a solution is only eliminated if there is enough information that confidently can exclude it. Raudberget (2010) further explains that the SBCE approach is reliant on three principles:

1. **Mapping the design space** By mapping the design space, it becomes possible to create a broad search of potential solutions.
2. **Integrating by intersection** By integrating various solutions to a main body, it becomes possible to eliminate those that are incompatible.
3. **Establishing the feasibility before commitment** By establishing the feasibility of solutions through further development of solutions that fulfil the set goals, it becomes possible to narrow down the funnel. Elimination of concepts are proceeded through iterations where the requirements are more detailed and specified.

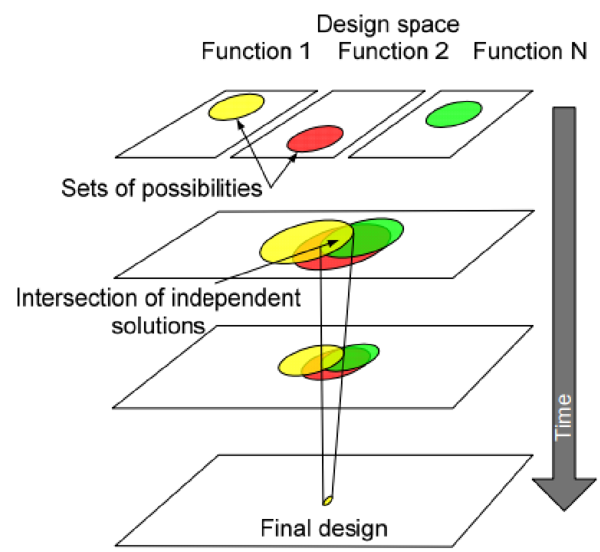

Figure 5 The three principles of SBCE illustrated by Raudberget (2010)

2.1.3. Complexity Management in PDP

The problem of complexity in product design is describe by Lindemann (2009) as *“the lack of ability of users to control complexity…”*. Therefore, by improving the control of complexity it becomes possible to reduce the problems and enhance the development possibilities in the development process (Lindemann, 2009).

By exploring and implementing Complexity Management thinking to the solution, it is possible to create a foundation of a library-system where both the workflow structure and activities rather support then hinder the designer’s decisions in the concept creation stage. This enables the designer’s ability to effectively explore the design space using geometry models in a CAD environment.

In order to be able to manage the complexity in the development process Lindemann (2009) breaks the driver down as *"the four main fields of complexity in product design"*. These four fields are: the market complexity, the product complexity, process complexity and the organizational complexity.

The complexities in the PDP are divided into external (Market) and internal (Product, Process and organization).

Market Complexity Lindemann (2009) describes the current general market situation as an environment where the effects of Globalization have become a major reason for why market complexity has increased. This trend has created an increase in product variants which in turn has increased the complexity and created new challenges for manufacturers (Lindemann, 2009).

Product Complexity One obvious challenge regarding the product complexity is the product structure (from now on referred to as product architecture (see chapter 2.3) (Lindemann, 2009).

The optimization of a product architecture can lead to a reduced product complexity (Lindemann, 2009) (Baldwin & Clark, 2000). One of the more applied approaches for this is through modular product design development. There are several different methods to create a modular design. The key objective is to create subsystems or "chunks" of the product which are independent of other chunks but at the same time keeping a high internal linkage. This, resulting in that a specific chunk can be redesigned or replaced without affecting the structural integrity of the whole system/product (Baldwin & Clark, 2000).

To enable the possibility of product development flexibility a comprehensive knowledge of the connectivity of product parts/sub-systems is needed. Therefore, this means complete knowledge of the dependencies between parts/sub-systems at an early stage in the development process, which is difficult to achieve (Lindemann, 2009).

Process Complexity A driver of process complexity is the difficult time restrictions. The development process needs to be fast and efficient, all this while maintaining the quality of the outcome. This has increased the use of concurrent engineering approaches at companies. The challenges of frequent changes of requirements and demands in collaboration with restraints as financial necessities, creates an environment where companies not only compete on the finalized product, but also on the optimal development process (Lindemann, 2009).

The development process consists of various collaborations between e.g. divisions and tools. The process complexity can be reduced if the understanding of the product is increased. There becomes a direct linkage that by clarifying the working object/product, the surrounding process can be optimized through the gathered insights from previous steps (Lindemann, 2009).

Organizational Complexity The number of disciplines involved when developing a product creates highly entwined processes that are performed by various numbers of cooperating organizational teams (Lindemann, 2009). Therefore, resulting in an environment that is extremely information driven. This information is spread across all the involved teams and if not managed properly, uncertainty can rise about if certain information is reliable (Lindemann, 2009). Lundin (2015) explains that in some cases the information does actually exist, but the developers do not have the knowledge or authority to access it which results in developers working with incomplete information.

The key issue is the creation of an efficient information flow between the whole organization. When a developer wants to create a new solution, he or she is highly dependent on the quality of information. If the information at hand is difficult to interpret or difficult to find, the ability to re-use already existing material vanishes. It becomes much easier for the developer to start over (Lundin, 2015).

2.2. CAE Technologies

In this section the theory regarding the computer technologies that are of relevance to the results of this project are presented.

2.2.1. CAD

Up until the 1990s the method to create and visualize new designs was creating drawings often by using computer programs. The new method to 3D computer-aided design models (3D CAD models) was first implemented in the beginning of 1990s. By combining solid blocks, cylinders and other geometries the 3D CAD models became a tool to represent designs. (Ulrich and Eppinger, 2012)

The reasoning for implementing this new tool to represent the designs where mainly due to the many advantages of 3D CAD models. Not only did it become possible to easily visualize how a certain concept looked in three-dimensions, the computational 3D environment allowed for the creation of photo-realistic images for assessment purposes. The method was also able to calculate the specific volume and mass for each design instantaneously and through cross-section views the drawings and details of the concept could be extracted. (Ulrich and Eppinger, 2012)

If the engineers decide to create detailed 3D CAD models assemblies with well-defined interfaces to all related sub-systems, in some cases, a full-scaled prototype of the concept can be eliminated. (Ulrich and Eppinger, 2012).

2.2.1.1. NX 12

The CAD-modelling system NX 12 was released by Siemens and is an integrated and advanced product development solution. One of the main strengths of the NX software is its powerful capabilities regarding to hybrid modelling where both constraint-based features and geometric modelling are integrated (Siemens, 2020).

Siemens NX 12 was chosen as the primary CAD system for the master’s thesis project, but it is worth mentioning that it is only one of several commercial CAD systems at it is possible to use other CAD software such as Catia, Solidworks, PTC etc.

2.2.2. Parametric CAD

At the early stages of the CAD modelling introduction, designers expressed resistance to the method due to the lack of possibilities to create variations. Shah (Shah, 2001) explains that only after the introduction of parametric based CAD models the designers started to accept the method.

As Cheng and Ma (2017) explain, the critical capability of the parametric CAD technique, is derived from the possibility to simpler integrate different quantitative knowledge surrounding the design into the model. Specific dimensions of the product model are controlled by a set of parameters and since these dimensions are the pillars of the product design, the models shape can be modified if the parameters have been applied properly (Shah, 2001). The underlying technology of using parametric models to implement variety is based on using constraints/parameters.

The parameters in a geometric model are the results of synchronized equations based on either an algebraic expression, dimension or geometry. By applying parameters, between two elements in the CAD model, if applied properly the variation can be created when the value of the algebraic expression is changed which results in a quick alteration of the CAD model while maintaining the structural integrity (Camba *et al,* 2016).

The three main benefits of parametric CAD modelling as presented by Shah (2001) are the ability to automatically change the propagation, the ability to re-use geometry and the ability to embody the design/manufacturing knowledge with geometry.

Shah (2001) further explains that the three mentioned benefits do not occur in all the techniques available for parametric modelling.

There is a need to understand the connection between the functional and physical aspects of a part in order to create an effective parametric CAD model. Only after this is done the appropriate structure and parameters can be implemented to the CAD model (Camba *et al*, 2016).

2.2.3. Synchronous Modelling and Subtraction Modelling

Subtraction Modelling The subtraction operation is a feature operation and as it implies it subtracts from created form features. The subtractions used to create threads, smoothen corners and create holes. The subtraction is a Boolean Operation and can be used when two or more solid bodies are sharing the same modelling space in the created part file (Ming et al, 2017).

When using the subtraction tool, a tool body and a target body is determined on the sketches representing the solid body. The sketch assigned as the tool body creates the subtraction on the target body. The depth of the subtraction is determined by the user (Ming et al, 2017).

Synchronous Modelling One of the features that is supported by using the NX software (see chapter 2.2.1.1) for developing CAD models is the Synchronous Modelling Technology. The Synchronous Technology allows the users to modify complex 3D model geometries through easy operations through the software. The altered geometry of the CAD model is created without a modelling history meaning that the user can manipulate the geometry without tracking the feature relationships and dependencies (Ming et al, 2017). The basics of the Synchronous Technology is that the user manipulates the geometry by "push-and-pull" actions on edges, faces and cross-sections (Ming et al, 2017).

Parametric versus Direct modelling Traditional parametric modelling techniques strictly follows a methodology where the created bodies are created through initial 2D sketches that are controlled trough e.g. algebraic expressions. A major difference by using a direct modelling approach is to allow the developer to experience more freedom than the traditional rigid method. This is done by simplifying the alteration of 3D models and therefore create an experience where 3D alterations are as easy as 2D modifications. Therefore, compared to traditional parametric modelling techniques a more direct modelling approach increases the flexibility and speed as well as simplifies the usage (Wang et al 2015).

Another difference between parametric and direct modelling is related to the time to alter geometrical variations. Even though parametric modelling presents a history which allows for the ability to change previous actions, these changes becomes difficult to identify if a developer is unaware how the initial parametric model was built. In those cases when a model is changed over a longer period of time with many involved parties a non-historic based direct modelling approach, where alterations can be made quickly, could increase the flexibility of alterations and reduce the time-consuming activities of understanding previously created parametric CAD models (Engineering, 2018).

2.2.4. CAE

Computer Aided Engineering (CAE) is a technique where computer systems are used to analyse the created CAD models on the functionality of the product. The software tool allows the developers to simulate different requirement cases on the created concept and study how the design decisions impact the results. This created the developers to get an understanding on what further developments on the tested CAD—Model is needed in order to achieve even better performance results (Ming et al, 2017).

There are several different analyses that can be conducted by using the CAE tool. Both kinematic and dynamic analyses are available. The most common analysis method is using Finite Element Method (FEM) which allows developers to determine e.g. deformation, stress, fluid flow and other challenging field problems that can support the developers on the impact of the created design on product requirements (Ming et al, 2017).

2.2.4.1. Ansys

ANSYS Mechanical is a Finite Element Analysis (FEM) software tool. The software is a general-purpose modelling plan for finite elements used to address common mechanical problems. The application of ANSYS analyses is wide and adaptable to serve the needs of the user (Muhammed and Shanono, 2020).

However, there are some initial decisions that have to be made before creating the analyses on a CAD-Model. The important decisions consist of determining what the goals are of the evaluation, to what extent the physical design representation should be realized before testing (only a part of a product or the entire system) and to what accuracy should the user set the testing (determination of mesh). By addressing these concerns, a trade-off regarding the computational expenditure versus the expected outcome results is predefined and controlled (Muhammed and Shanono, 2020).

2.2.5. PLM

Schertz and Whitney (2001) defines PLM systems as *"…the integration tool that connects all product data"*. Saaksvuori and Immonen (2005) explains the term product data as the information broadly related to the product. The authors state that product data can be categorized broadly within three different groups: The product definition data, the product lifecycle data and the metadata that both describes the lifecycle and product data.

The first categorized group is connected to the PDM software. In this context product data represents the functional and physical elements of a product. This is done by storing technical, conceptual and abstract data i.e. it embodies data that describes the fit and function, form, properties of a product and then visualizing the data to the user by connecting them. Visualization in the form of concept illustrations and images of product are also categorized within this group (Saaksvuori and Immonen, 2005).

Product Lifecycle Management (PLM) was developed as the problem arose within information management and created incompatibilities between not only different departments in companies but also across disciplinary boundaries. It was needed to keep information throughout the whole lifecycle. The usage of PDM systems where no longer enough and instead there was a need to identify and store information for a product throughout the lifecycle of a product (Stark, 2015). The main difference are the scope and purpose of the systems. A PDM tools primary aim is to managing data related to the product as efficiently as possible whereas the PLM systems primary aim is to create a holistic approach of the whole business surrounding the product (Saaksvuori and Immonen, 2005).

2.3. Product Architecture

To explain what product architecture is, Ulrich and Eppinger (2012) break down a product to two terms:

Physical The different components, sub-assemblies and individual parts are the *physical elements* of a product.

Functional The overall desired functionality performance of a product are the *functional elements* of a product.

As an example, to further explain the functional elements, Ulrich and Eppinger (2012) presents the case of a printer. Examples of functional elements of a printer are “store ink”, “store paper”, “communicate with user” etc. The common approach to present the functional elements are through schematics. Theses schematics are later interpreted and transformed into components, specific technologies or other principles. A similar view is shared by Eckert and Jankovic (2016) as they define the product architecture as a system that arranges sub-parts of a product (physical elements) in a certain structure in order to meet the functional requirements (functional elements).

The physical elements are first introduced in the concept phase. These physical elements can then either remain or be changed later in the PDP during the detail design phase.

In order to merge the functional and physical elements of a product, the physical elements are arranged into several different building blocks which are referred to as “chunks” (Baldwin and Clark, 2000). The chunks consist of different components that together fulfil a specific function of the product. By doing so, the product architecture is created (Ulrich and Eppinger, 2012). According to Ulrich and Eppinger (2012) the definition of a product architecture is, *“…the scheme by which the functional elements of the product are arranged into physical blocks and by which the blocks interact.”*

2.3.1. Platform Modelling

In difference with the product architecture which describes the structure of a product, a product platform addresses how variants are created and their commonalities (Kreimeyer, 2014). Kreimeyer (2014) describes product platforms as the set of different product architectures, modules and of interfaces which results in that a number of design alternatives can be developed and launched. A similar definition is presented by Robertson and Ulrich (1998) as they describe a platform as sets of products that share common assets. The commonalities that are shared in a platform can be e.g. physical parts and the relating features, processes (manufacturing or assembly) and knowledge (design know how). The purpose of creating platforms is to generate support for a company when creating products that need to fulfil the demands that are set by the costumer. The platform enables to possibility reuse the commonalities between the product variants (Robertson and Ulrich, 1998).

2.3.2. Enhanced Function-Means (EF-M)

The Function-Means method is built upon describing the functional elements of a product through a hierarchical approach by decomposing the functions from top level to subordinate sub-systems (Johannesson et al, 2017). The method also follows Hubka's law where Hubka (1988) described that "…the primary functions of a machine system are supported by a hierarchy of subordinate functions, which are determined by the chosen means". The original method of the use of functional modelling through F-M was developed by Tjalve (1976) and Andreasen (1980). The method is based on identifying Functional Requirements (FR) of a product and describing the appropriate Design Solution (DS) that fulfils the specific FR. The method has since been further developed and Schachinger and Johannesson (2000) presented an enhanced version of the F-M method, named Enhanced Function-Means (EF-M), by inserting the aspect of constraints (C) as a relationship between the FRs and DSs. The insertion of constraints allows the users of the method to understand the "why" of choosing a DS for a FR through adding requirements. Johannesson et al (2017) explains that the EF-M tree is the carrier of two lines of information answering the questions for both "why things are" as well as "why things are the way they are".

A visualization of different relationships in an EF-M tree can be seen in Figure 6. The FRs are the functional elements that define a product or a part of a product, which either actively or passively contributes to fulfil a purpose through manipulating the behaviour internally or externally. A FR is solved by its specific

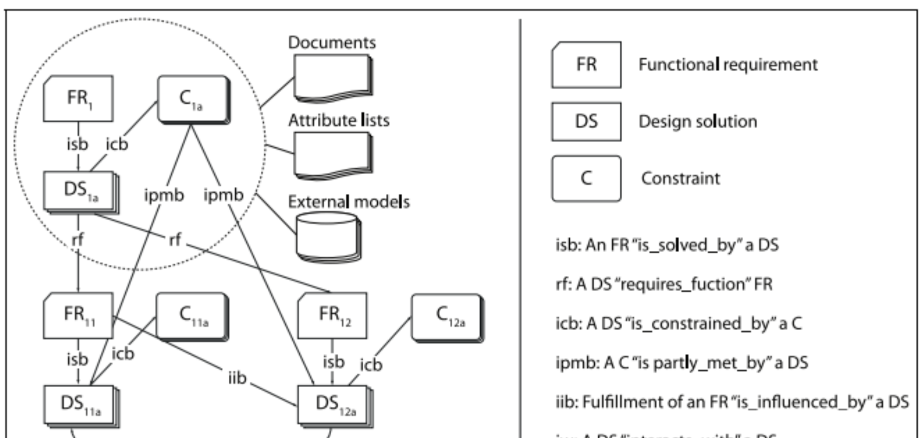

Figure 6 EF-M Tree illustration adapted from Johannesson and Claesson (2005)

mean which is the DS. The purpose of adding the Cs are to set limitations on the potential design space (see chapter 2.1.1) of the DSs. The limitations are set as requirements which guide what a DSs must fulfil in order to be a viable DSs (Johannesson et al, 2017).

The hierarchy of the EF-M (see Figure 6) is a Top-Down structure (Schachinger and Johannesson, 2000) (Johannesson et al, 2017) where the first step of creating the EF-M tree is to determine the overall FR which is named as FR1. FR1 can be solved by different DSs. Each FR should ultimately be solved by only one DS where the ratio becomes 1:1 (Johannesson et al, 2017) (Raudberget et al, 2015). In the case where a FR have many possible DSs, the guideline is that the FR only can be realised by one DS at a time. As the 1:1 ratio is achieved the DS solution is further decomposed into two or more FRs (Raudberget et al, 2015).

The EF-M tree is further guided by the relationships between the three pillars of the method FR, DS and C. Between the FR and DS a relationship named is solved by (isb) and the relationship is constrained by (icb) represent the relationship between a DS and C (Schachinger and Johannesson, 2000).

As the EF-M tree is progressed to a lower level in the hierarchical structure more relationships are introduced. The require function (rf) represent the relationship between a DS and sub-FRs (can be seen in Figure 6 in the relationship between DS1 and FR11, FR12). As Johannesson et al (2017) explains the new constraints on the sub-FRs are either allocated from the original constraint (e.g. dimensional constraints C1 = C11 + C12) or transferred directly (e.g. Quality constraint C1=C11=C12). The constraints C11 and C12 for the sub FRs (see Figure 6) can also be completely new and not be transferred top-down. If a constraint from a higher level of the tree influences lower level DSs the relationship is partly met by (ipmb) is mapped out (Schachinger and Johannesson, 2000) (Johannesson et al, 2017).

The last two relationships represent the dependencies in the product/system. The relationship of two DSs that interact with(iw) each other and influenced by (iib) which represents if there may be a restriction of fulfilling a FR if a DS influences another DS's FR (Johannesson et al, 2017).

The structuring of the EF-M tree is explained by Levandowski (2014a) and can be seen in Figure 7.

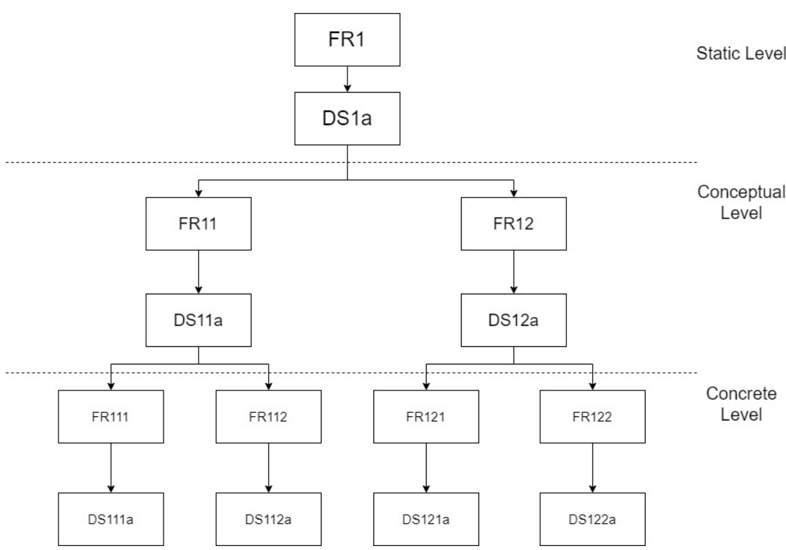

Figure 7 Illustration of EF-M Tree Levels

As can be seen the EF-M tree is structured into three different sections which are the Static, Conceptual and concrete level:

The Static Level describes the different defined functions of the product that represents its core purpose. This level rarely changes in between the creation of different product design alternatives since they all intend to solve this top-level function (Levandowski, 2014a).

The Conceptual Level represent the different conceptual design solutions for its respective FRs. The purpose is to create DS solutions that fulfill the upper level DS and thereby the top layer FR (Levandowski, 2014a).

The concrete Level are the building blocks that realize the DS on the conceptual level. The Concrete Level of the EF-M tree represents the last functional description and at this stage the description of the product features is close to the intended physical embodiment (Levandowski, 2014a).

By mapping out all the three layers of the EF-M tree the product architecture is create representing how a product is built up in a structured approach (Levandowski, 2014a).

2.3.3. Modularity

Ulrich and Eppinger (2012) divides the product architecture into two concepts, Modular and Integral product architecture. The modular architecture is achieved when one single chunk can satisfy one or several functional elements. On the opposite, the integral product architecture exists when several different functional elements overlap into several chunks or are spread out over multiple chunks making the interactions between functions and chunks difficult or in some cases non-existent.

The different types of product architecture modularity as explained by Ulrich and Eppinger (2012) can be roughly divided into three different categories see Figure 8:

The Slot-Modular Architecture The chunks within the Slot-Modular Architecture have different interfaces to the body therefore making the incompatible for changing positions.

Bus-Modular Architecture In the case of a Bus-Modular Architecture there is a common bus (or body) where the different chunks can be connected to. The interface between the body and the chunks are the same which allows for chunks being rearrange without affecting the structural integrity.

Sectional-Modular Architecture In the case of a Sectional-Modular Architecture the connection of the different chunks is reliant on having the same interface and no guiding single body to which chunks connect exists. By connecting the different types of chunks through identical interfaces, the system is created.

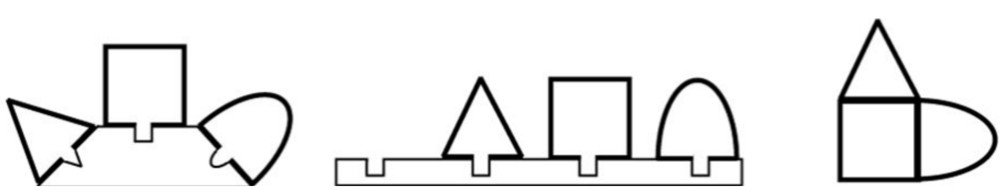

Figure 8 The three different types of modularity in product architecture as presented by Ulrich and Eppinger (2012)

As the chunks represents the building blocks of a product and the product architecture represents how the arrangement of these chunks affect the function of the product, the enablement of change is therefore controlled by the architecture. The modular chunks can if created properly be interchanged and modified without affecting the rest of the product, therefor making the identification of the chunks a strong advocate for inter alia reuse and flexibility in use (Ulrich and Eppinger, 2012).

3. Methods

In the following chapter all the method and approaches used to create the results of this master thesis project are presented.

The chapter follows the sequence of the carried-out work by explaining how each method and approach has been used as well as the purpose of using it for the sections Data collection, System Requirement Identification, Proposed Approach and Proof-Of-Concept.

3.1. Data Collection

The following section presents the methods used during the Data Collection phase of this master's thesis project.

3.1.1. Literature Review

Use of secondary data (publications and literature) enable the possibility to examine previously executed work to increase the knowledge on the examined topics. Even though the secondary data provides a broader view of the problem and surrounding topics there are disadvantages of analyzing others work. Such disadvantage can be that there is an uncertainty regarding the reliability and/or the methods used to conclude the findings (Sørensen *et al*, 1996).

The search for the literature was primarily done by using the search engine of Google Scholar and the available publications and literature at the Chalmers Library and its search engine. The literature research consisted of research reports, doctoral dissertations and books. The search started off by using key words such as: Design space exploration and early concept development before evolving to the different topics presented in chapter 2.

The literature review was used because there was a lot of uncertainties surrounding the problem, needs and potential solutions at the early stages of this project. This lack of knowledge creates the need to widen the scope and fully explore the situation. An exploratory research is defined by Stebbins (2001) as a situation when the researcher is lacking knowledge about a specific problem. Therefore, the researcher needs to explore the literature, since there is a belief that the exploration will result in valuable information.

3.1.2. Interviews

The primary data collection for this project was done by conducting two interviews and an observation session. The use of primary data was to confirm the findings of the secondary data collection as well as gathering insight from experts (Ulrich and Eppinger, 2012).

The used technique in the executed interviews were through two semi-structured interviews, where a specific topic had been identified beforehand and questions are prepared surrounding that topic. Even tough lead questions are asked the interviewee has room to present his or her in depth insights and present specific point that they deem interesting for the discussed subject (Williamson, 2003).

The two interviews were conducted with a senior engineer with over 15 years of experience of methodology development and design optimization at a leading aircraft engine manufacturing company during two occasions.

The purpose of the interviews was to both confirm the findings done by the secondary data collection as well as broaden the knowledge with the insights from the expert. The interviews where recorded and transcribed before relevant statements for this project were transferred into a Statement List. The Statement List was used as support for the creation of the needs for the system as well as mapping the industry standard.

3.1.3. Observation

By observing how a user navigates in a system or with a product it is possible to reveal important need from a user (Ulrich and Eppinger, 2012). The observation can either be conducted as a passive or active observer. The ideal observation is where the observer can collect data in an environment when its used.

The observation was conducted at an aircraft engine manufacturing company where the company's participant demonstrated how different processes work and how they are connected to the different databases. The observer was passive, and the observation was set up as a demonstration where the company's system was explained.

The purpose of the observation was to understand how the company uses database solutions to store product information and map how it is done as well as gathering general thoughts from the interviewee regarding the modelling processes and database usage.

The results of the observation is presented as a mapping of the existing systems at the company. The mapping illustrates the handling of information and files of a product during the development process. The purpose of each system is explained.

The outcome of the observation was used as support for the creation of the needs for the system as well as mapping the industry standard.

3.2. Requirement Identification

In the following section the methods used to develop the requirements for the sub solution are presented. The main methods for developing the requirements were the Holistic Requirement model and the usage of Quality Function Deployment.

3.2.1. Modified Holistic Requirement Model

The Holistic Requirement Model (HRM) is a method where the collected needs are segmented (Burge, 2007). The two types of requirements that were used during this method was the Operational Requirements (OR) which represents the needs from the Needs List and Non-Functional System Requirements (NFSR) representing the requirements for the proposed approach.

Operational Requirements Are the requirements that explain he major purpose of a system. These requirements describe a systems capability and the fundamental purpose (Burge, 2007).

Non-Functional System Requirements Are requirements where the purpose is to explain what a specific system has to achieve in order to satisfy the defined OR (Burge, 2007).

The alignment to the QFD is illustrated in Figure 9. The WHAT's room of the QFD are transferred directly from the Needs List. The HOW's room are captured by Translating the Needs to Non-Functional System requirements based on the HRM principles.

The purpose of using the method was to create more clarification about the vague needs and translate them into system requirements for the proposed approach. The use of the method also allowed the possibility to transfer the system requirements to a QFD where an importance ranking on the requirements can be calculated and the most critical requirements could be broken down to sub-solution requirements.

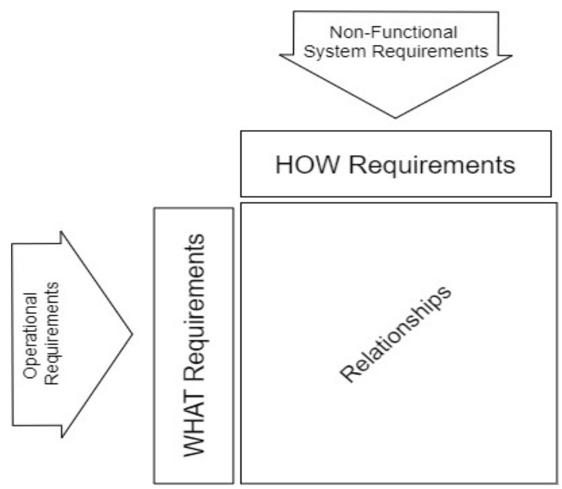

Figure 9 Illustration HRM's alignment with QFD

3.2.2. Modified QFD

Quality Function Deployment (QFD) is a method where the needs for a product or a system are converted into requirements through a systematic level breakdown. (Bergman and Klefsjö, 2012).

For this project the QFD was modified to satisfy the purpose of execution. The conventional QFD process consists of four stages. Due to this project being focused on the development of the approach only the first two phases of the QFD were applied which represent the Product planning and the Product Design stages. The weights of the needs were created through the application of the Pairwise Comparison method.

The purpose of the QFD was to create more clarity on how specific sub solutions of the system could satisfy the important needs. The importance of a need was calculated by the sum of its respective requirements based on the QFD calculation principles. By understanding the importance values from the calculations of the system requirements, it was possible to screen and further break down the requirements to more specific sub-solution requirements.

3.2.3. Pairwise Comparison

Pairwise Comparison is a method to compare different criteria versus each other to determine a weight which represents the importance of that specific criteria.

The idea for the method is to create a matrix with the criteria and apply them on both the rows and columns. The diagonal relationships are eliminated as comparing criteria A versus A is irrelevant. The lower triangle of the relationship's matrix is also eliminates as comparing criteria A versus B and B versus A represents the same purpose (DesignWiki, 2020).

The comparison (see Figure 10) starts by systematically going through each criterion at the rows and compare it individually against the criteria on the column. For example, if criteria A is deemed more important than criteria B, the letter A is placed in that corresponding cell and the comparison is continued to the next row. If two criteria are evaluated as equally important both letters are placed in that corresponding cell (DesignWiki, 2020).

The assignment of the weights is done through summarize the total amount of appearances in the cells of each individual criteria letter. This creates a ranking on which criteria have appeared more than others.

Needs		A	B	C	D	E	F	G	H	I
Functionality	A		A	C	D	A	F	A	AH	I
Durability	B			C	D	B	B	B	H	BI
Quality	C				D	C	F	C	H	C
…..	D					D	F	D	D	I
…..	E						F	E	H	E
…..	F							F	FH	I
…..	G								H	I
…..	H									H
…..	I									

Figure 10 Example of a Pairwise Comparison

The basic principle to assign the weight is that the total of all individual weight must add up to 100%. Through a simple equation the percentage of the total for each individual criterion is determined (DesignWiki, 2020).

The purpose of using the Pairwise Comparison is to organize the needs from their relative dependence of each other. It is worth mentioning that the method is based on comparing two needs and deciding which need is more important. Therefore, the weight can be suggested for biased decisions. However, the benefits of mapping the difference of importance is valuable for the creation of the approach since it allows for prioritization and structure.

3.3. Sub-Solutions

In the following section an explanation on how the different Sub-Solutions have been applied and used to create the proposed approach is presented.

3.3.1. EF-M

The purpose of using the method EF-M (see chapter 2.3.2) was to create a foundation for both the PDM-system as well as supporting CAD Model Setup.

The Static and conceptual level of the EF-M Tree and the relationships between the FRs, DSs and C were mapped out.

The concrete level of the EF-M Tree was used through analysing the existing product. Trough that analysis the knowledge about the geometrical design space, from the existing solution, is transfer.

The result of the EF-M tree was used to create the initial structure for the PDM-System.

3.3.2. PDM

The purpose of using the PDM system (see chapter 2.2.5) was to use it as the storage facility for the CAD files. It is the shell where all the files are documented in order to create a database where the user is guided to create the DSs for the identified FRs in the conceptual level. It is the interface point of the created platforms (see chapter 2.3.1) of products where the user can navigate and add new DSs to expand the database.

The specific PDM structure that is set up is based on the EF-M Tree. The PDM system also allows for the use of a SBCE approach (see chapter 2.1.2) when creating the concepts.

In order to create an easy interface, that adds to the simplicity during use, the PDM system structure is based on the documented EF-M tree for the static and conceptual level. The static level represents the Assembly files whereas the conceptual levels are stored as part files.

3.3.3. CAD

The purpose of using CAD models (see chapter 2.2.1) was to create the alternative DSs in a CAD environment through using parametric CAD models (see chapter 2.2.2) for the controlled scalability on the baseline solution. The parametric dependencies create a Geometrical Design space (see chapter 2.1.1) for an intended part. The Geometrical Design Space Exploration was done through using synchronous modelling and subtraction modelling (see chapter 2.2.3).

The choice of using simpler models was determined based on the complexity management principles (see chapter 2.1.3).

By using simpler models, it was possible to create a controlled environment for mapping the parametric dependencies and quickly alter the designs of the DSs for the conceptual level FRs.

In order to create modularity between the different FRs, an universal interface was created following the bus-modularity principles (see chapter 2.3.3).

3.3.4. CAE

The purpose of using the CAE tool (see chapter 2.2.4) was to analyse the created product concepts. In order to follow the SBCE principles (see chapter 2.1.2) there is a need to present an analysis on the feasibility of the developed concepts. By applying stress and deformation analyses on the created concepts it is possible to understand which concepts under performs, which concepts can be further developed, and which concept exceed the set requirements.

3.4. Proposed Approach

The following section introduces the method and approaches used to create the proposed approach of this project.

3.4.1. Flowchart

To capture and categorize the activities of a system it is important to clarify and make the process understandable for the interpreter (Prasad and Strand, 1993).

There are different methods to illustrate the process when using a flowchart. Block diagrams are most useful when the intent is to illustrate the function of a process. It most commonly is created by mapping the input and output activities (Prasad and Strand, 1993).

In this project the method was used by illustrating a block diagram for the activities needed from a User's Perspective when interacting with the proposed approach. The used blocks for the created flowchart can be seen in Figure 11 and consist of mapping de action, decision and system interaction activities.

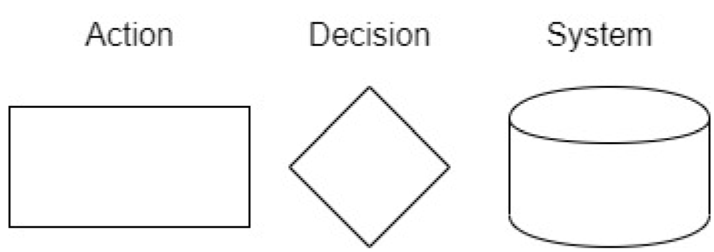

Figure 11 Illustration of the used Blocks in the User perspective Flowchart

The purpose of using the flowchart was to illustrate how the user would interact when using the proposed approach. Secondly, the flowchart was used to demonstrate the presented User Perspective process on a case product. The flowchart created a guideline of activities that were applied on the case product.

3.5. Proof-Of-Concept

In order to validate the proposed approach, a Proof of concept in the form of a demonstration was conducted. The method used to illustrate the demonstration was to apply the activities of the proposed approach on a case product.

3.5.1. Case Product

A jet engine bracket was chosen due to the available information about the geometrical design space restrictions, the baseline product and the load conditions for the product and future designs. The product was obtained from the GE bracket challenge. The challenge was done in 2013 from GE aviation as an open innovation initiative for the public (GrabCAD, 2020).

The purpose of the challenge was to allow the public to explore different geometries for the jet engine bracket (GrabCAD, 2020). As the purpose of the Library system is to allow users to explore the geometrical design space of a product through flexible CAD models, it was determined that it would serve as a great case product to use as a demonstrator for the proposed approach.

The purpose of using a case product was to demonstrate the activities from the created flowchart on the proposed Library system.

3.6. Application on Proposed Approach

The methods and approaches used when illustrating the proposed approach are presented in the following section.

3.6.1. NX

The purpose of using NX 12 (see chapter 2.2.1.1) was to use the unique hybrid modelling technologies.

In order to create flexible CAD-models it was possible to take advantage to both use feature-based tools such as subtracting Boolean operations as well as the unique Synchronous modelling Technology (see chapter 2.2.3) in order to manipulate the geometry of the concept.

Parametric CAD models on a simplified case product are created in order to create scalable concepts. The parametric dependencies are also mapped in order to be able to create a controlled geometrical design space for a concept. This is done through introducing Max and Min values of parametric dependencies based on relationships. The relationships are manually determined based on examining the created baseline solution and the geometrical design space requirements on the case product.

3.6.2. Ansys

The purpose of using Ansys (2.2.4.1) was to use the Finite Element Method and test the load case requirements on the created design alternative concepts.

The setup of the analysis was to use default mesh 2 on all the concepts. The material choice was determined to Titanium alloy. It is worth mentioning that due to the use of lower mesh the specific extremes of the stress analysis may be inaccurate. There is a possibility to create analyses with higher mesh density but due to both time and software restraints the analyses were conducted with lower mesh.

The different load cases were tested by analysing the Equivalent (von-Mises) stress solution adding force and fixations based on the requirements on the case product. The torsion load case was created by adding the moment solution following the requirements. The solve of a total deformation analysis was also added to all the load cases to gather further insights.

3.6.3. Mock-up

A mock-up can be created in order to visualize a product or a process. The created mock-up can act as a tool that transfers information. The transferred information can be represented as illustration of intended process activities or intended system layouts (Riascos et al, 2015).

The purpose of using digital mock-up was to illustrate the created Library Systems interface during use. This was done by creating a layout in PowerPoint that describe the User perspective activities when interacting with the Library system.

3.7. Qualitative Feedback

A feedback from practitioners in the industry on the created proposed approach was conducted through interviews.

3.7.1. Feedback Interviews

An unstructured interview technique was used in order to gather the feedback. An unstructured interview is not set up with preparation question but is rather conducted as a conversation in order to gather information (Williamson, 2003).

The purpose of using this method was to present the created Library system to practitioners in the industry that both work within product development as well as the daily use of PLM and PDM systems.

Three interviews were conducted, two of them with product developers and the third with a database designer to increase understanding on if the proposed library system is feasible.

The interviews where both used to get feedback on if practitioners are interested in the created Library system as well as creating a foundation for future work recommendations based on the input of the interviewees.

4. Data Collection

In the following chapter the results of the Data collection are presented.

4.1. Exploration of the Problem

During the collection of data, through interviews and literature, many different fields were explored. The result of the fields investigated are illustrated in Figure 12.

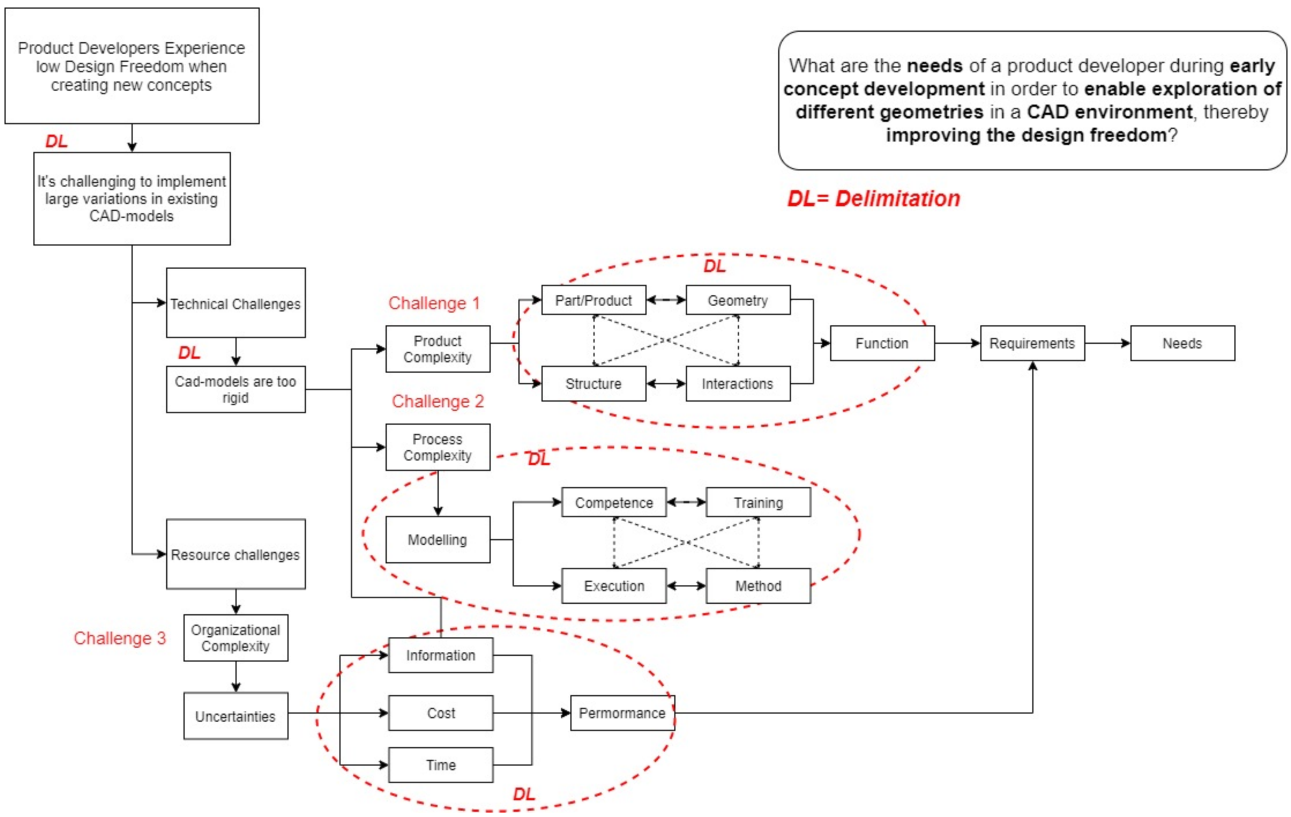

Figure 12 An illustration of the conducted literature study with delimitations (DL) and identified challenges regarding the problem mapped out

The three main challenges of increasing the flexibility of CAD models are derived from the complexity management principles (see 2.1.3). Delimitations are set to further investigate the subjects within the identified challenges seen in Figure 12.

Each identified challenge consists of different subjects. The literature study of these challenges is the foundation for the Identified Issues. The Identified issues, in collaboration with the qualitative data of the interviews and observation, create the Needs list for the Library system as well as the mapping of the current industry standard.

4.1.1. Impact of complexity on CAD Models

The challenges (see Figure 12) in all the four fields of complexity can be the contributors for the challenges in the problem definition (see chapter 1.2) either by themselves or in connection to other fields.

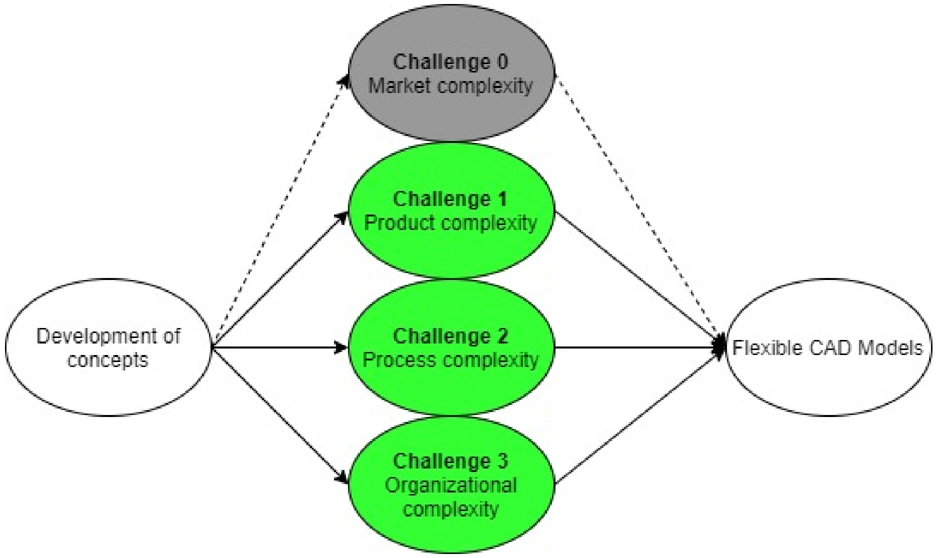

Figure 13 Illustration of impact of the complexities on CAD Models

To be able to narrow down the broad scope and enable in depth research, some limitations are set to the existing complexities on the PDP.

The field of market complexity is in this master's thesis project excluded as it is highly dependent on a company's size, segment, financial situation, product portfolio etc (Lindemann, 2009).

When classifying the Product Complexity, the main issue is to understand the product architecture (see chapter 2.3) and its underlying structure and the benefits of identifying them at an early stage.

The Process Complexity can be specified in different ways. In this project, the Process Complexity is representing the tools used by the developer when modelling and storing concept, therefore the challenges surrounding CAD software and other relevant tools are explored.

The Organizational Complexity is narrowed to the handling of information concerning the product between the involved parties and systems in the PDP.

The underlying issues for the three challenges (see Figure 13) that need to be investigated are therefore:

- Understanding the product (Product Complexity)
- Handling and understanding the CAD Software/relevant tools concerning the product (Process Complexity)
- Handling and understanding the Information concerning the product (Organizational Complexity)

4.2. Identified Issues

The following issues have been found within the three internal complexities (see chapter 4.1.1).

4.2.1. Identified Issues regarding Product Complexity

Issues regarding understanding the product:

- A product that only satisfies the functionality can still be deemed as inadequate. This phenomenon can be simply explained through a product such as a cell phone. It is no longer adequate to just sell a phone that is used to call and receive calls. Even though this is the primary functionality of a phone, the customers are expecting a lot more from a cell phone product. This has resulted in more complex products to satisfy the customers. The issue arises when the complexity of the product is not properly controlled which leads to developers not fully understanding the connection between the functional and physical connections of the product (Lindemann, 2009).

- The lack of a methodology incorporated to the development process which considers the product structure leads to missed opportunities for control and optimization of designs. (Lindemann, 2009).

- When a developer creates a concept, he or she uses his/her experience to unconsciously constructs different connections for realizing the functionality through structuring to achieve the intended behaviour of the product (Gero and Kannengiesser, 2004). Without properly documenting and establishing these connections issues can arise when reworking a product or trying to reuse previously executed work.

- The optimization of a product architecture can lead to a reduced product complexity. By mapping the Product architecture, it becomes possible to better understand the product. Developers oversee the need of documenting the product architecture and therefore limit the possibility to reuse the existing knowledge of the product (Baldwin & Clark, 2000).

- When creating a product, companies tend to fail to embrace the full spectrum of use for the product and therefore limit the product to a goal or need. As the goals and needs fluctuate the issue arises as the product are not flexible and become rigid. This reduces the possibility to adapt an existing design to satisfy the new needs (Simpson, 2001).

4.2.2. Identified Issues regarding Process Complexity

Issues regarding handling and understanding the CAD Software/relevant tools concerning the product:

- Using CAD-models today is essential for the development of a concept. When discussing reusability of models, the CAD approaches today are very well developed for the design output representation, but the issue arises regarding understanding the modelling. There is a lack of describing how a developer has modelled the CAD-model and why certain activities have been built in a certain order. This results in difficulties to manipulate a model (Heikkinen *et al*, 2018).

- When reusing CAD-models, the existing models must be easy to interpret and manipulate. The issues arise with understanding the dependencies in a CAD model where the developer is not fully aware of what can and cannot be altered in the model. By not understanding the developer’s manipulation choices often results in crashed models. The lack of clarity of the dependencies can also create errors that are not noticed visually, but which can create complications further ahead in the modelling process (Cheng and Ma, 2017). Kasik (2005) similarly argues that the CAD systems today lack the ability to ensure the continuity of morphing of operations (the continuity of morphing being that geometry does not drastically change when changing a simple parameter). There is a need of a system that can control and limit the parametric changes (Kasik, 2005).

- When developers create models there are difficulties to translate the intention of the design into the CAD-models. The issues arise as the CAD-models are too rigid and the wanted implementation is not possible with the existing models. Therefore, starting from scratch is easier (Heikkinen *et al*, 2018). The inconvenience of the models also results in the developers having questions regarding e.g. which plane to use, what constraints to set and when to apply operations. Without addressing the questions properly, the issue arises where the developers tend to focus on the shape of the geometry rather than the robustness of the CAD-model (Cheng and Ma, 2017).

4.2.3. Identified Issues regarding Organizational Complexity

Issues regarding the handling and understanding of the information concerning the product:

- The companies produce a large amount of information surrounding the product. Therefore, it tends to spread out in the organization. The relevant information regarding (such as the products requirements and development information) a product always must be present for the developer. Challenges arise when key information is not properly stored resulting in lengthy operations for developers to gather the necessary data (Lundin, 2015).

- The lack of proper documentation of information leads to developers not remembering or understanding the previously conducted work. This consequences in that the misplaced documentation is a contributing force for why use and potential reuse of CAD model designs are limited (Camba et al, 2014). Kim et al (2007) and Lundin (2015) similarly argues that issues arise when designers are unaware of existing information. Lundin (2015) further argues that the reason for this is the lack of a centralized product information source for the developers during the early concept development stages.

- The literature is also in a consensus that the lack of relevant information is a key issue for why designers are unable to reuse previous work.

- The responsibility of handling information and working throughout different platforms creates a disruptive working environment for the developers. This creates a reluctancy to displace time to potentially find relevant information (Lundin, 2015).

4.3. Observation

The aim and purpose of the observation can be seen I chapter 3.1.3.

The company primarily uses three systems (see Figure 14) for handling information of a product during the development process.

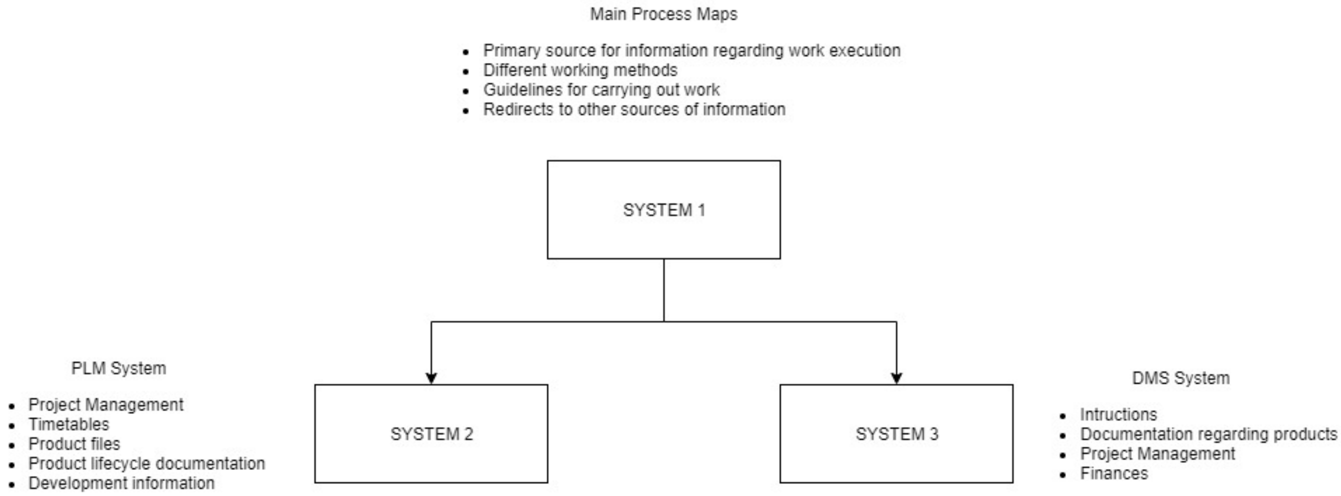

Figure 14 An overview of the three interacting systems for a developer during the development of a product

SYSTEM 1 can be interpreted as the top level of information and consists of different Process Maps of different fields. This represents the different working methods at the company. Within these Process Maps the developers can find guidelines on how a developer should conduct different steps of the process. SYSTEM 1 is the primary source of information regarding work execution as well as the source where the developers can be redirected to other sources of information and tools.

There are many systems and software's connected to SYSTEM 1 but as the scope of the thesis project is regarding a product during the concept development process, two other systems are relevant for observation (see Figure 14).

SYSTEM 2 is the Product Lifecycle Management (PLM) system used at the company. It contains the documents and files for a product throughout its lifecycle. In the aspect of the development process the PLM system is connected to the CAD software and stores files for the parts and assemblies in a structured systematic approach. SYSTEM 2 also stores the Project Management documents as well as the timetables of a project.

SYSTEM 3 is a Document Management System (DMS) System that primarily is a software that previously had been used more frequently before the introduction of the PLM system at the company. SYSTEM 3 contains different instructions for the developers. Documentation regarding the product are also stored in the DMS system as well as the project management and financial documentation.

The observation also resulted in valuable information gathered about how different sub sections of the database were handled at the company.

4.3.1. CAD models at the observed Company

The Company operates in NX (see chapter 2.2.1.1) when creating CAD models for the products. The primary approach is a modelling technique where models are created through subtraction modelling (see chapter 2.2.3). Full product parametric models (as an explicit use of expressions) (see chapter 2.2.2) is also used at the company but to a smaller extent. As the aim is to explore flexible and scalable CAD models the following observations are made on the use of parametric models at the company.

The parametric CAD models are stored in the PLM system in a systematic segmented structure. Each segment is a key element for the creation and handling of these models.

The PLM system is directly connected to the CAD software where alteration on the parametric dependencies at the top level can automatically modify all corelated part files. This creates the possibility of flexible assemblies which can be modified dependent on the input values on the dependencies.

The critical dependencies on the parametric CAD models are identified and transferred to an excel spreadsheet. The manipulation of the values in the spreadsheet result in geometrical changes in the part-files. There is no sequential order of the inputs for the parametric dependencies, but the different parts of the assembly are updated in a pre-defined order to minimize corruption in the files.

4.3.2. PLM Functionalities at the Observed Company

As explained by the interviewee, the PLM system is very complex due to all its applications and the number of files existing.

To reduce some of the complexity the systems interface provides simplicity for the user of the database system. The User has the possibly to create shortcuts for his or her projects, which are presented at the home page of the system. This creates individualized interfaces for the Users at the company.

The system only allows one developer at the time to work with a specific CAD file. This is created by the developer freezing the part as the work starts, excluding the possibility for other developers to work on that specific file. As a file is unfrozen a new version of that file is created and stored in the system. This is done to prevent duplicates of files as well as managing the different versions in a structured way. The different files can either be accessed by manually finding them in the system or through searching a specific serial number of a file which has been assigned by the PLM system.

4.4. Statment List

The result of this interview was the creation of a Statement List (see Figure 15) (see Appendix B) with gathered statements from the interviewee from the conducted semi-structured interviews. The statements were based on the questions (see Appendix A) presented by the interviewer as well as the thoughts of the interviewee. The interview approach and purpose can be read in chapter 3.1.2.

The statements are gathered on the subject of the three identified challenges in chapter 4.1 and 4.1.1.

The statements are divided into three fields: Challenge 1(Product), Challenge 2 (CAD) and Challenge 3 (information). Each statement is classified with their respective field and a number. These classifications are created in order to act as one of the sources for the creation of the Needs List.

The statements are transferred directly from the transcription of the answers gathered from the interviews (see chapter 3.1.2).

PS 7	you have to do a functional decomposition
PS 8	these functional decompositions do exist from previous work.
Challenge 2 Process Complexity Statement - CAD	
CS 1	In some cases, we use parameterized CAD models that can adapt to the other geometry to a certain degree
CS 2	we reuse some of the previous models
CS 3	The bottleneck of creating new models from scratch does exist
CS 4	it takes a lot of time to set up new parametric models that can be reused
CS 5	How smooth this process of reuse is dependent on how the new geometry looks eg. it needs to fit in with the other components
CS 6	We have parametric CAD models that we use so we don't have to start over from scratch
CS 7	On the other hand, we must adjust the models a little so that it fits together.
CS 8	In most cases you have to manually adjust the interface
CS 9	we primarily work with CAD models as a basis for all or analyses, especially when we look at different variants of a product
CS 10	You always want to be able to compare a model with something that’s why we usually have a baseline based on a previous model
CS 11	you usually have an idea of what could be done better and then you want to compare the new variant against the baseline
CS 12	you can’t really escape the idea of the need for a baseline to compare against
CS 13	But then if you want to model a whole new part or product, you have to model it from scratch
Challenge 3 Organizational Complexity Statement - Information/PLM	
IS 1	Another important aspect of which is reusing the working methods
IS 2	All our CAD files are in a system called TeamCenter, which is a large database of e.g. CAD files.

Figure 15 A segment of the statements from the interview regarding the three previous identified Challenges for increasing flexibility in CAD models, see Appendix B

4.5. Needs List

The Needs List is essential for the development of the proposed approach. Therefore, extensive work was conducted to create a Needs List that can connect the knowledge gathered from the Literature review (see chapter 4.1), the statements gathered from the interview as well as the results from the Observation (see chapter 4.3). All the needs created are delimited to the challenges presented in chapter 4.1 and 4.1.1. It is worth mentioning that the needs are created based on the writer’s knowledge at the time.

By creating the Needs List based on both primary and secondary data, it became possible to use the Needs list as a foundation for the creation of the requirement specification for the system and later serve it as a supporting decision to determine if the proposed approach fulfills the needs.

The results of the collection of needs can be partly seen in Figure 16 as well as the enhanced Needs List in Appendix C.

The Need list presents individual identified needs for the development of the approach as well as the corresponding source from where the need has been derived from. Each need was determined by analysing the identified issues, the statement list and the observation results. Since there is no collaboration with a company for creating a system on a specific product, the gathered needs are general and vague. This creates the need to translate them into more concrete system requirements as the work is progressed.

Needs list		Sources
1	Reduces the amount of sources	Observation, (Lundin, 2015), (Camba et al, 2014)
2	Preserves the reliability of the information	IS 7, (Lundin, 2015)
3	Presents the availiability of the information	IS 5, (Lundin, 2015), (Kim et al, 2007)
4	Prevents duplicates of documents	Observation
5	Enlightens the need of information	(Lundin, 2015), (Kim et al, 2007)
6	Provides clarity on previously executed work	IS 5, (Camba et al, 2014), (Kim et al, 2007)
7	Allows reuse	CS 2, CS 3, (Camba et al, 2014), (Heikkinen et al, 2018), (Lindemann, 2009), (Gero and Kannengiesser, 2004), (Simpson, 2001)
8	Provides suport for developers decision	IS 6, IS 8, (Lundin, 2015),
9	Provides understanding on existing CAD Models	CS 8, (Heikkinen et al, 2018)
10	provides a standarized work method	IS 6, IS 8, (Heikkinen et al, 2018), Kasik (2015), (Lindemann, 2009)

Figure 16 Outtake of the Created general Needs List based on interviews, observation and Literature Study (see Appendix C for the detailed Needs List

4.6. Industry Standard

It is important to clarify that for this thesis project the "Industry Standard" is defined as the representative industrial approach collected from the data of the interviews, observation, and literature. The mentioned "Industry Standard" has not been agreed upon but is rather completely based on the best knowledge of the writer at the given time.

The mapping of an industry standard was created to use as a comparison for the developed approach to determine how it differs from the existing standard. The industry standard maps how/if the companies avoid the issues that exist (see chapter 4.2) by analysing the results from the interviews, observations and the literature review.

The current state of art in Industries are to use very advanced and detailed CAD models as a starting point when creating new design alternatives. Simpler CAD are occasionally used but not stored or documented to the same extent in the databases (see chapter 4.4). Since the previously decisions haven't been documented in a CAD environment it becomes difficult to understand what can be changed and what must remain. This confirms the identified issue of an increasing complexity without establishing a controlling environment (Lindemann, 2009) (seen in chapter 4.2)

Currently two main modelling approaches are used in the industry. The advanced models are either parametrically or non-parametrically built. The use of parametric modelling is applied in the current industry to increase the flexibility of CAD models in order to explore design alternative (see chapter 4.3).

Even though the information from the collected primary and secondary data addresses that there is a need to increase the flexibility to explore design alternatives, there are flaws to the existing approach. The modelling is heavily dependent on the output representation which results in a lack of describing how the developer actually modelled (Heikkinen *et al*, 2018) (see chapter 4.2). This in turn results in a false sense of flexible CAD models as the flexibility is very restricted to the already predefined design.

Another aspect is that the parametric CAD model in the industry today can consist of a large amount of dependencies. Even tough parametric dependencies increase flexibility of CAD models the lack of controlling the limits of the dependencies result in contradicting results (Kasik, 2005) as without knowing what values can be changed and by how much the alterations of the parametric values may result in corrupted models (Cheng and Ma, 2017) (see chapter 4.2).

By following the industry standard using the advanced CAD models it also becomes difficult to reuse sections of the model due to all the dependencies overlapping between different Design Solutions creating an integrated product architecture (see chapter 2.3) where it is difficult to remove a section without corrupting the CAD model (Gero and Kannengiesser, 2004) (se chapter 4.2).

When trying to create new design alternatives, the industry standard is to optimize the existing solution by implementing small variations on the already working existing solution (see chapter 4.4). The impact of optimization work on existing CAD models on the Geometrical Design Space is illustrated in Figure 17.

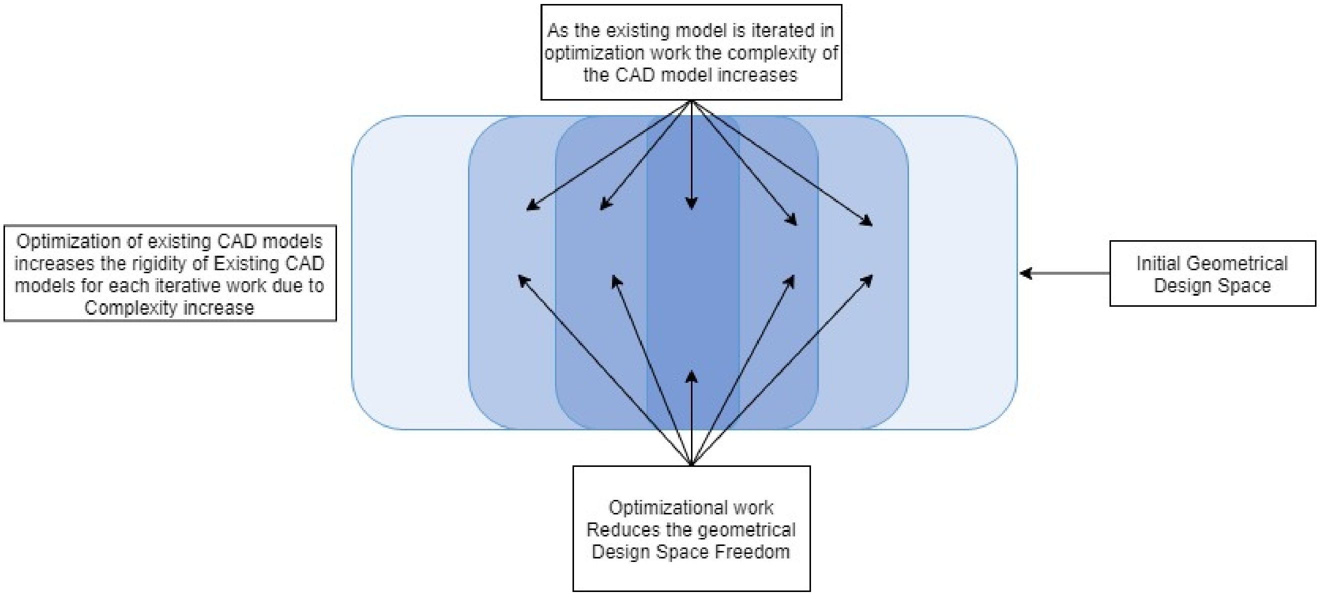

Figure 17 Illustration of the decreasing Geometrical Design space as existing CAD models are used during optimization work

An analogy to further explain the figure is to imagine the CAD models used in the industry as an ice block cube and the developers as carvers. The carver hacks on the ice cube to create a design for the ice block but as the carving progresses, it becomes more and more difficult to alter the chosen design and go back and explore another design. The same goes for the CAD models in the industry standard as the early choices made when creating the initial design and CAD model restricts the developers to explore other feasible designs due to the rigidity (Simpson, 2001) (see chapter 4.2). When developing new design alternatives, the developers do not want to start from scratch and therefore avoid the proper early development process stages and directly try to use the detailed design models as a starting point. This is a result of time and resource constraints which results in that optimization work on the already existing CAD models is the only viable option for altering the design. To create a new novel design solution would take a lot of time and resources without knowing if the new design would even perform as well as the already existing design. The iterative process of optimizing the product continuously decreases the geometrical design space freedom (see chapter 2.1.1).

The database system, PLM systems (see chapter 2.2.5), that are used in today's industry tracks the whole lifecycle system of the product. Even tough PLM systems are used, the information about the product is spread out over multiple databases (see chapter 4.3). With all the information stored, the navigation in the database system is complicated and difficulties arise when developers try to find the necessary components or/and information for creating a product in CAD environment (Lundin, 2015) (see chapter 4.2).

5. System Requirement Identification

In the following requirements the results of creating the requirements for the proposed approach are presented.

5.1. Modified QFD Application

The explanation for the use of the Quality Function Deployment (QFD) can be seen in chapter 3.2.2). For this project only the two first phases of the QFD are used (see Figure 18).

Product planning The first stage of the QFD is performed through collecting the needs of the customers and translate them into product characteristics. To be able to differentiate the different product characteristics the needs of the customers are weighted in a scale of importance. This way it becomes possible to understand which product characteristics best satisfy the customers. (Bergman and Klefsjö, 2012).

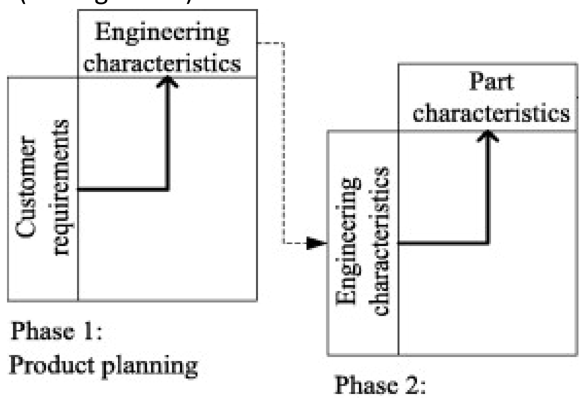

Figure 18 First two phases of the QFD

Part Development As the HOW's have been identified and the needs weighted, the second phase of the QFD aims to develop the sub-solutions of the product/system. The most valuable sub-solutions are identified through the QFD principles (Bergman and Klefsjö, 2012).

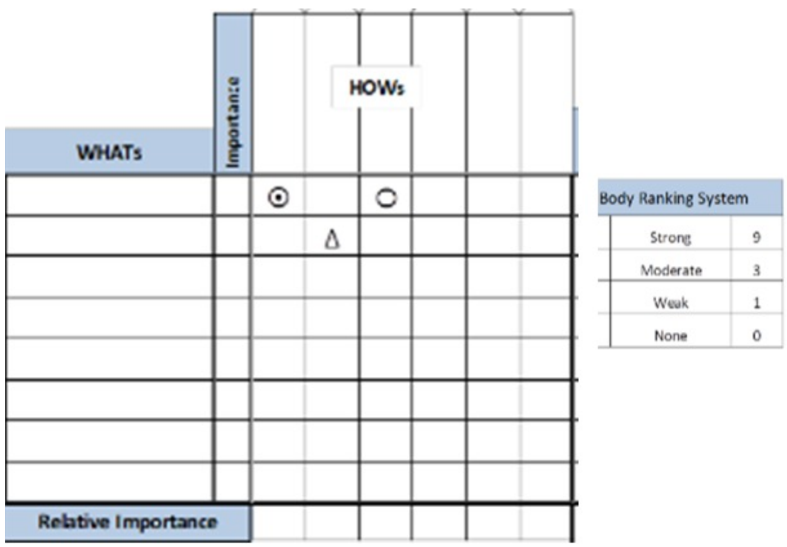

Figure 19 The Modified QFD with the illustration of the WHAT, HOW and Relationship rooms

The main framework to conduct and document the QFD approach is through the use of Hose of Quality (HoQ) (Bergman and Klefsjö, 2012). The HoQ is a further developed need-metrics matrix where different "rooms" of the HoQ are filled out to progress the systematic segmentation of the two QFD phases. The key element of the HoQ is the Need-Metric matrix and it represent the WHAT and HOW rooms of the HoQ (see Figure 19) (Ulrich and Eppinger, 2012).

The WHATS represent the customer needs and the HOWS represent metrics correlated to the solving of the WHATS. The main body of the HoQ represent a relationship matrix where each WHAT is compared to the different HOWS and depending on the strength of the relationship between the two, a value of either 9(Strong), 3(Moderate), 1(Low) or blank (no relationship) is assigned (see Figure 19). These values are later combined with the weighting of the need to determine the importance of a metric (HOW) (Ulrich and Eppinger, 2012) (Bergman and Klefsjö, 2012).

The results of the QFD 2 follows the phases of the QFD principles. The purpose of executing QFD 2 on the different sub-systems was to translate the Non-Functional System Requirements which were translated from the Needs List (see chapter 4.5) into Sub-Solution Functional Requirements (S-SFR). The S-SFR build the foundation to finding the building blocks (Sub-Solutions) of the approach and if a building block is able to solve the S-SFR it is deemed that the need of the system is fulfilled.

5.2. Pairwise Comparison

The purpose of using the Pairwise Comparison Method can be seen in chapter 3.2.3.

The results of the Pairwise Comparison (see Appendix D) are used to determine a weight for each need to later use it during the QFD relationship calculation. Therefore, this method serves as a building block for the QFD development.

Both the rows and columns of the matrix are setup with the needs transferred from the Needs List (see chapter 4.5). The needs are assigned with representative letters matching on both headers in the rows and columns of the matrix (see Figure 20).

		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
A	Reduces the amount of sources	X	A	A	AD	A	A	G	AH	A	AJ	A	A	AM	A	A
B	Preserves the reliability of the information	X	X	B	BD	B	BF	G	H	BI	B	B	B	M	B	B
C	Presents the availiability of the information	X	X	X	CD	CE	F	G	H	I	J	K	CL	M	CN	O
D	Prevents duplicates of documents	X	X	X	X	D	DF	G	DH	DI	DJ	DK	L	M	DN	DO
E	Enlightens the need of information	X	X	X	X	X	EF	EG	EH	I	J	K	L	M	N	O
F	Provides clarity on previously executed work	X	X	X	X	X	X	FG	FH	FI	F	FK	FL	FM	FN	FO
G	Allows reuse	X	X	X	X	X	X	X	G	GI	G	G	G	G	G	G
H	Provides suport for developers decision	X	X	X	X	X	X	X	X	H	HJ	H	H	H	H	H
I	Provides understanding on existing CAD Models	X	X	X	X	X	X	X	X	X	IJ	IK	IL	M	IN	IO
J	Provides a standarized work method	X	X	X	X	X	X	X	X	X	X	J	J	M	JN	JO
K	Provides understanding on the modeling tree	X	X	X	X	X	X	X	X	X	X	X	KL	M	N	O
L	Provides understanding on parametric dependencies	X	X	X	X	X	X	X	X	X	X	X	X	M	LN	LO
M	Preserves the robustness of CAD models	X	X	X	X	X	X	X	X	X	X	X	X	X	M	M
N	Enlightens the critical parametric dependencies	X	X	X	X	X	X	X	X	X	X	X	X	X	X	NO

Figure 20 Outtake of the complete Pairwise Comparison Matrix

Each row is compared to the individual column and it is determined if one need is more important than the other.

After completing the entire matrix of filling out all the comparisons between the needs, the analysis resulted in that the most important needs were the allowance for reuse of knowledge and the decrease of repetitive and time-consuming rework. These needs were followed by the need that the system should provide support during decision making, provide simplicity, preventing disruptive activities and increasing the design freedom for the developer. The extensive results of the calculation and needs can be seen in Appendix D.

5.3. Holistic Requirement Model

In order to translate the needs from the Needs List (see chapter 4.5) the method Holistic Requirement Model was used (see chapter 3.2.1).

The idea of this exercise was to try concretizing the vague needs to some early stage Non-Functional Requirements for the proposed approach. The Non-Functional System Requirements (N-FSR) can be seen in Figure 21.

The N-FSR are created by following the principles of HRM (see chapter 3.2.1). For each need from the Needs List, which represents the Operational requirements, the question: What must the system achieve to fulfil the define Operational Requirement, is asked.

Each need is analysed and the answer to the question is defined as the Non-Functional System Requirement for that specific need. For example the Operational Requirement (Need from needs list): *reduce the number of sources* is translated to the Non-Functional System Requirement: *Centralize Information*. Same principles are used for all the Operational Requirement (needs). Even though the N-FSR are still quite vague it is possible to used them as one of the sub-systems in the QFD thanks to the alignment of the HRM-method with the QFD process.

Non-Functional System Requirements
Centralize information
Identify relevant information surrounding the product
Distribute information surrounding the product
Highlight available information regarding the product
Organize information in a structured way
Suggest relevant information for the developer
Detect duplicate documents
Detect duplicate partfiles
Remove dublicates
Store relevant information regarding the product
Communicate previous executed work to the developer
Communicate existing CAD-Models
Create workguidlines for the developer
Structure modeling tree
Create robust models
Map parametric dependencies
Highlight critical parameters
Establish flexible CAD Models
Organize product dependencies
Generate produt understanding
Follow concept development principles
Reduce wasteful work for the developers
Adapt the application
Communicate with developer through interface
Enjoy the design activity
Provide simplicity for the developer when navigating the system
Capture the intention of design
Store project progress
Store CAD-Model files
Customize interface environment base on developers needs
Control the system environment
Comply with development method

Figure 21 The created Non-Functional System Requirements for the system

5.4. QFD 1 Sub-Systems

The results of the QFD 1 are presented by firstly mapping the three Sub-Systems which are based on the three challenges seen in chapter 4.1.1. The needs from the Needs List (see chapter 4.5) and Non-Functional System Requirements are categorized to System A (Organizational Complexity), System B (Process and Product Complexity) and System C (Database)

The Sub-Systems created the foundation for the System of Systems QFD which represents the complete list of requirements for the proposed Approach.

		1	2	3	4	5	6	7	8	9	10	11
		SYSTEM A										
		Organizational Complexity										
		Centralize information	Identify relevant information surrounding the product	Distribute information surrounding the product	Highlight available information regarding the product	Organize information in a structured way	Suggest relevant information for the developer	Detect duplicate documents	Detect duplicate partfiles	Remove dublicates	Store relevant information regarding the product	Communicate previous executed work to the developer
1	Reduces the amount of sources	9	3	9	3	3		1	1	1	9	3
2	Preserves the reliability of the information	3	9			3		3	3	3	3	
3	Presents the availiability of the information	3	3		9	3	1				1	1
4	Prevents duplicates of documents	1	3	1				9	9	9	3	
5	Enlightens the need of information	1		1	3		9	1			3	9
6	Provides clarity on previously executed work		3	3	3		3				9	9
7	Allows reuse	3	1	9		3					3	9
8	Provides suport for developers decision		1		1	3	1				3	3

Figure 23 System A results of the QFD relationship mapping

In Figure 23 the results for System A can be seen. The needs regarding the Organizational Complexity are transferred from the Needs List to the WHATS room and the same principles are applied when transferring the Non-Function System Requirements to the HOWS room of the QFD HoQ. The relationships are mapped based on the QFD principles seen in chapter 5.1.

		12	13	14	15	16	17	18	19	20	21
		SYSTEM B									
		Process Complexity							Product Complexity		
		Communicate existing CAD-Models	Create workguidlines for the developer	Structure modeling tree	Create robust models	Map parametric dependencies	Highlight critical parameters	Establish flexible CAD Models	Organize product dependencies	Generate produt understanding	Follow concept development principles
9	Provides understanding on existing CAD Models	9	1	1		3	1				
10	provides a standarized work method		9		1						
11	Provides understanding on the modeling tree	1		9		1	1				
12	Provides understanding on parametric dependencies					9	3	1			
13	Preserves the robustness of CAD models				9			3	1		
14	Enlightens the critical parametric dependencies						9	1			
15	Presents the optimal manipulation seequence of dependencies					3	9	1			
16	Allows adaptable CAD models				3			9	3	1	
17	Reduces the product Complexity								9	3	
18	Increases the product understanding								3	9	1
19	Provides support for the concept development process								1	1	9

Figure 22 System B results of the QFD relationship mapping

The same activities are conducted when creating System B and System C QFDs and the results of the categorization of the need, Non-Functional System Requirements and the mapped relationships. The results can be seen in Figure 22 for System B and in Figure 24 for System C.

		22	23	24	25	26	27	28	29	30	31	32
		SYSTEM C										
		Databse										
		Reduce wasteful work for the developers	Adapt the application	Communicate with developer through interface	Enjoy the design activity	Provide simplicity for the developer when navigating the system	Capture the intention od design	Store project progress	Store CAD-Model files	Customize interface environment base on developers needs	Control the system environment	Comply with development method
20	Reduces rework	9		3	1		3	3	1		1	
21	Allows overall adaptability		9	1		1		1		3		3
22	Allows ineractions with the developer			9		3				3		
23	Enables the "fun-part" of designing			3	9					1	1	
24	Is easy to use				1	9				3	1	1
25	Allows capture of design intent						9					
26	Allows project documentation							9	3		1	
27	Has to manage previous versions of CAD Models	1				1		3	9			
28	Allows retrival of previous versions	1						3	9		3	1
29	Allows individualization									9	3	
30	Prevents disruption of work	3				1					9	
31	Provides simplicity									1	9	3
32	Increases the design freedom	3			3	3	1	1	3		3	1
33	Allows simultanious creation of concepts					1			1		3	9

Figure 24 System C results of the QFD relationship mapping

5.5. QFD 1 System-Of-Systems

The QFD 1 System-Of-System is created to generate a ranking of the identified Non-Functional System Requirements. The modified QFD HoQ consists of five different sections which can be seen in Figure 25 and in Appendix E for an enhanced illustration.

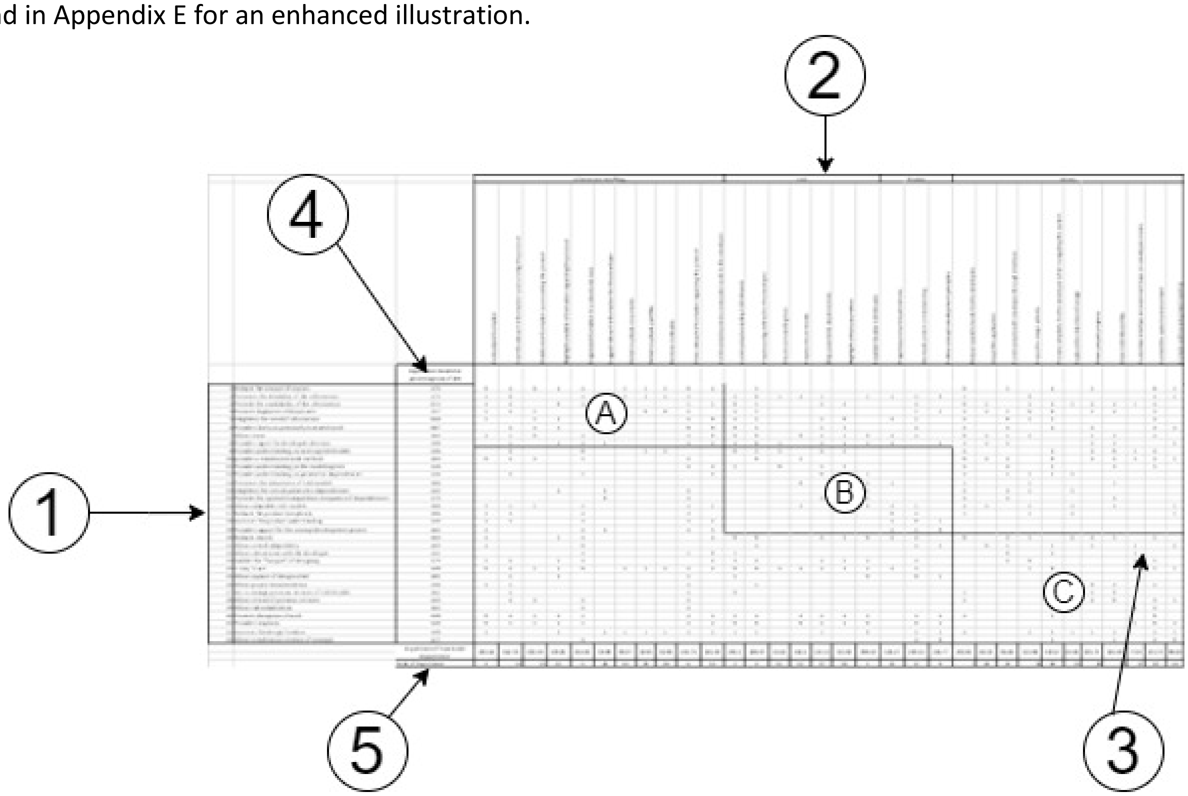

Figure 25 An overview of the Created QFD 1 System-Of-Systems and the different sections numbered

1. **WHAT's Room** The results of the WHAT's room in Figure 25 is the created Needs List (see chapter 4.5) which represents the Operational Requirements of the entire system following the principles of the Holistic requirement Model (HRM) (see chapter 3.2.1).

2. **HOW's Room** The results of the HOW's room is occupied by the Non-Functional System Requirements (see chapter 5.3), following the principles of the HRM.

3. **Relationship Matrix Room** The results of the relationship matrix room are the foundation for the creation of the importance values of the Non-Functional System Requirements.
The relationships from the three Systems (A, B and C) seen I chapter 5.4 are directly transferred to the QFD System-Of-Systems. The mapping of relationships then continues by analysing each row systematically and evaluating against the N-FSR in the columns based on the QFD principles in chapter 5.1.

4. **Weight of WHATS** The results of the Weight of Needs room are transferred directly from the calculation results from the use of the Pairwise Comparison method (see chapter 5.2). The weights are presented as a percentage of 100 where a higher percentage represents a higher Need importance. These weights are one of the foundations for the creation of importance values of the Non-Functional System Requirements.

5. **Importance Value Room** for N-FSR The results of the Importance Value Room (see Figure 26 and Appendix E) are derived by calculating a value for each individual Non-Functional System

Importance of Non-Functional System requirement	281.63	162.78	105.19	104.85	253.92	59.99	49.07	50.95	50.95	243.75	165.19	291.3
Rank of Improtance	4	14	21	22	5	28	31	29	29	6	13	2
	Centralize information	Identify relevant information surrounding the product	Distribute information surrounding the product	Highlight available information regarding the product	Organize information in a structured way	Suggest relevant information for the developer	Detect duplicate documents	Detect duplicate partfiles	Remove dublicates	Store relevant information regarding the product	Communicate previous executed work to the developer	Communicate existing CAD-Models

Figure 26 Outtake of the Importance value results of the N-FSR, see Appendix E for complete figure

Requirement. The calculation is executed by systematically multiplying the relationship strength value of a Non-Functional System Requirement when compared to a need with the weight of the need. The calculation is complete when all the needs have been compared to an individual functional requirement.

As can be seen in Figure 26 the results of the importance value presented the rankings of the Non-Functional System Requirements. The best performing Non-Functional System Requirements are translated to the QFD 2 process (se chapter 5.1) for another iteration to translate the N-FSR to more concrete Sub-Solution Requirements for the proposed approach.

5.6. QFD 2

The results of the QFD 2 phase are three QFD’s for each individual Sub-System QFD 1 (see chapter 5.4) where the Non-Functional System requirements are transferred to the WHATs room and the S-SFR represents the HOWs room. The S-SFR are solutions that need to be solved in order to fulfil the most valuable needs of the system.

The QFD 2 phase for the Systems A and C (see chapter 5.4) are combined where the highest ranked Non-Functional System Requirements are transferred from the QFD 1 phase to the QFD 2 phase.

The proceeded Non-Functional System requirements are iterated once again by the use of the Holistic Requirement Model (HRM) (see chapter 3.2.1 and 5.3) to create Sub-Solution Functional Requirements for the proposed approach.

Proceeded N-FSR from System A and C to QFD 2
Centralize information
Highlight available information regarding the product
Organize information in a structured way
Suggest relevant information for the developer
Store relevant information regarding the product
Communicate previous executed work to the developer
Reduce wasteful work for developers
Enjoy the design activity
Store CAD-Model files
Control the system environment
Comply with development method

HRM

Created Sub-Solution Functional Requirements for System A and C
Create a single interface platform for the user
Base the system architecture on the product architecture
Create a system that visually supports the developer in the development process
Create a system interface that supports the developer with both functional and physical knowledge reuse
Create a system interface that is user friendly
Store CAD-files in an organized and accessible manner
Create a system that allows the user to individually control aspects of the interface layout
Illustrate the role of the proposed approach in the development process

Figure 27 Created Sub-Solution Functional requirements for System A and C N-FSR based on the HRM principles

The result of the new iteration of the HRM for QFD 2 system AC can be seen in Figure 27. The Non-Functional System Requirements are transferred to the WHATS room of the QFD 2 and the created Sub-Solution Functional Requirements seen in Figure 27 are transferred to the HOWS room in the System A & C (see Appendix F).

The weighting of the WHATS room requirement is done by summarizing the total of all the translated importance value from the QFD 1 System-Of-Systems (see Appendix E). Each individual importance value is divided with the total sum. This to create the weight of that specific Non-Functional System Requirement by retaining a percentage on how important an individual N-FSR is within the specific system. The results of the weighting are seen in Appendix F.

The same activities are done to create the System B QFD 2. The results of the HRM translation of the proceeded N-FSR from system B can be seen in Figure 28.

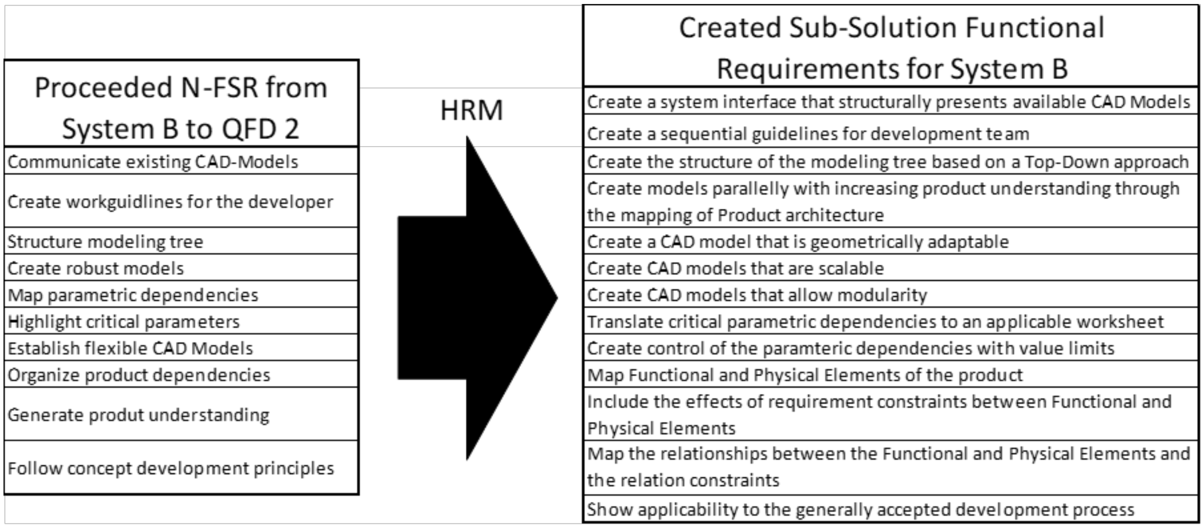

Figure 28 Created Sub-Solution Functional requirements for System B N-FSR based on the HRM principles

The completed System B QFD 2 can be seen in Appendix F and the calculation results of the weights for the system B Non-Functional System Requirements can be seen in Appendix F. The same principles are used for the weighting as in the presented System A & C QFD 2.

The outcome of the QFD 2 for Sub-Solutions System B and System AC (see Appendix F) was the Sub-Solution Functional Requirements (S-SFR) (see chapter 5.7) that act as the requirements that need to be solved by the proposed approach. Since the S-SFR can be directly linked to the gathered needs due to the systematic breakdown methodology of the QFD process, by presenting methods that solve different specific S-SFR it can be established that a Sub-Solution fulfils the needs.

5.7. Sub-Solution Functional Requirement List

The highest ranked Sub-Solution Functional requirements seen in the QFD 2 System AC and System B are transferred to a Sub-Solution Functional Requirement list. Collectively 17 Requirements for the sub solutions are created to serve as a guideline for identifying solutions that can fulfil the requirements seen in Figure 29. As these requirements are created by systematically breaking down the needs, from the Needs List and applying them in the modified QFD using the Holistic Requirement Model, the important needs are deemed fulfilled if a sub solutions fulfils the Sub-Solution Functional Requirements (seen in Figure 29).

Even though a lot of effort has been put to into cascading and organizing requirements through a systematic breakdown and weighting, the validity of this approach could have been improved. The results describe 17 requirements that are relevant for the solutions, but the underlying data could have been more sufficient. However, both time restraints and limitations of this project are acknowledged and based on the best knowledge of the writer at the given time this data provided the possibility to progress the project even though it is acknowledged that the underlying could have been improved.

	Sub-Solution Functional Requirement List
S-SFR1	Create a single interface platform for the user
S-SFR2	Create a system interface that structurally presents available CAD Models
S-SFR3	Create models parallelly with increasing product understanding through the mapping of Product architecture
S-SFR4	Create a CAD model that is geometrically adaptable
S-SFR5	Create CAD models that are scalable
S-SFR6	Create CAD models that allow modularity
S-SFR7	Translate critical parametric dependencies to an applicable worksheet
S-SFR8	Create control of the paramteric dependencies with value limits
S-SFR9	Map Functional and Physical Elements of the product
S-SFR10	Include the effects of requirement constraints between Functional and Physical Elements
S-SFR11	Map the relationships between the Functional and Physical Elements and the relating constraints
S-SFR12	Base the system architecture on the product architecture
S-SFR13	Create a system that visually supports the developer in the development process
S-SFR14	Create a system interface that supports the developer with both functional and physical knowledge reuse
S-SFR15	Create a system interface that is user friendly
S-SFR16	Store CAD-files in an organized and accessible manner
S-SFR17	Create a system that allows the user to individually control aspects of the interface layout

Figure 29 Created Sub-Solution Functional Requirement List

6. Sub-Solutions fulfilment of S-SRL

In the following chapter a presentation on what methods and approaches are used in order to fulfil the 17 identified Sub-Solution Requirements are presented.

6.1. Platform Modelling with EF-M

As Michaelis et al (2014) explains by using platforms that are thoughtfully developed it is possible to increase flexibility to allow development of variants over an extended period of time. Since a products physical parts are evaluated on how well they achieve their respective functionality and performance it becomes evident that by mapping functions to respective physical parts, the understanding of the product increases and allows the possibility for the developers to reuse knowledge (Michaelis et al, 2014).

Schachinger and Johannesson (2000) also states that the main aim of a requirement specification is to create a description of the desired outcomes of a product from the viewpoint on the required behaviour. Therefore, the authors argue that a product description through a requirement specification is rigid and dependent of completeness before realization. Michaelis et al (2014) also claims that the main benefits of using the Function-Means approach is the ability to capture the different potential conceptual considerations through capturing the design rational.

Michaelis et al (2014) explains that basing a solution on a platform-based approach with the intention of capturing design solutions through the products functionality, it is possible to transfer the EF-M tree structure to another system such as CAD (see chapter 2.2.1) or PDM (see chapter 2.2.5) software and mimic it. Gero and Kannengiesser (2004) also state that new requirements can arise during anytime of the development process, which makes the environment within the process very dynamic. This further facilitates that basing the solution on a platform-based approach that is adaptable is the optimal solution. The EF-M tree can also be modified at any time and allows for new FRs and DSs be added at any time creating new relationships.

Therefore, by creating a platform modelling approach **(see chapter 2.3.1)** system focusing on mapping the functional elements (see chapter 2.3) of a product through using a function model approach such as EF-M (se chapter 2.3.2), would fulfil the Sub-Solution requirements (S-SRL 9, 10, 11, 12, 14, see chapter 5.7 for the S-SRL): **The use of the methods also supports** the Sub-Solution Requirements : S-SRL 2, 3, 6, 13, 15 (see chapter 5.7).

The Platform Modelling approach together with mapping the product architecture with the EF-M approach **is the core** of the proposed solution to create a Library system that allows Geometrical Design Space Exploration with flexible CAD models.

6.2. PLM

PLM systems (see chapter 2.2.5) are well documented and are frequently used as a database in the Industry today (see chapter 4.3). In order to create the proposed approach of a Library System consisting of CAD models that are flexible and adaptable it is important to define what type the database is used as the shell to incorporate the solution. The aim is to increase the design freedom and increase the exploration of design alternatives. Therefore, it is redundant to use a database that takes into the consideration the whole lifecycle process of a product.

A challenge that is both acknowledged by the observation and statement results is that the databases used in the industry standard can be very complex and challenging to navigate in (see chapter 3.1.3 and 3.1.2). Lindemann (2019) argues that in order to reduce the complexity when storing information, it is important to create a structure that follows a method. A clear structure is shown to increase both the understanding of users as well as effectives the work which can lead to reduced waste time during usage (Lindemann, 2009).

Therefore, by creating a PDM system that follows the structure of the **core** of this solution (Platform modelling by using EF-M see chapter 6.1) the proposed solution can fulfil the Sub-Solution Requirements (S-SRL 1, 2, 12, 16 and 17 see chapter 5.7) as well as support the Sub-Solution Requirements (S-SRL 3, 5, 7, 8 see chapter 5.7).

6.3. CAD

CAD modelling (see chapter 2.2.1 and 3.3.3) is the heart of the proposed approach The aim of the project was to create a Library System consisting of flexible and modular CAD models that can be used to explore design alternative. Therefore, it is important to identify what type of modelling techniques should be applied to present a possible solution for the problem. Firstly, it was decided that the software NX 12 (see chapter 2.2.1.1) is an appropriate software due to the hybrid modelling possibilities. Scalability of models, geometrical manipulation and modularity are the three sought attributes. The scalability can be created by the use of parametric dependencies. In order to address the identified issues of parametric models which lacked clarity of limits (see chapter 4.2), the parametric dependencies should be mapped and relationships should be created. This allows the possibility to create a controllable geometrical design space for the design alternative exploration.

The geometrical manipulation is possible due to use of the unique synchronous modelling technique (see chapter 2.2.3) in NX 12 together with subtraction modelling technique (see chapter 2.2.3).

In order to create a Library system of modules of different design solutions, a universal interface should be created between the interacting modules. A potential solution is to create the universal interface based on bus-modularity (see chapter 2.3.3). To identify the area of interface, the product architecture mapping by EF-M (see chapter 2.3.2 and 6.1) can be used to identify where the conceptual level DSs interact with each other.

Therefore, by creating CAD models in NX12 using controlled Parametric Dependencies with Max and Min values, Synchronous and Subtracting modelling techniques and a modular universal interface it is possible to fulfil the Sub-Solution Requirements (S-SRL 3, 4, 5, 6, 7, and 8 in chapter 5.7) as well as support the Sub-Solution Requirements (S-SRL 16 and 17 in chapter 5.7) .

6.4. CAE

In order to create a Library System that allows for exploration of design alternatives, there has to be a comparison between the created design alternatives versus the baseline in order to be able to increase knowledge about the designs. To achieve this a CAE software (2.2.4) such as ANSYS (see chapter 2.2.4.1) should be used where different mechanical analyses can be created virtually.

Therefore, by creating a Library System that incorporates comparison between deign alternatives through data collected from virtual testing the Sub-Solution Requirements (S-SRL 3, 13, 14 and 15 in chapter 5.7).

7. Proposed Approach – Library system

The proposed approach Library System is presented by creating a User Interface flowchart (see chapter 3.4.1). In order to illustrate the created flowchart, it is broken down to five sub-systems that clarify the activities within them. The Sub-systems also demonstrates how different agents interact with each other during the use.

The created flowchart is divided into two categories. The first category is the preparation work required to create a platform for an existing solution where the intent is to explore new design alternatives. Sub-System 1 presents the PDM and CAD-model setup activities. Sub-System 2-5 illustrates the execution category which presents the actions for when a User interacts with the created Library system.

7.1. System Map Proposed Approach – User Perspective in Library System

The result of the creation of the system map for the proposed approach is illustrated in Figure 30 and the sub-systems of the flowchart are presented in the following chapters. The flowchart was systematically created with the order being illustrated by the sub-systems (1-5) on the figure. The flowchart presents how the different sub-solutions (see Chapter 6) incorporates into the Library System.

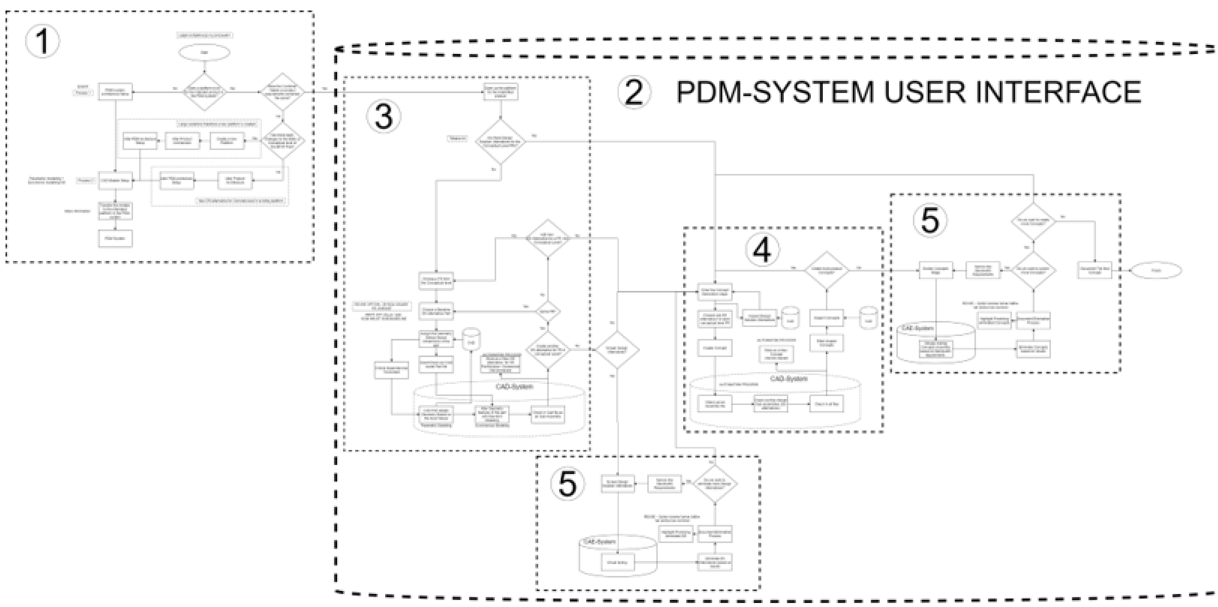

Figure 30 Illustration of the created Flowchart for the Proposed

7.1.1. Sub-System 1

The first step of creating the flowchart is to determine the process of the preparation work. The first scenario is if no previous platform, for a product that the development team wants to alter the geometry on, exists. The process is illustrated in Figure 31.

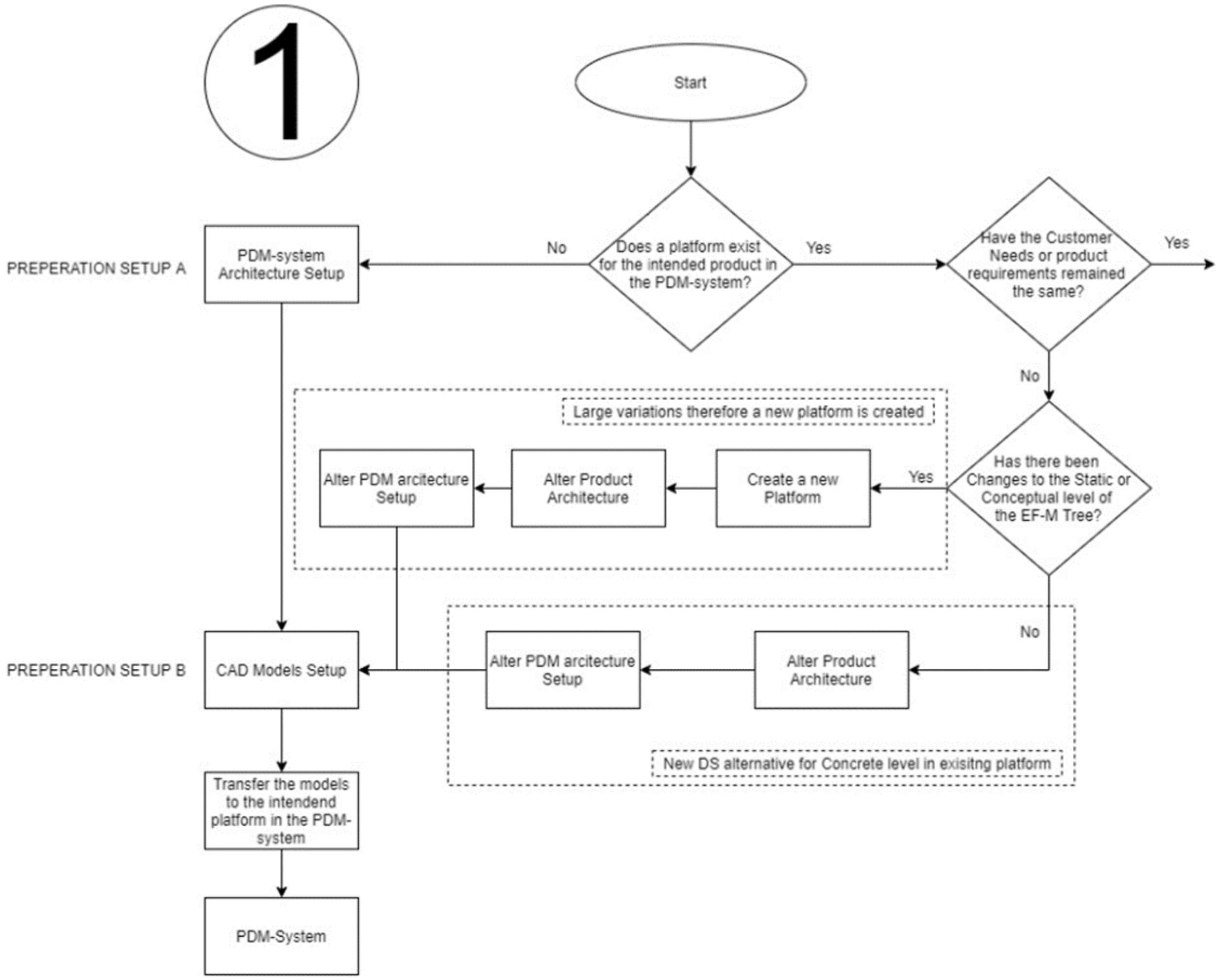

Figure 31 Illustration of the preparation work which represents Sub-System 1 in the Proposed Approach

The first step is to create a structure for the PDM architecture. During the creation of the activities SBCE (see 2.1.2) and Complexity management (see 2.1.3) principles are taken into consideration. The structure is determined by using already existing information on the product which the platform is built around. The activities to create the PDM structure can be seen in Appendix G. Four previous activities has to be transferred from the previous work done when creating the initial existing product solution: The existing solution geometry as a baseline, A functional decomposition of the existing product, the identified customer needs of the existing solution and the requirement specification of the existing solution.

As the initial architecture is created for the PDM-System, the second phase is to create the setup for the CAD models.

A demonstration of the PDM architecture setup application will be presented further on in the report as a digital mock-up illustration.

The CAD model setup is created by examining the concrete level of the existing solution and determine how it is composed. This creates the foundation for the baseline solution where the geometrical design space requirements are translated into constraints by applying parametric dependencies that controls the ability to manipulate the geometry of a CAD model.

The parametric dependencies are mapped, and a MAX and MIN value limit is created for the driving dependencies of geometrical change. The limits are created from mathematical relationships, analysing which dependencies are related and at what values they exceed the geometrical design space requirements.

The different parts of the product are derived from the existing solutions conceptual level (see chapter 2.3.2) of the EF-M tree that was mapped during the creation of the PDM structure setup. The individual FRs of the Conceptual level are solved by their specific DS solution. The DSs on the conceptual level represents the different modules. For each module a parametric Baseline is created.

In order to create a modular (see chapter 2.3.3) system a universal interface area between the modules is created following the bus modularity principles.

A demonstration of the CAD Model setup application will be presented further on in the report on a case product.

7.1.2. Sub-System 2

Sub-System 2 contains the activities made in Sub-Systems 3-5. Sub-system 2 represents the Users interface with the library throughout the concept development process activities seen in chapter 2.1. The outcome of using the library system is to enable the user to create different geometrical concepts through the SBCE principles (see chapter 2.1.2) where different modules are combined creating full concepts.

The concepts are then tested by using CAE (see chapter 2.2.4) tools such as Ansys (see chapter 2.2.4.1) to support the decision making for developers during the screening process.

By creating a library system that allows the user to analyse the virtual test results before deciding which concepts to eliminate the SBCE principle can be achieved.

7.1.3. Sub-System 3

As the architecture has been setup in the preparation work (Sub-System 1) the user is ready to use the library system. The activities in Sub-System 3 (see Figure 32) guides the user to create different geometrical concepts for each Functional Requirement (FR) in the conceptual level (each module). The result of this activity is alternative Design Solutions (DSs) geometries in CAD which all fulfil the FR. This sub-system represents the idea generation phase of concepts in the Product development Process (see chapter 2.1)

When creating a new geometrical design for a FR the User can explore different designs by firstly entering the values to determine the Geometrical design space of the concept. This is done by following the created MAX an MIN values and manipulating the driving dependencies of the parametric CAD model.

As the geometrical design space has been created the user can check out the CAD models from the library system to the NX software and manipulate the geometry in the CAD model by using synchronous and subtraction modelling techniques (see chapter 2.2.3). The user has free reins when creating the new geometry. When the sought geometry has been achieved the CAD, model is checked in back to the library system and a new part version is stored as a new Design Solution for the chosen Functional Requirement in the library system.

A proof of concept through a demonstration of these activities will be presented further on in the report on a case product.

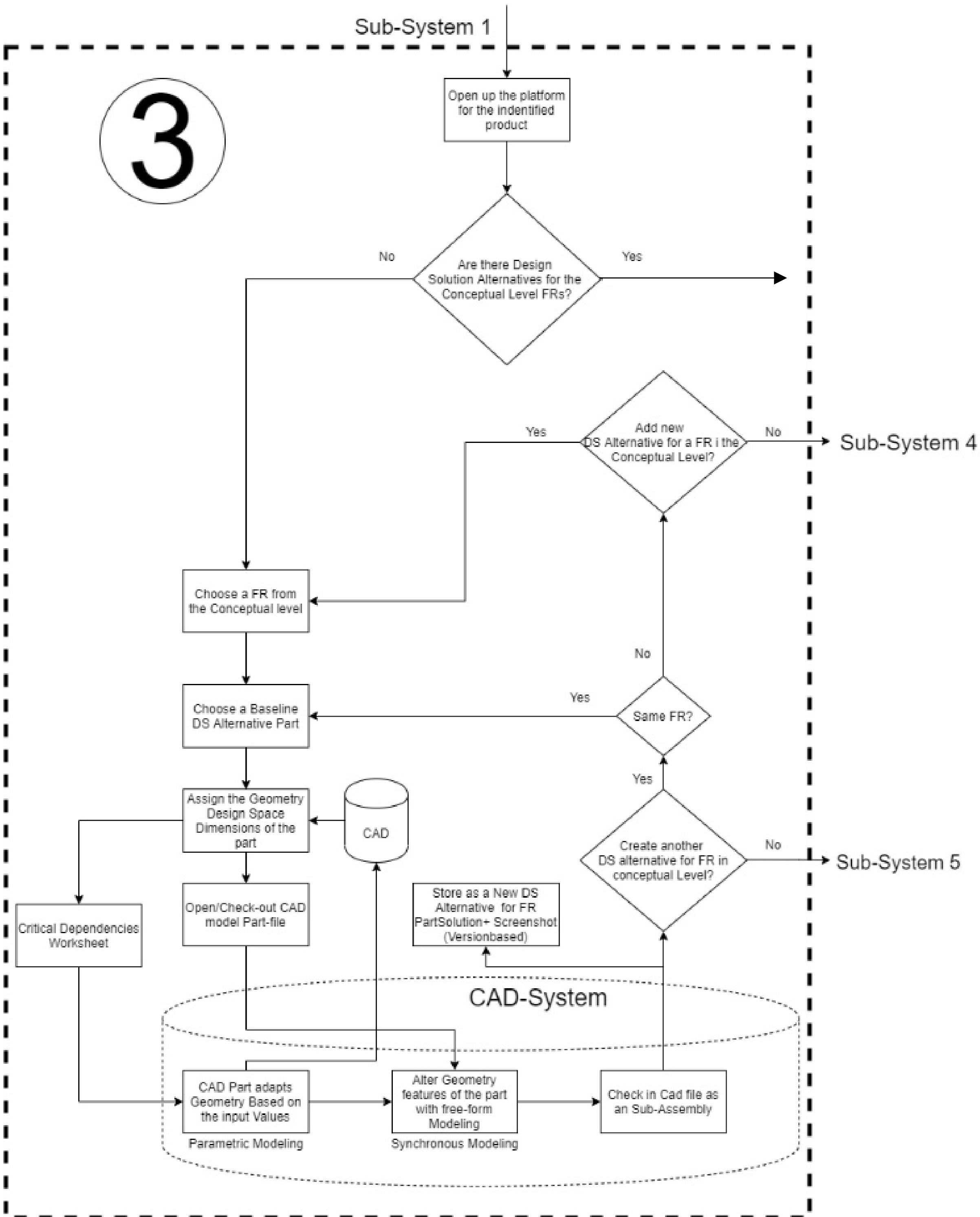

Figure 32 Process map of the Users activities when creating different concepts for the Conceptual level Functional Requirements

7.1.4. Sub-System 4

As the alternative Design Solution Geometries have been created the user enters Sub-System 4 (see Figure 33) of the library system which is the concept generation stage. The concept generation phase follows the principles of SBCE (see chapter 2.1.2) where different sets of DSs from different FR can be combined to embody a product concept.

An assembly file and the chosen DS for the FRs are checked out. The Assembly is created in NX by applying assembly constraints on the created universal interface.

As the assembly is checked in to the Library System a Concept versions is created which is stored under the Static Level Functional Requirement representing a Product Concept.

The different product concepts can be inspected where the user can see the composition of the concept.

A proof of concept through a demonstration of these activities will be presented further on in the report on a case product.

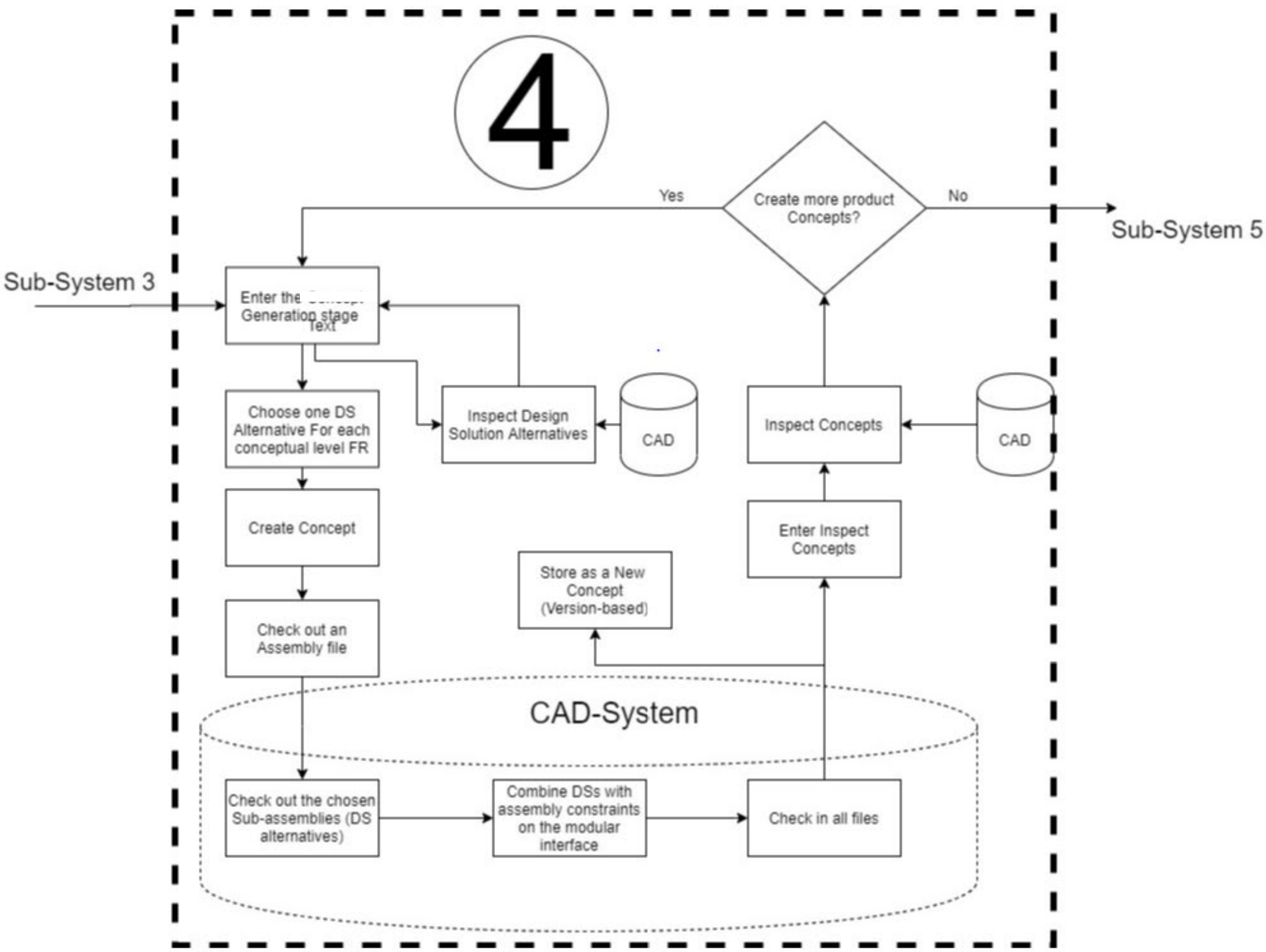

Figure 33 Process map of Sub-System 4 which represents the product concept generation stage

7.1.5. Sub-System 5

As the Concept generation is completed the user enters Sub-System 5 (see Figure 34) where it is possibility to virtually test the generated product concept assemblies through the integration of CAE software. This supports the developers for the Concept Screening stage in the product development process (see chapter 2.1) and follows the principles of the SBCE approach (see chapter 2.1.2) where the idea is to not eliminate concepts based on assumptions but only eliminate based on knowledge which in this case represents the data results collected from virtual testing.

The users can test out pre-defined load cases on the concepts and analyse the results. Dependent on the result the users can determine if a concept should be eliminated our evaluated with more virtual tests with e.g. increased forces on the load cases. If a concept does not pass the load requirements but is deemed as an interesting concept, the user has the option to document it as a promising concept. The promising concepts can either be remodelled by using it as a baseline in a new design development or be stored in the case of it becoming relevant in a future scenario.

The winning concept/concepts are documented thoroughly, and the documentation is stored in the Library system.

A proof of concept through a demonstration of these activities will be presented further on in the report on a case product.

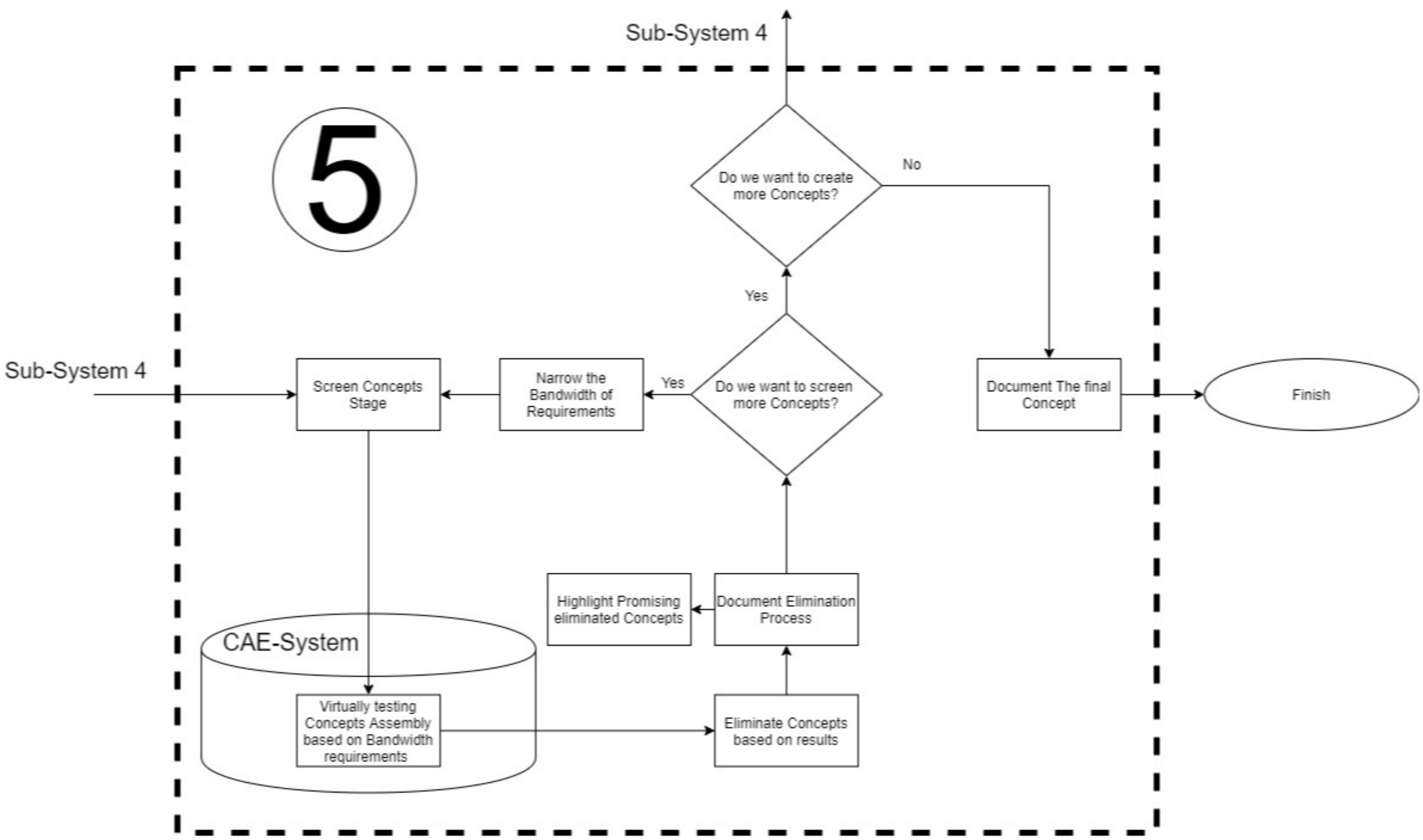

Figure 34 Process Map of the activities in the Concept Screening stage of the Library system

8. Proof-Of-Concept – Demonstrator

In the following chapter a demonstration of the created proposed approach is presented. A case product is introduced with its corresponding requirements and the results for each sub-system in the User Interface Flowchart (see chapter 7.1) is showcased through the demonstration.

8.1. Description of Case Product

The product for the proof of concept, which serves as demonstrator of the method, is a jet engine mounting bracket (see Figure 35). In chapter 3.5.1 an explanation for why this particular product was chosen as the case product as well as the purpose of the demonstration is presented.

Figure 35 Illustration of the Case Product jet engine bracket. Picture from (GrabCAD, 2020).

The GE bracket challenge presented both Geometrical Design Space restrictions for the product as boundary conditions and Load conditions that should be applied on the new designs.

The overall geometry of the bracket has been simplified in order to easier demonstrate the proposed approach but other than that the same boundary and load conditions are applied on the different designs.

The boundary conditions that are applied on the design are directly derived from the GE Bracket Challenge and the values have been translated to mm instead of inches:

Boundary Conditions (Geometrical Design Space requirements) see Figure 36:

- Geometry is resting on an infinitely stiff plate
- The new geometry must fit within the envelope of the original design ("Design Space")
    - The Geometry Design Space of the envelope was measured from the original model
    - A simplified Baseline was created for the Proof-Of-Concept. The following Boundary conditions still apply for the simplified baseline Model.
- Minimum wall thickness of 2 mm
- Interface 1: 20 mm diameter pin. The pin is considered infinitely stiff
- Interfaces 2-5: The bolts are considered infinitely stiff.

- Interfaces 2 – 5: Nut face MAX Inner Diameter: 10 mm. MIN Outer Diameter 14mm. The bolts are to be considered infinitely stiff.

The new geometrical concepts will need to fulfil the four load conditions that have been derived from GE bracket challenge requirements on the new designs (GrabCAD, 2020).

Load Conditions (see Figure 37):

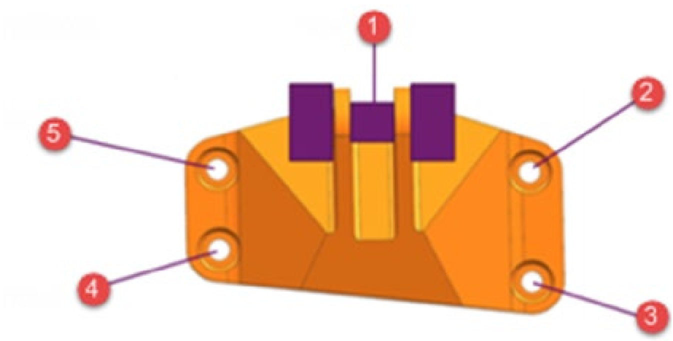

Figure 36 The five interfaces on the Bracket. Picture from (GrabCAD, 2020).

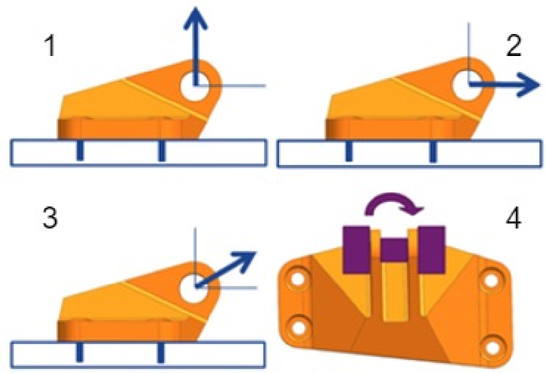

Figure 37 The four load conditions on the case product (GrabCAD, 2020).

- Assume yield strength is 903 MPa
- Load Case 1: Maximum static linear load of 35 600 N, applied vertically.
- Load Case 2: Maximum static linear load of 37 900 N, applied horizontally.
- Load Case 3: Maximum static linear load of 42 260 N, 45 degrees from vertical.
- Load Case 4: Maximum static torsional load of 565 Nm, horizontal at intersection of centreline of pin and midpoint between clevis arms.
- Target the lightest Designs

8.1.1. EF-M

In order to illustrate the results of the PDM architecture setup and foundation for the CAD models setup, the activities presented in Sub-System 1 chapter 7.1.1 was applied on the jet engine bracket.

The first activity is to create EF-M Tree (see Figure 38) for the Case Product and map the static and conceptual level of the tree. The mapping follows the EF-M principles seen in chapter 2.3.2 and the description on how the method has been applied can be seen in chapter 3.3.1.

It is assumed that a Customer Needs analysis, Requirement Specification and Functional Decomposition on the Case Product Exists prior to these activities as described in chapter 7.1.1.

The Static level functional requirement is derived from the GE Bracket Challenge description of the jet engine bracket.

The conceptual level consists of two FRs which are the plane and engine interfaces. The two FR create DS modules. The Design solutions for the conceptual level is mapped out as seen in Figure 38.

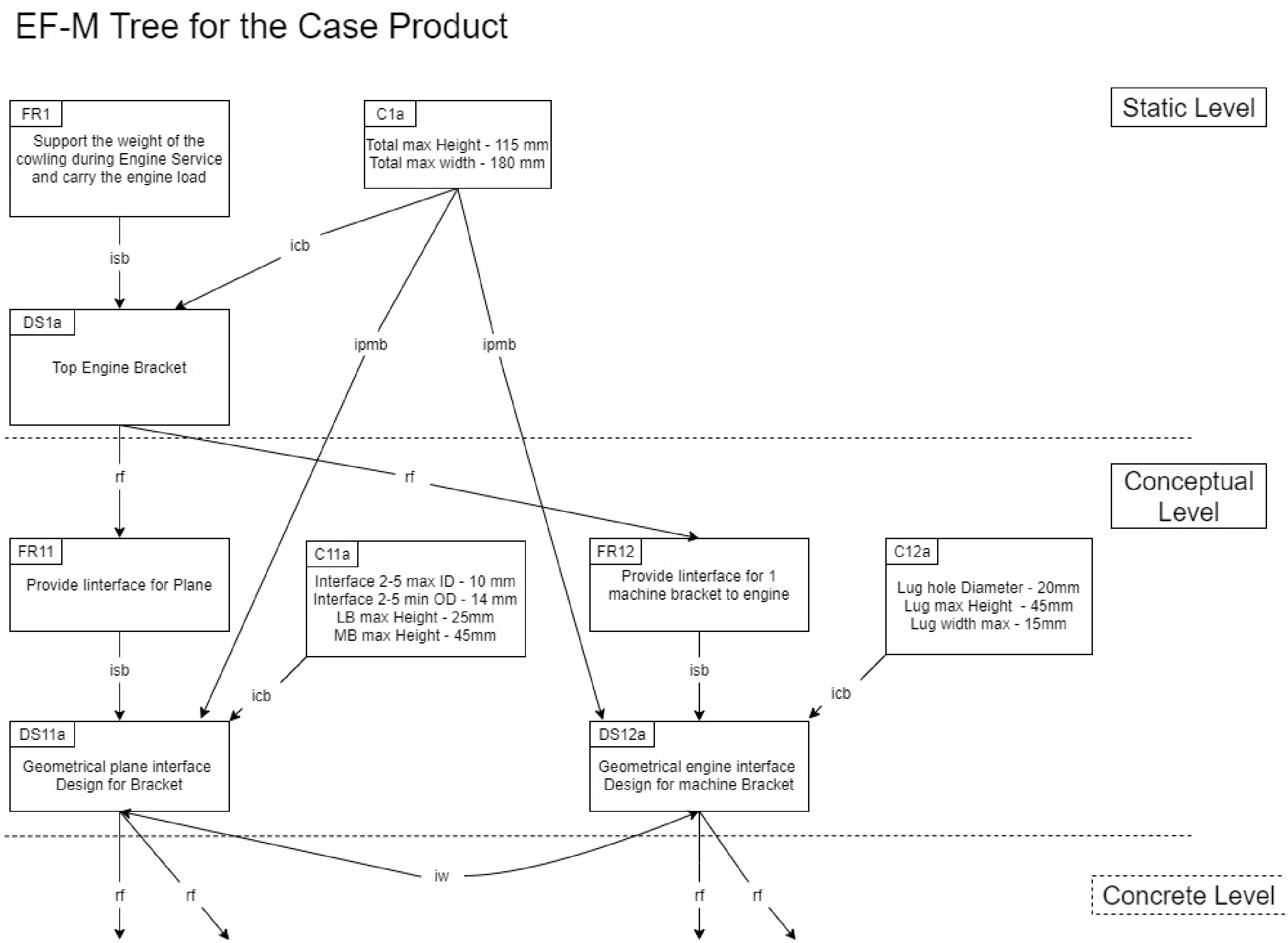

Figure 38 EF-M tree of the static and conceptual level on the Case Product

In order to determine the Constraints seen in Figure 38, the existing solutions concrete level (the design embodiment) of the Engine Bracket is examined to set the dimensions for the baselines envelope. The baselines envelope determines the Geometrical Design Space (see chapter 2.1.1) restrictions.

The constraint on the static level (C1a in Figure 38) is partly met by the two underlying Design Solutions on the conceptual level.

New individual constraints for DS11a and DS12a are mapped as C11a and C12a in Figure 38. The individual constraints are translated from the Boundary Conditions for the case product (see chapter 8.1).

The relationships (see chapter 2.3.2 and 8.1.1) rf, iw, isb, icb and ipmb are mapped out for both the static and conceptual level in the EF-M tree as can be seen in Figure 38.

Relationship iw in Figure 38 illustrates the area of interface between the two DSs which is later used to create the universal interface between the two existing modules.

8.1.2. PDM-Setup

In parallel with the work created in chapter 8.1.1 the creation of the PDM structure (see chapter 7.1.1) is done. To understand how the work will be presented see chapter 3.3.2.

The documented EF-M tree is used as a guideline for the PDM structure. The illustration of the PDM structure is done with a Mock-Up (see chapter 3.6.3).

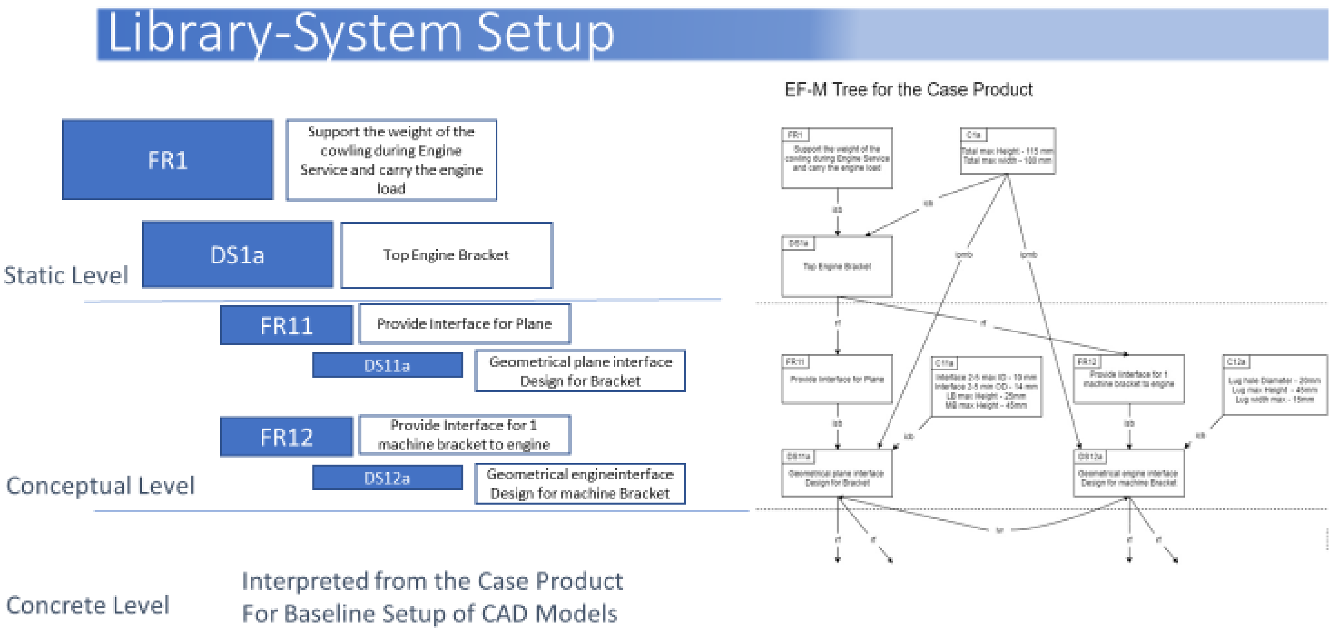

Figure 39 Mock-Up illustration of the Library-System Interface - user perspective

As can be seen in Figure 39 the PDM structure is created based on the work executed in 8.1.1. The EF-M tree structure of the static and conceptual level are directly transferred and translated to the PDM structure. The illustration in Figure 39 (see Appendix H for detailed illustration) is presented as the Users point of view when interacting with the PDM system.

A description for each FR and DS is presented where the descriptions are transferred from the documented EF-M Tree.

The specific PDM structure is used to easier visualize where geometrical design solutions are stored and what FR the design solutions fulfil.

The user has the possibility to enter each FR on the illustration in Figure 39. FR1 contains assembly files which represents different generated concepts and FR11a and FR12a contains the different DS alternatives for the conceptual level FRs.

8.1.3. CAD-Setup

The activities for the setup of the CAD models can be seen in chapter 7.1.1 and the purpose for the specific setup of the CAD models can be seen in chapter 3.3.3.

The CAD model setup is done by creating parametric part models for the Case product (see chapter 8.1). A universal interface is created to allow the exploration of different sets of design alternatives following the SBCE principles (see chapter 2.1.2).

The first step of creating the baseline is to choose one of the modules as a starting point. FR12 is chosen and the Geometrical design Space restrictions are mapped out on a drawing sketch to serve as a guideline when creating the parametric CAD model.

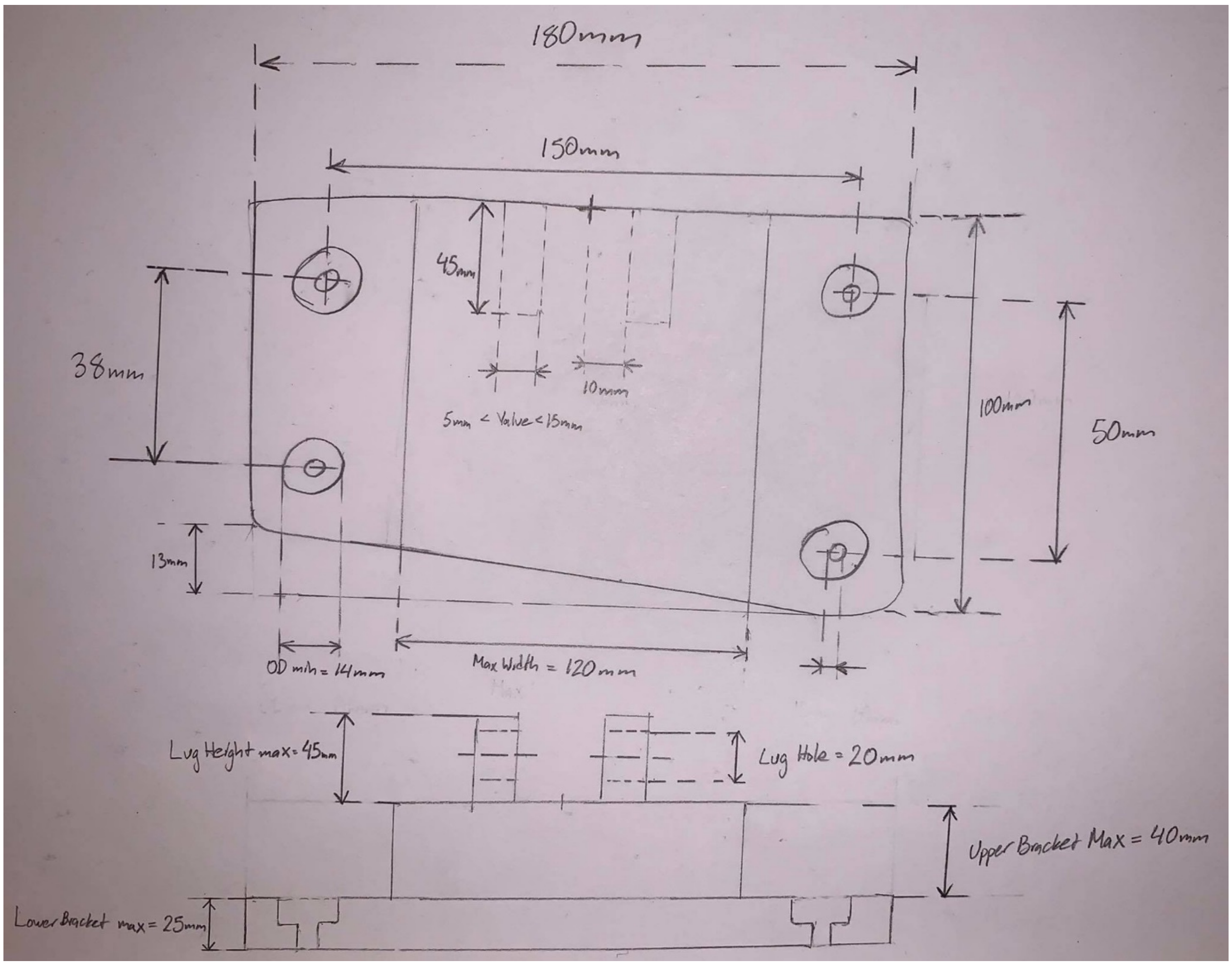

Figure 40 Sketch of the Geometrical Design Space Restrictions for the Case Product

After the sketch is completed (see Figure 40) the baseline for the fulfilment of FR12 (see chapter 8.1.1). The Parametric Models are created in NX (see chapter 2.2.1.1).

As can be seen in Figure 41. The Parametric Dependencies are mapped out and named in a 2D sketch. The first sketch contains the inner holes and the lower bracket body. The 2D sketch follows the Geometrical Design Space Restrictions presented in chapter 8.1.

As the 2D sketch is completed an extrude is applied to create a solid body. The height of the solid body is restricted to the maximum value 25 mm following the envelope restrictions of the case product. The inner holes are created by subtraction operations (see Appendix H).

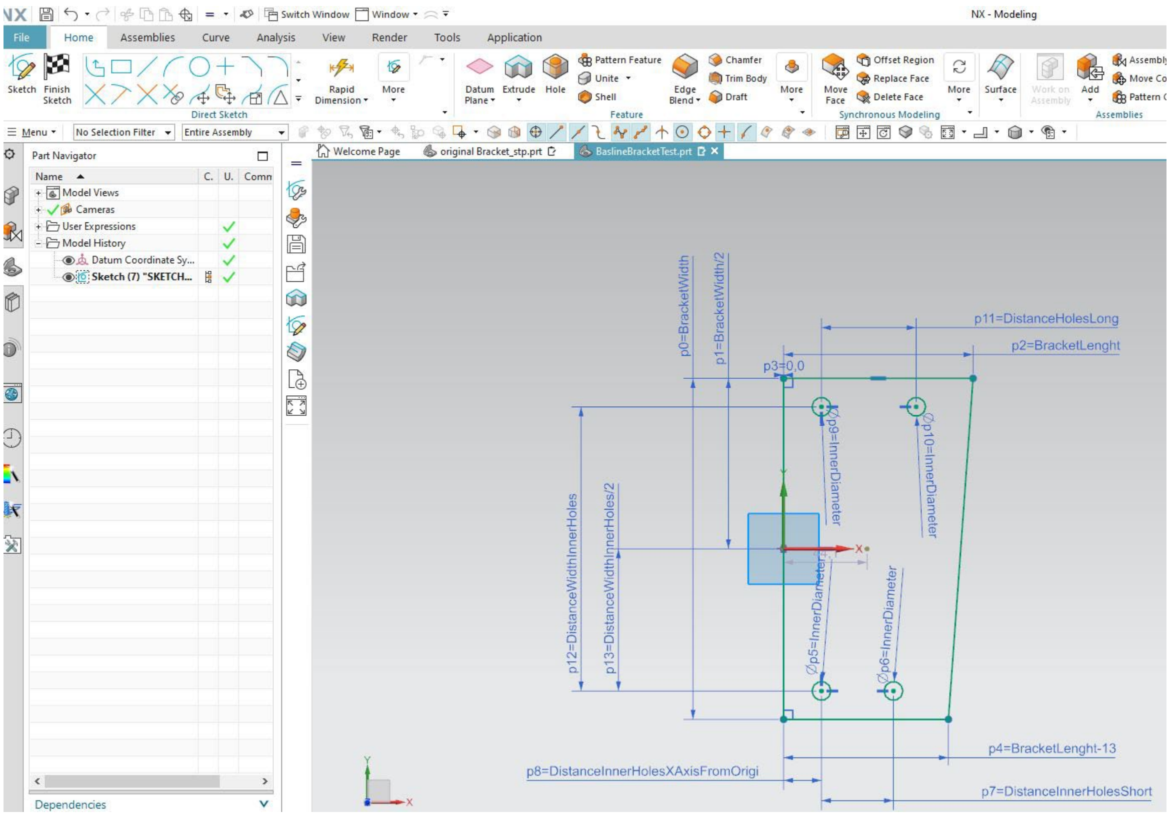

Figure 41 2D sketch of the bracket with named parametric Dependencies in NX

A second sketch is created on top of the extrude to create the upper body of the bracket as well as creating the subtraction to create the upper hole on the lower bracket body. Parametric Dependencies are applied on the second sketch and the extrude is also parametrized (see Figure 42) (see Appendix I for detailed screenshots).

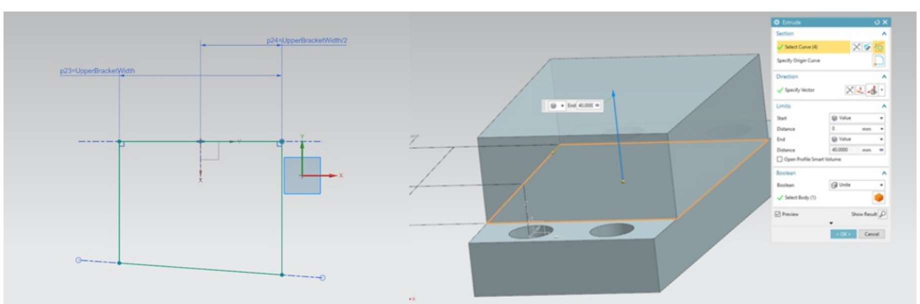

Figure 42 illustration of the Upper Bracket body sketch and extrude

As the upper body is complete the universal interface is created. The universal interface is created following the bus modularity principles (see chapter 2.3.3). A third sketch is placed on the upper surface of the second extrude. Parametric dependencies are created and a subtraction operation on 2 mm is created (see Appendix K).

As the universal interface is created the baseline for the fulfilment of FR12 is completed. The complete parametrized baseline part can be seen in Figure 44 and Appendix J.

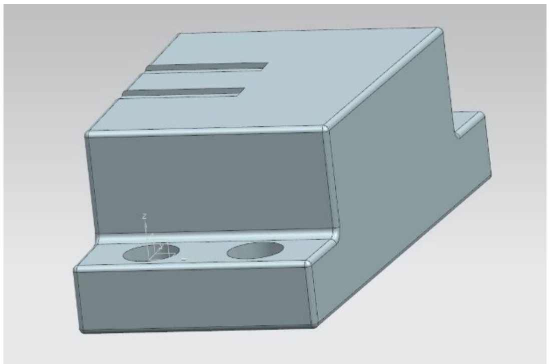

Figure 44 Complete baseline part for the fulfilment of FR12 based on the Case Product

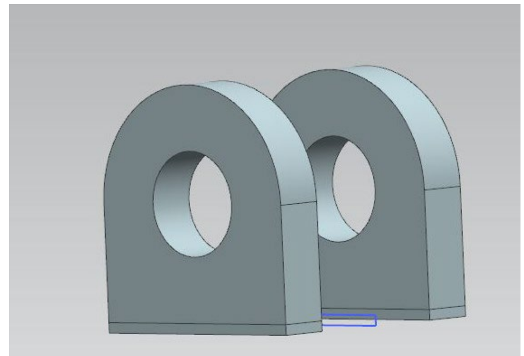

Figure 43 The completed Lug baseline for the fulfilment of FR11 based on the Case Product

The same process is done to create a baseline for the fulfilment of FR11. A universal interface is created as the first sketch of a plate with the matching interface length of 45 mm and a height of 2 mm to match the brackets interface depth.

A second 2D sketch is created which illustrates the Lug and the parametric dependencies are mapped out.

An extrude is created to create the body of the lug and a subtraction operation is applied to create the pin hole of the fixed value 20 mm.

The completed Lug (see Figure 43) fulfils the FR11 and follows the Geometrical Design Space restrictions presented in chapter 8.1.

An assembly of the both Conceptual level Baselines is created to illustrate the fulfilment of FR1. The baseline assembly can be seen as DS1a (see Figure 45).

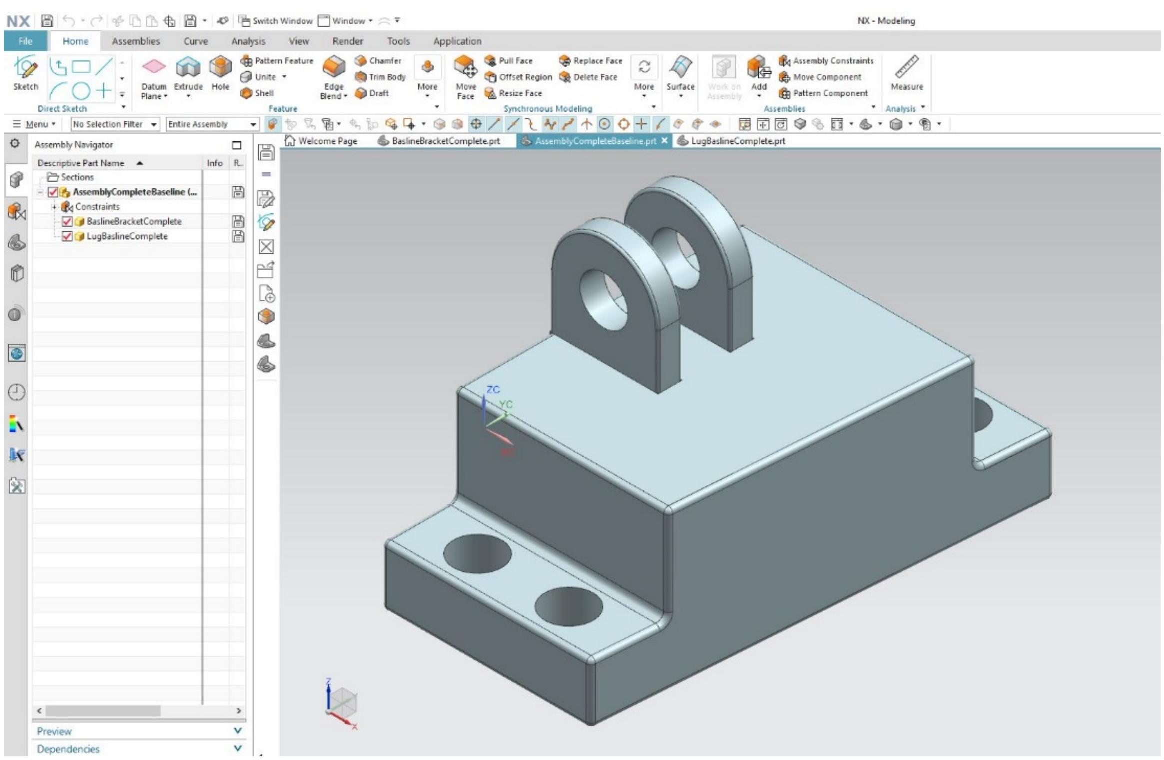

Figure 45 The created baseline assembly

8.2. Application on proposed Approach

The following section presents the application of the proposed approach (see chapter 7) through demonstrating the activities.

8.2.1. Geometry Design Space Restrictions

In order to Create a Scalable CAD baseline model that ensures that no corruption in the model is possible, the MAX and MIN values of the parametric dependencies are identified to guide the developers to not exceed the Geometrical Design Space Envelope. As a demonstrator a C-Code program (see Appendix M) is created which illustrates how the users are interacting and manipulating the parametric values in a controlled environment without the possibility to corrupt the model. By guiding the users with MAX and MIN values it is possible to decrease the complexity and increase the control following the complexity management principles in chapter 2.1.3.

The parametric dependencies for the baseline solution can be seen in Appendix L. As can be seen in Figure 46 a corruption test is done to emphasize the importance of identifying MAX and MIN values to control and guide the User during the Geometrical Design Space assignment in order to create a part that cannot corrupt and fail the boundary conditions in chapter 8.1.

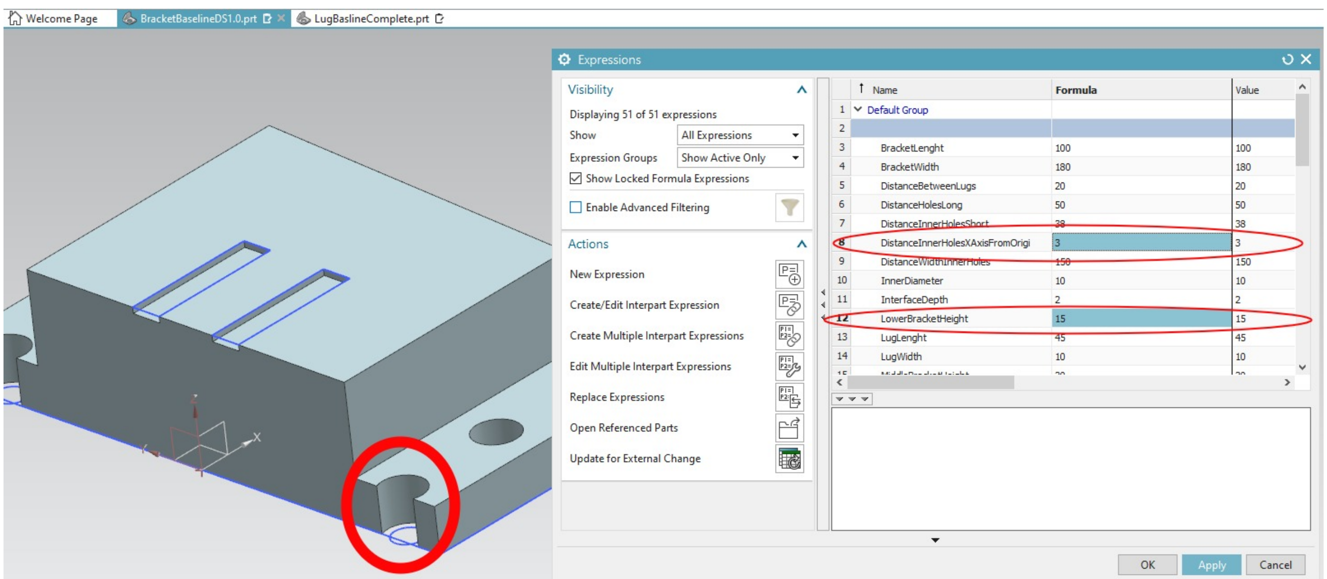

Figure 46 Illustration of two CAD part Model Geometrical Design Space Requirements failures by modifying two parametric dependencies without any support such as MAX and MIN values

Without any guidelines it is difficult for the user to know what relationships exists between the parametric dependencies. Therefore, the relationships are mapped to create a sequential guideline for the inputs on the parametric dependencies. The MAX and MIN values for the driving dependencies are updated depending on what previous values are entered by the user.

In order to create this sequence, the parametric dependencies are mapped in three categories which are the FIXED VALUES (FV) based on Geometrical Designs space restrictions, INTERVAL FIXED VALUES (IFV) based on Geometrical Design Space Restrictions and INTERVAL RELATIONSHIP VALUES (IRV). The presented names of the Parametric Dependencies follow the mapped out parametric dependencies in the NX part files for the Bracket and Lug (see Appendix L for full parametric list).

$FIXED\ VALUES\ Bracket$:
$DistanceBetweenLugs = 20mm$
$DistanceInnerHolesShort = 38mm$
$DistanceHolesLong = 50mm$
$DistanceWidthInnerHoles = 150\ mm$
$InterfaceDepth = 2mm$
$LugInterfaceLength = 45mm$

$INTERVAL\ RELATIONSHIP\ VALUES\ Brakcet$

$$Relationship(1): Min\ DistanceInnerHolesXAxisFromOrigi = \frac{UpperHoleDiameter}{2} + 2mm$$

$$Relationship(2): Min\ BrackerLength = Min\ DistanceInnerHolesXAxisFromOrigi + DistanceHolesLong + \frac{UpperDiameter}{2} + 2mm$$

$$Relationship(3): BrackerLength - 2mm - \frac{UpperHoleDiameter}{2} - DistanceHolesLong$$

$$Relationship(4): Min\ BracketWidth = 2mm + UpperHoleDiameter + DistanceWidthInnerHoles + 2mm$$

$$Relationship(5): Max\ UpperHoleDepth = LowerBracketHeight - 2mm$$

$$Relationship(6): Min\ UpperBracketWidth = DistanceBetweenLugs + (LugWidth * 2)$$

As the relationships between the dependencies are mapped, an optimal sequence for the input is created. The Sequence consists of MAX and Min Values that are either INTERVAL FIXED VALUES that are translated from the Geometrical Design Space Restrictions in chapter 8.1. These intervals are not dependent on relationships. The second Case are the INTERVAL RELATIONSHIP VALUES which are translated from the relationships. The specific sequence is important since the relationships are dependent on previous inputs.

$SEQUENCE\ OF\ INPUT\ FOR\ BRACKET$
$1. UpperHoleDiameter$: $Min = 14mm$ $Max = 25mm$
$2. BracketLength$: $Min = Relationship(2)$ $Max = 100mm$

$3. DistanceInnerHolesX: \quad Min = Relationship(1) \quad Max = Relationship(3)$
$4. BracketWidth: \quad Min = Relationship(4) \quad Max = 180mm$
$5. LowerBracketHeight: \quad Min = 4mm \quad Max = 25mm$
$6. UpperHoleDepth: \quad Min = 2mm \quad Max = Relationship(5)$
$7. LugInterfaceWidth: \quad Min = 5mm \quad Max = 15mm$
$8. UpperBracketWidth: \quad Min = Relationship(6) \quad Max = 120mm$
$9. UpperBracketHeight: \quad Min = 4mm \quad Max = 40mm$

The Sequence is one of the first activities in Sub-System 3 in chapter 7.1.3. The user choses the baseline DS for the FRs in the conceptual level as the baseline to start from. This activity can be seen in Figure 47 as a mock-up illustration for the user interface in the PDM-System.

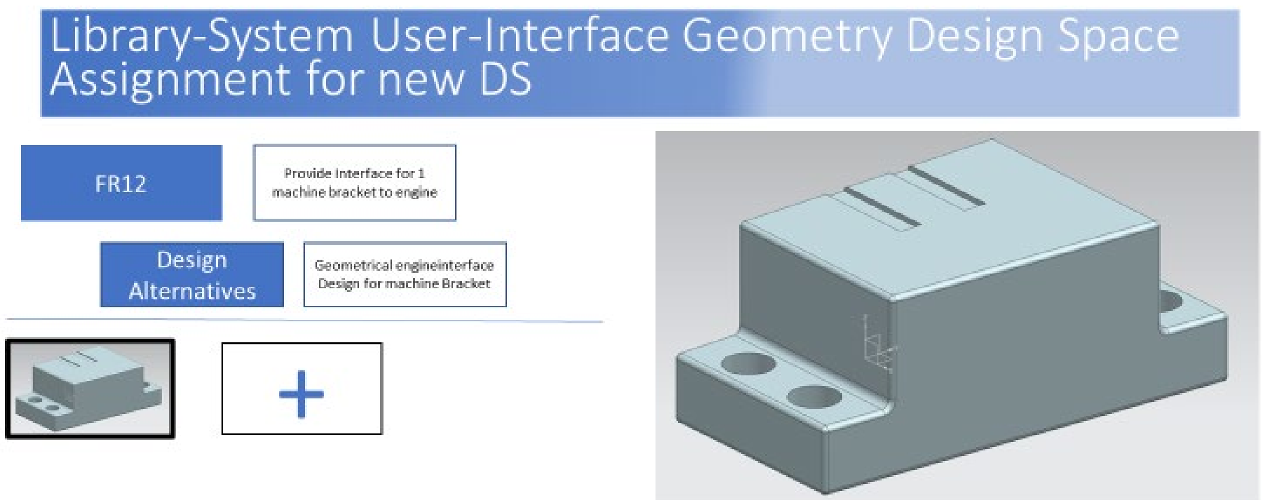

Figure 47 Illustration of Baseline selection process

The second stage for the user is to assign the wanted geometrical design space without corrupting the model, which can be done thanks to the mapped-out sequence of input, before manipulating the geometry with synchronous and subtraction modelling (see chapter 2.2.3).

In order to visually illustrate how the user is interacting with the PDM-system during the value assignment a C-program (see source code in Appendix M) is created to demonstrate how the user is guided to follow the specific max min values in order to not corrupt the file and fulfil the set geometrical design space requirements from 8.1.

To illustrate the CAD models scalability range, a scenario where the user inserts lower versus higher allowed values presented by the relationships calculations is created. As can be seen in Figure 49 the user inserts lower allowed values. As the values are inserted the part CAD models is Checked out and stored as a new DS for the Conceptual level FR. The geometry is uppdated based on the inputs from the user. An illustration on the results of the inputs in Figure 49 can be seen in Figure 48.

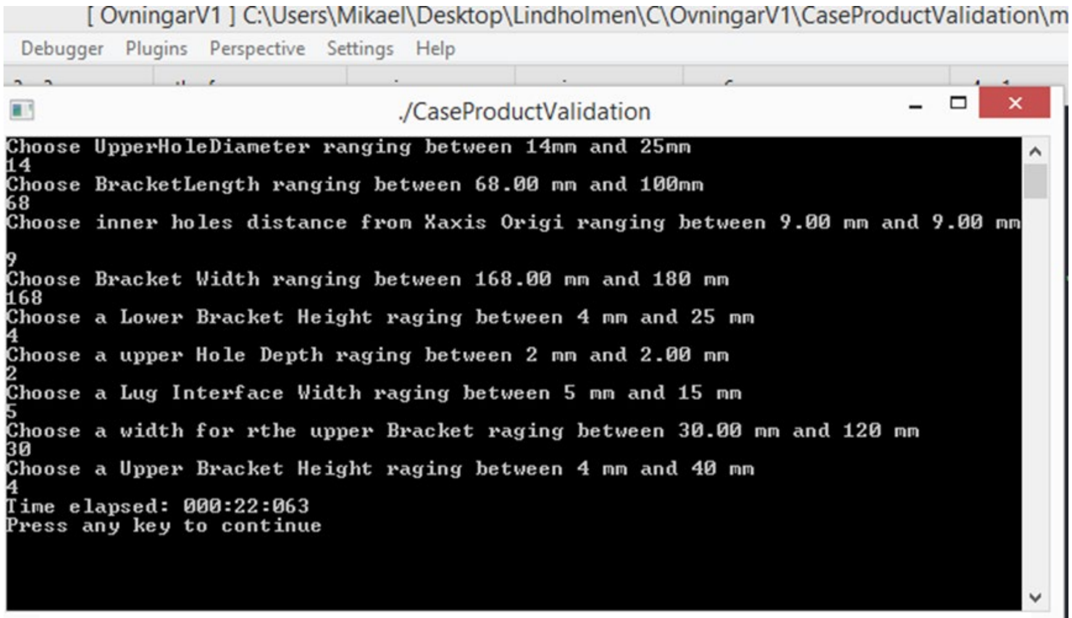

Figure 49 The user inserts the lowest allowed value on the sequential mapped dependencies

As can be seen in the Figure 48 the new baseline design space is significantly smaller both in height and in width compared to the bracket illustrated in Figure 47. Even though the aesthetics of the bracket has changed, all the Geometrical Design Space restrictions from chapter 8.1 are intact thanks to the controlled manipulation of the parametric dependencies.

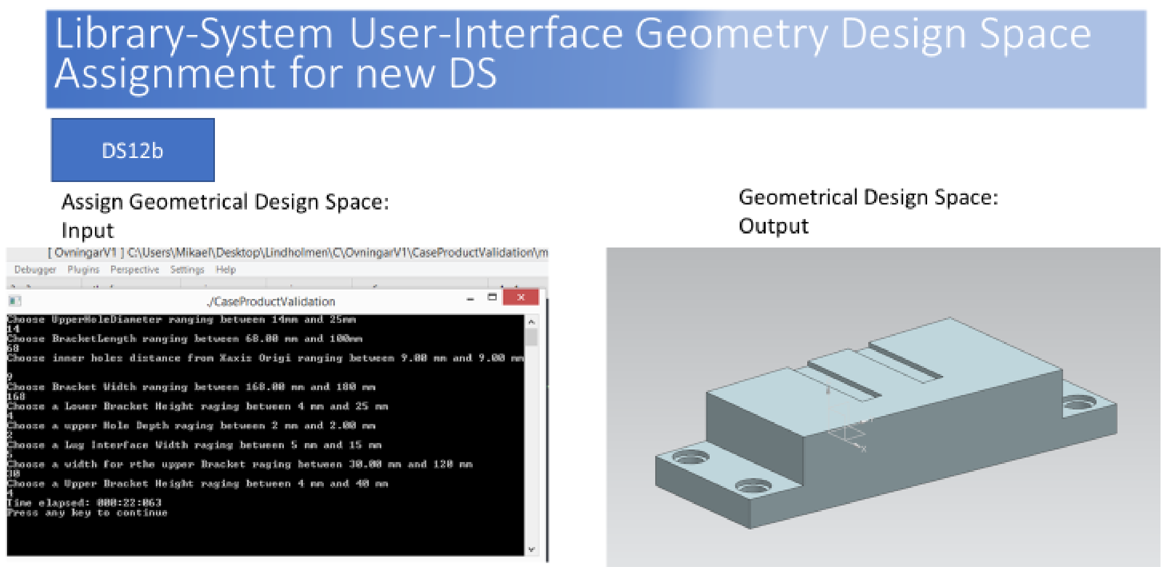

Figure 48 Illustration of user interface when assigning the geometrical design space for the bracket

The MAX MIN limits are also detecting if a value that is not ranging between the calculated values is placed as an input by the user. By doing this it becomes possible highlight and prevent mistakes before they occur. An example of an error message can be seen in Figure 50. The User is presented with a MAX and MIN value between 40mm and 120mm. When inserting the Value 125mm the user is notified with a warning message that points out the input value is outside the specified range.

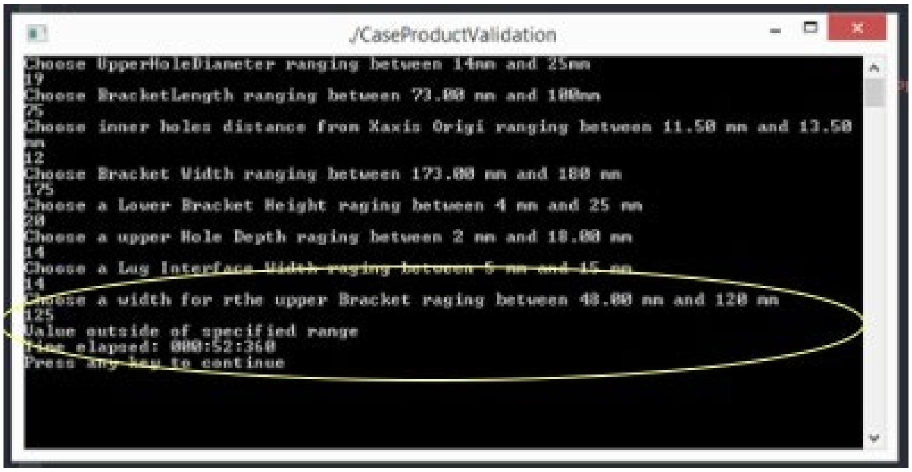

Figure 50 Warning Message for the user when a value exceeding the allowed range is inserted as an input value during Geometry Design Space Creation

The same principles are used when creating DSs for the Lug. FIXED VALUES, RELATIONSHIP VALUES and INTERVAL FIXED VALUES are used. The sequence for the MAX and MIN values are also mapped and follows the Geometrical Design Space Restrictions.

$FIXED\ VALUES\ Lug$:
$IntefaceLength = 45mm$
$IntefaceDepth = 2mm$
$Distance\ from\ Origi = 10mm$
$LugHole = 20\ mm$
$InterfaceDepth = 2mm$

$INTERVAL\ RELATIONSHIP\ VALUES\ Brakcet$
$Relationship(10)$: $BracketTotalHeight = LowerBracketHeight + UpperBracketHeight$

$SEQUENCE\ OF\ INPUT\ FOR\ BRACKET$
1. $LugLength$: $Min = 24mm$ $Max = 45mm$
2. $LugHeight$: $Min = 24mm$ $Max = 45mm$
3. $LugWidth$: $Min = 5mm$ $Max = 15mm$

8.2.2. Design Solution Generation

After the completion of assigning the Geometrical design space the user starts manipulation the geometry of the specific DS alternative. The activities at this stage are presented as mock-ups (3.6.3) as the PDM interface for the users and CAD parts(see chapter 2.2.1) in NX (2.2.1.1). The modelling methods used are synchronous and subtraction modelling (2.2.3). The activities illustrate the user interface for Sub-System 3 in chapter 7.1.3.

As the Geometrical Design space is created for a new solution the user starts the manipulation of the geometry in NX. The only guideline for the user is that the new geometry must fit the new geometrical design space envelope and cannot exceed that set geometry boundaries.

As a geometry is finished and a new DS is created the user determines if another DS for the same FR should be created or if the development should proceed to the next FR.

Four different DSs are created for FR12 (see chapter 8.1.1 and 8.1.2) (Provide interface for 1 machine bracket to engine) representing the geometrical engine interface design alternatives for machine bracket.

The time for creating the four different bracket design solution resulted between 3-7 min for each DS alternative. The different DSs are stored in within the specific FR tab as different DS following the PDM structure created in chapter 8.1.2.

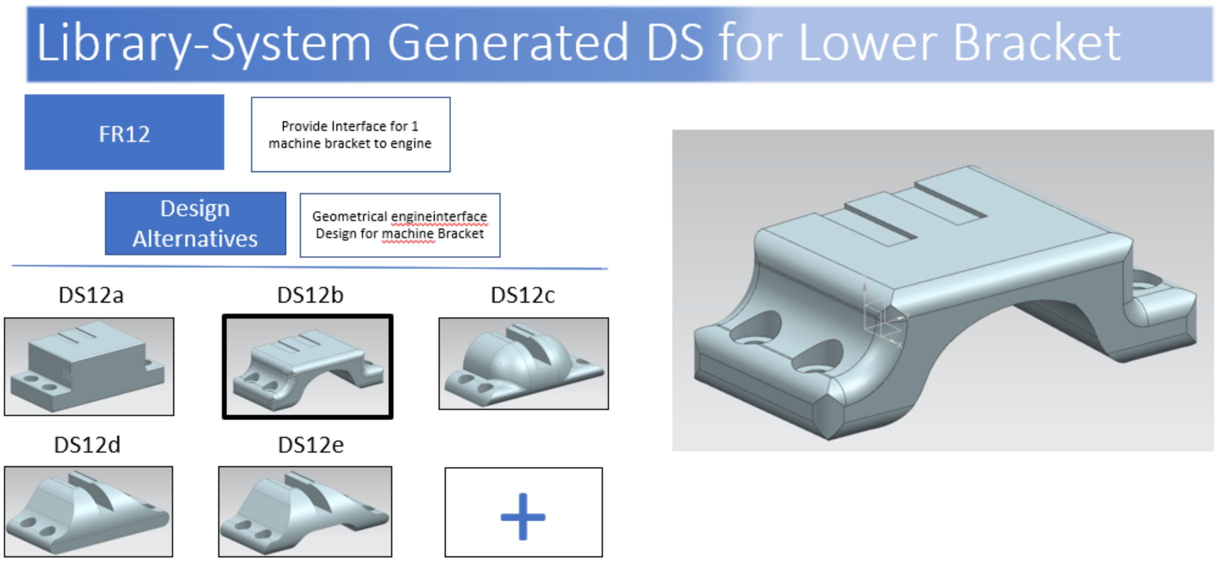

Figure 51 Illustration of the User Perspective of the PDM-System after the user has created and stored four different DSs for FR12. Enhanced screenshot of the created CAD parts can be seen in Appendix O.

The user can investigate the different DS solutions and read the values that was used as inputs when creating the baseline geometrical designs space.

An illustration of the user perspective after creating different DSs and storing them in the PDM-system can be seen in Figure 51 and enhanced CAD screenshots of the created DSs can be seen in Appendix N.

The same principles are followed as the Lug DSs are created (see Figure 52). Four different solutions are created. The time to create the DSs for the Lug took between 1-4 min. All the DSs for FR11 are attachable to the DSs from FR12. An illustration on the created DSs for FR11 can be seen in and enhanced screenshot of the created CAD parts can be seen in Appendix O.

As the different CAD parts are created and completed for both conceptual level FRs it is possible to create different assemblies by combining different sets following the SBCE principles(see chapter 2.1.2).

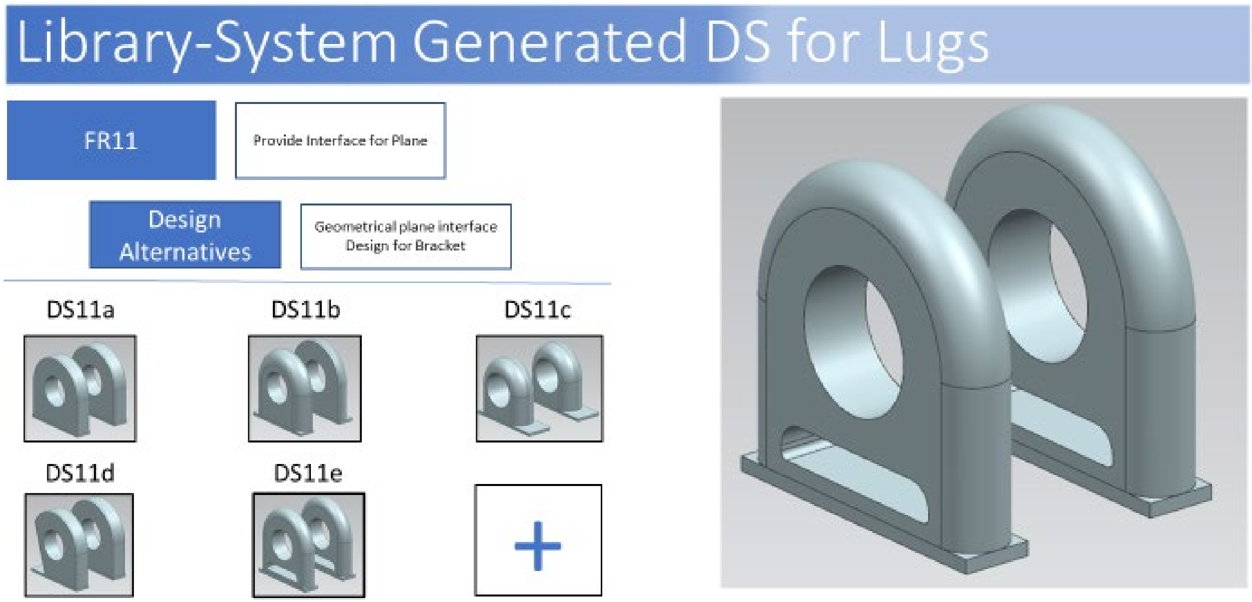

Figure 52 Illustration of the User Perspective of the PDM-System after the User has created and stored four different DSs for FR11. Enhanced screenshot of the created CAD parts can be seen in Appendix XX.

8.2.3. Concept Generation

The Concept Generation stage follows the SBCE principles where different sets of concepts are created by combining one DS from each FR. The activities from Sub-System 4 are illustrated through mock-ups (see chapter 3.6.3) and CAD (see 2.2.1) part and Assembly models in NX (see chapter 2.2.1.1and 3.6.1).

In order to create the different concepts that fulfils the static level FR (see chapter 8.1.1), concepts are generated by choosing a DS of each FR from the conceptual level. Thanks to the parametric dependencies and the universal interface all the DS are compatible. Four different jet engine bracket concepts are created in order to demonstrate the activities in Sub-System 4 (see chapter 7.1.4). By creating different concepts using a universal interface many different designs can be explored and therefore increasing the Geometrical Design Space Exploration (see chapter 2.1.1) for the jet engine bracket.

The four concepts are created by randomly combining one DS alternative for each conceptual level FR. Each concept is stored as a static level DS alternative for the static level FR, where the user is able to investigate the created concept and the underlying sub-DSs. An illustration of the combination of two DSs creating a Concept for the jet engine bracket as an assembly can be seen in Figure 53.

By combining DS11d and DS12d (see Figure 53) a DS alternative for FR1 is created and stored as DS1b. DS1b (see Figure 54) is an assembly file where the chosen DSs part files are imported. The Modelling tree of the Assembly model follows both the PDM structure (see chapter 8.1.2) and the EF-M tree (see chapter 8.1.1) for the static and conceptual level creating simplicity for the user to understand exactly what DSs have been used to create the assembly and where to find it in the PDM system. Assembly constraints are created on the universal interface surfaces in order to attach the two DSs together and create an assembly.

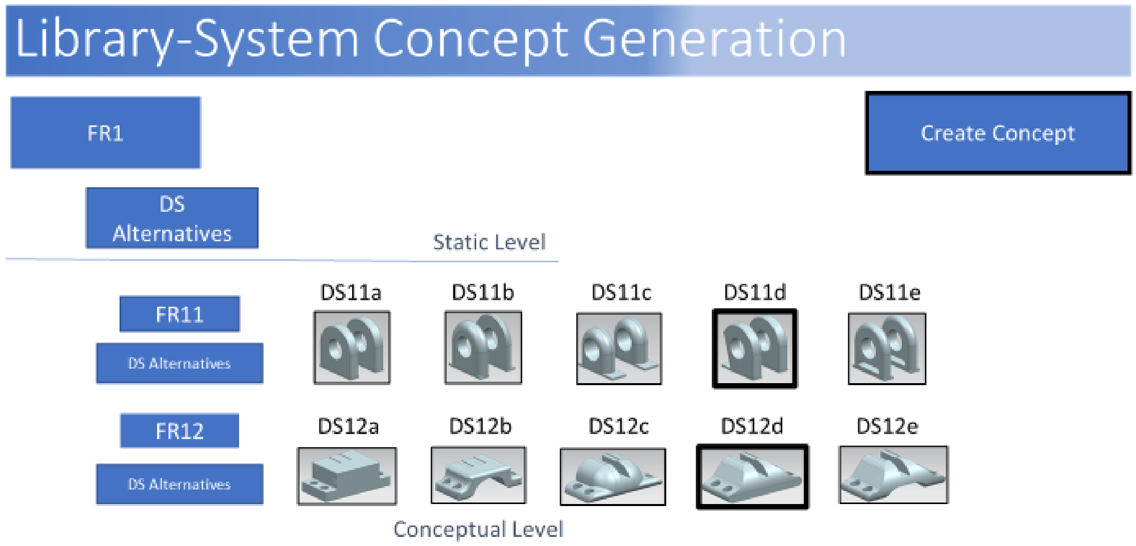

Figure 53 illustration of the combination of two DSs creating a Concept for the jet engine bracket as an assembly model in NX

The created Assemblies (see Appendix P) are created by combining different sets(see Figure 53) and each concept is assigned a name which it from now on will be referenced to:

DS1b = DS11D & DS12D = Sport (see Figure 54)

DS1c = DS11E & DS12C = Vacuum Cleaner

DS1d = DS11C & DS12B = Table

DS1e = DS11a & DS12E = Bridge

Enhanced screenshots of the assembly models from NX can be seen in Appendix P.

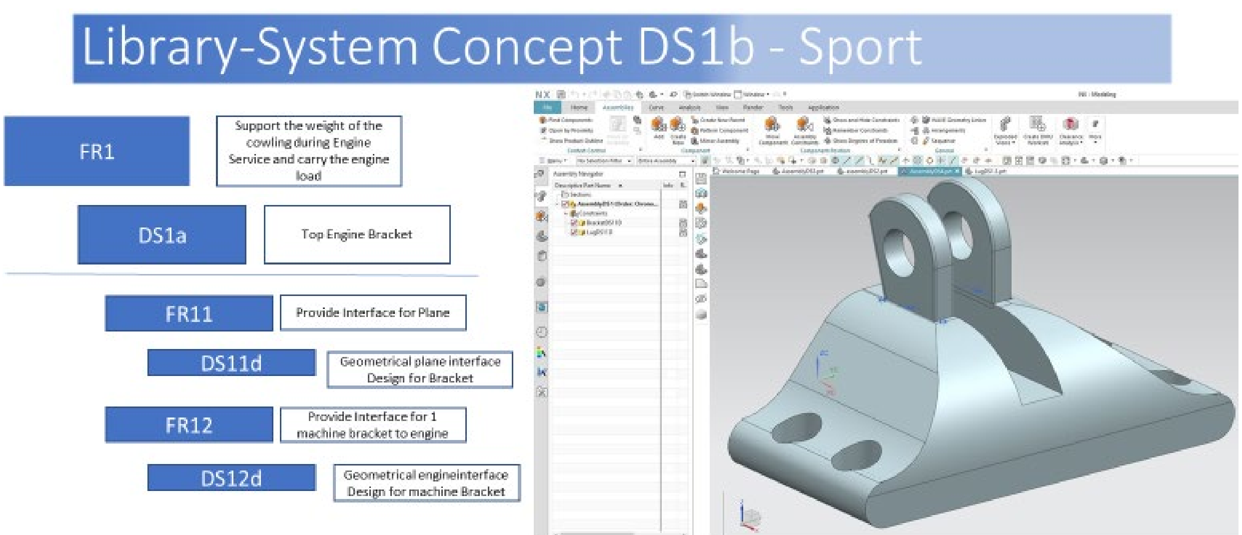

Figure 54 Illustration of the created concept DS1b. Enhanced screenshot on the Assembly model can be seen in Appendix P

8.2.4. Concept Screening

The concept screening is a phase in the PDP (see chapter 2.1) where developed concepts are compared to determine which concepts should proceed to further development and which concepts should be eliminated. This stage illustrates the activities in Sub-System 5 in chapter 7.1.5. The work for this stage was to evaluate the assembly models to the four different load cases presented in chapter 8.1 for the jet engine bracket by virtual testing the concepts in Ansys (see chapter 2.2.4.1).

The different concept assemblies are saved as stp files and the Ansys workbench is set up. The choice of material is titanium alloy and a default mesh is created for the assembly model. A Fixed Support is applied on the bottom surface of the assembly model following the load case requirements (see chapter 8.1). The Forces are applied following the load cases and the results after running the solve operation is how well a concept handles equivalent von Mises stress based on the forces and what the total deformation is in mm and visual support exposing the vulnerable areas of the design. It is acknowledged that there was a possibility to use a higher resolution for the mesh in order to prevent the risk of imaginary stress peaks. Even tough the stress results can be improved the created results are sufficient to compare the concepts versus each other.

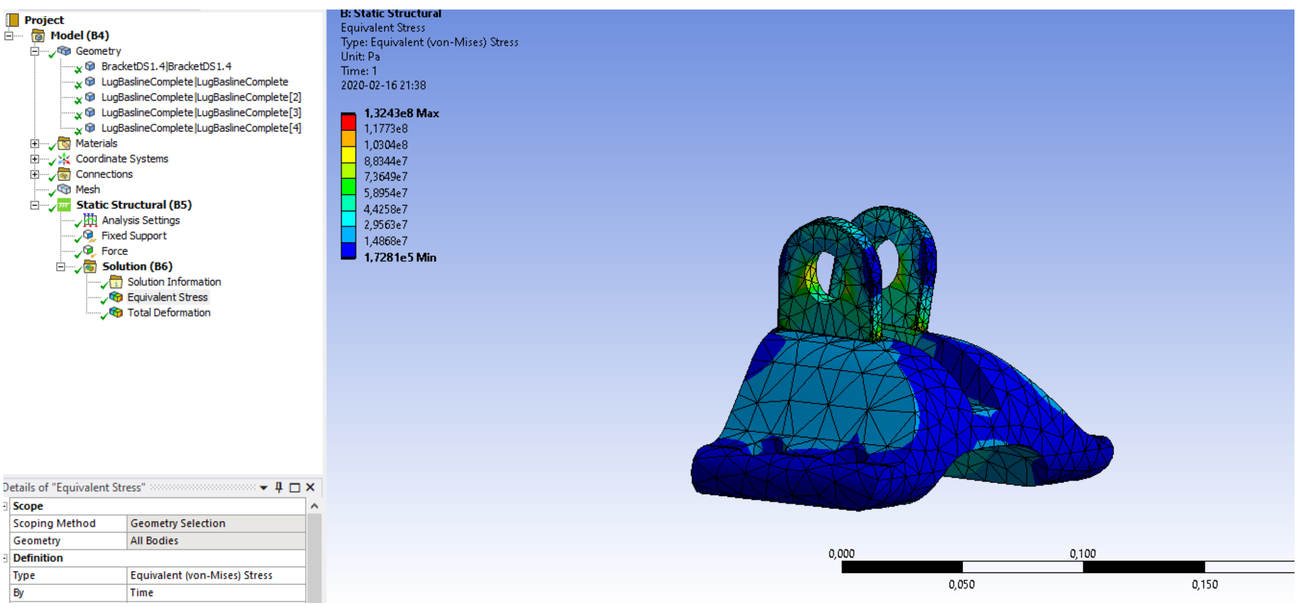

Figure 55 Equivalent von-Mises Stress results for Concept DS1e

The Ansys results for the equivalent von-mises stress and total deformation of load case 1, analysis of a static linear load of 35 600 N applied vertically, for the assembly concept DS1e can be seen in Figure 55 and in Figure 56.

An equivalent von-Misses stress and total deformation analysis for the remaining load cases are also done to concept DS1e and can be seen in Appendix Q.

The remaining concepts and the baseline (DS1a(baseline), Sport, Vacuum Cleaner, Table) are analysed in Ansys on the four load cases and the illustration of the results for the stress and deformation analysis for each load case on each concept can be seen in Appendix Q.

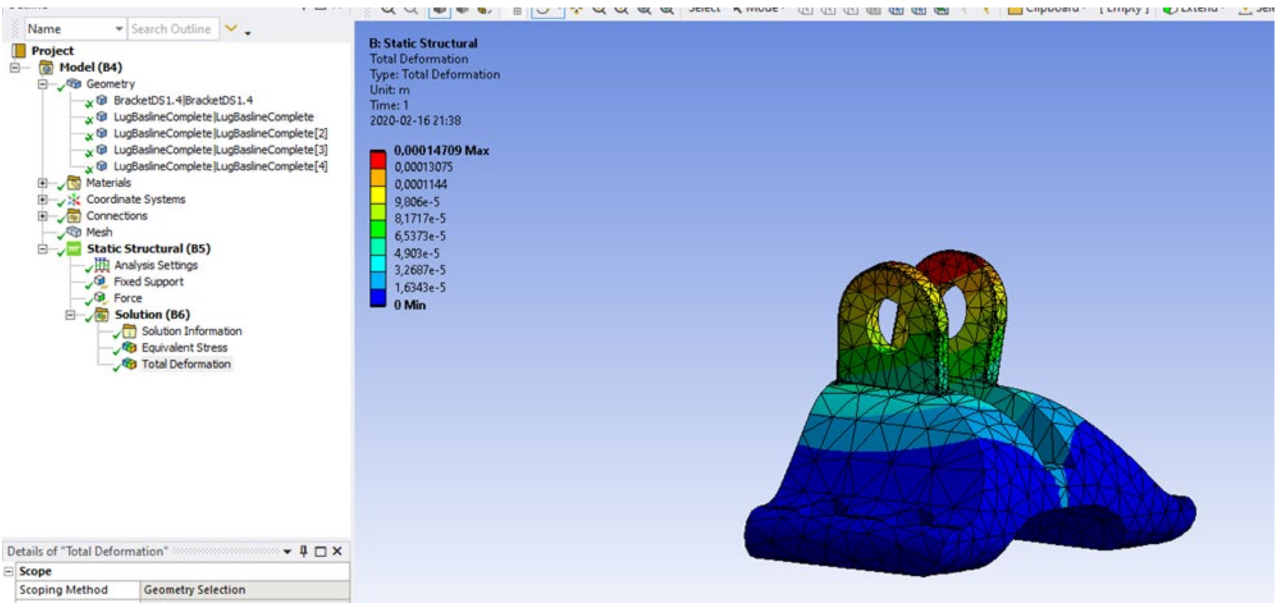

Figure 56 Total deformation results for load case 1 on concept DS1e

The results of applying the four load conditions (transferred from chapter 8.1)

- Assume Yield Strength is 903MPa
- Load Case 1: Maximum static linear load of 35 600 N, applied vertically.
- Load Case 2: Maximum static linear load of 37 900 N, applied horizontally.
- Load Case 3: Maximum static linear load of 42 260 N, 45 degrees from vertical.
- Load Case 4: Maximum static torsional load of 565 Nm, horizontal at intersection of centreline of pin and midpoint between clevis arms.
- Target the lightest weight designs

The results from the analyses (see Appendix Q) are transferred and put into a table (see Table 1) where all the concepts are compared to each other based on the gathered data. The volume of each concept is analysed by using the Measure body tool on the assemblies in NX. Screenshot on the results can be seen in Appendix Q.

Table 1 Results of the Load Cases on all the created concepts

		v-MS = von-Misses Stress (Max) in Mpa - Allowed strss 903 MPa								
		TD (MAX) in mm - Allowd deformation unknown								
		Load Case 1		Load Case 2		Load Case 3		Load Case 4		Volume mm^3
Concept		v-MS	TD (mm)	v-MS	TD (mm)	v-MS	TD (mm)	v-MS	TD (mm)	
DS1a	Baseline	146MPa	0.034	588MPa	0.166	408MPa	0.088	581MPa	0.130	931631
DS1b	Sport	319MPa	0.280	744MPa	0.280	432MPa	0.125	561MPa	0.265	624674
DS1c	Vacuum Cleaner	384MPa	0.065	933Mpa	0.162	552MPa	0.162	746MPa	0.265	614026
DS1d	Table	184MPa	0.104	796MPa	0.360	474MPa	0.150	502MPa	0.169	466779
DS1e	Bridge	132MPa	0.147	772MPa	0.306	434MPa	0.141	426MPa	0.208	461630

In parallel with examining the results the spread of the effects of the force application is also analysed to examine where the Max stress values are located on the design as well as where on the design more reductions can be made to spread the stress on the product. The concepts that performed the worst are highlighted as red, while concepts that have achieved the highest results and acceptable results are highlighted green respective yellow (see Table 2).

Table 2 Evaluation of the Load Case results for each concept

		Load Case 1		Load Case 2		Load Case 3		Load Case 4		Volume mm^3
Concept		v-MS	TD (mm)	v-MS	TD (mm)	v-MS	TD (mm)	v-MS	TD (mm)	
DS1a	Baseline	146MPa	0.034	588MPa	0.166	408MPa	0.088	581MPa	0.130	931631
DS1b	Sport	319MPa	0.280	744MPa	0.280	432MPa	0.125	561MPa	0.265	624674
DS1c	Vacuum Cleaner	384MPa	0.065	933Mpa	0.162	552MPa	0.162	746MPa	0.265	614026
DS1d	Table	184MPa	0.104	796MPa	0.360	474MPa	0.150	502MPa	0.169	466779
DS1e	Bridge	132MPa	0.147	772MPa	0.306	434MPa	0.141	426MPa	0.208	461630

As can be seen in Table 2 the results showed that concept Bridge demonstrated the best performance based on the Load conditions and the wish of the lightest weight. Concept Vacuum Cleaner demonstrated the worst performance and concept Sport and Table demonstrated inconsistent results (but both do fulfil the yield strength requirements).

Through the interface of the PDM system the user can highlight concepts Sport and Table as potentially promising which results in that a yellow colour is applied to those DSs. Concept vacuum cleaner is eliminated at this stage and is marked red while concept Bridge can be further investigated and therefore marked green. The PDM user interface for this activity can be seen in Figure 57.

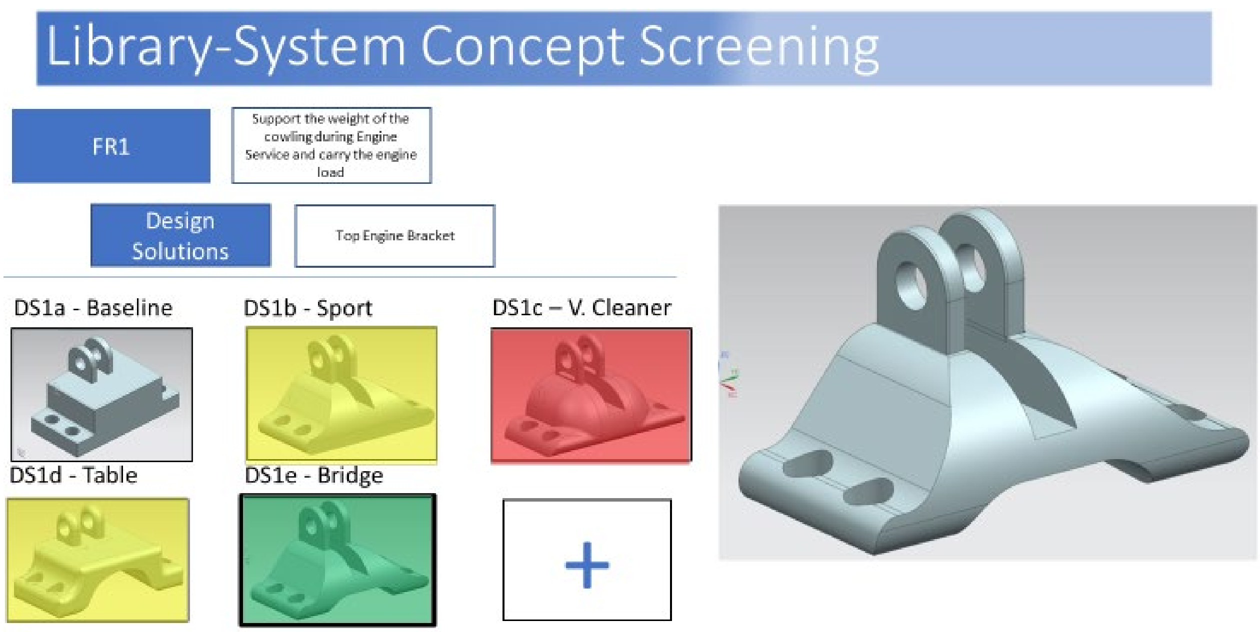

Figure 57 Illustration of the user perspective of highlighting the concepts based on the results from the virtual testing

8.2.5. Reuse Option

In order to illustrate how created parts can be reused the proceeding concept from the screening stage in chapter 8.2.4 is further developed.

The demonstration to illustrate the possibility to reuse is done by examining the winning concepts Bridge. By examining the results, it is possible to see that there is not an even spread and that there is room to further develop the concept.

Instead of starting over and creating a new design alternative by using the baseline CAD model as a starting point it is possible to use DS 12e (see figure Figure 51 in chapter 8.2.2) as the baseline and start the development of a new Design alternative from there.

One new Design alternative for the lower bracket (FR12) is created named DS12F and a new lug design alternative (FR11) is created named DS11F.

The new design solution DS12F further reduces the weight by more subtraction on the solid extrusions based on analysing the spread from the winning concept. The new DS11F reduces weight by subtracting material underneath the pinhole.

The new concept DS1F – Golden Bridge (see Figure 58) is created by applying assembly constraints on the universal interface (se chapter 8.1.3) and a new Ansys analysis following the four load cases (see chapter 8.1 and 8.2.4) is created to analyse if the new optimized concept achieves acceptable results. The new

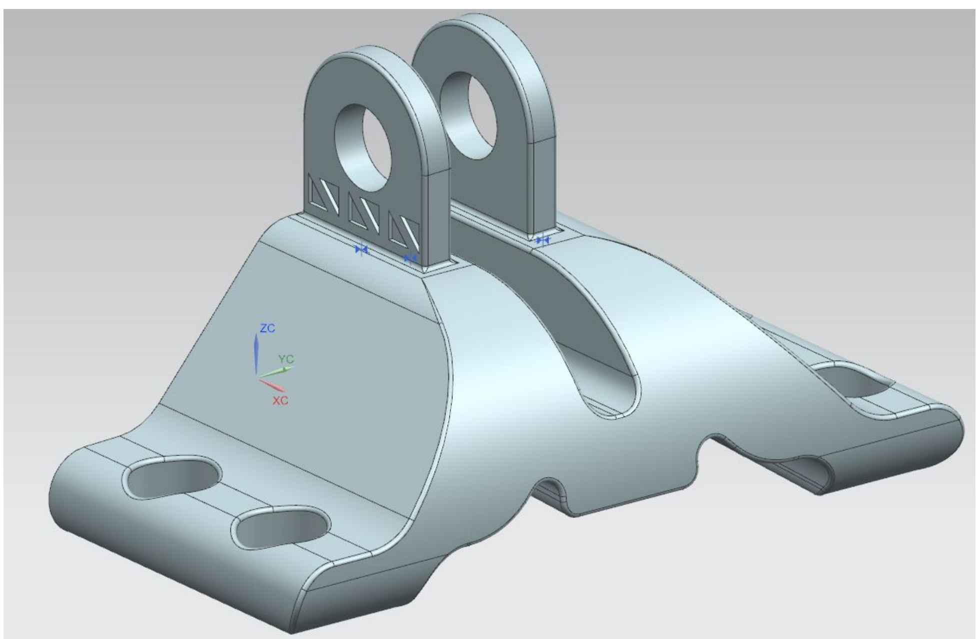

Figure 58 The new Concept Golden Bridge derived from concept Bridge as a baseline.

additional features and changes on concept Golden Bridge (see Figure 58) is a decreased width of the inner middle rift, added radius on walls in middle rift, subtraction of solid on the lower bracket, changed incline of walls and changed radius on the walls compared to concept Bridge.

Table 3 Evaluation of Load Case results between concept Bridge and Golden Bridge

		Load Case 1		Load Case 2		Load Case 3		Load Case 4		Volume mm^3
Concept		v-MS	TD (mm)	v-MS	TD (mm)	v-MS	TD (mm)	v-MS	TD (mm)	
DS1a	Baseline	146MPa	0.034	588MPa	0.166	408MPa	0.088	581MPa	0.130	931631
DS1e	Bridge	132MPa	0.147	772MPa	0.306	434MPa	0.141	426MPa	0.208	461630
DS1f	Golden Bridge	179MPa	0.169	635MPa	0.382	459MPa	0..184	719MPa	0.231	408225

The results of the load case analysis (see Appendix R) on concept Golden Bridge is compared to the baseline and concept Bridge (see Table 3). The result shows that the new design has a better spread of the stress when the forces of the load cases is applied as well as the new Design Alternative having a lower volume than concept Bridge. Concept Bridge still outperforms the new concept Golden bridge in some of the load case tests. Here there is a need for a trade-off discussion regarding the importance of reducing weight versus best performance. Regardless, both concepts fulfil the set performance requirements.

8.3. Industry Standard vs Proposed Approach

As the demonstration of the proposed approach is completed, the final phase is to compare the Industry Standard (see chapter 4.6) to the Proposed Approach in order to illustrate how they differ. The comparison can be seen in Figure 59.

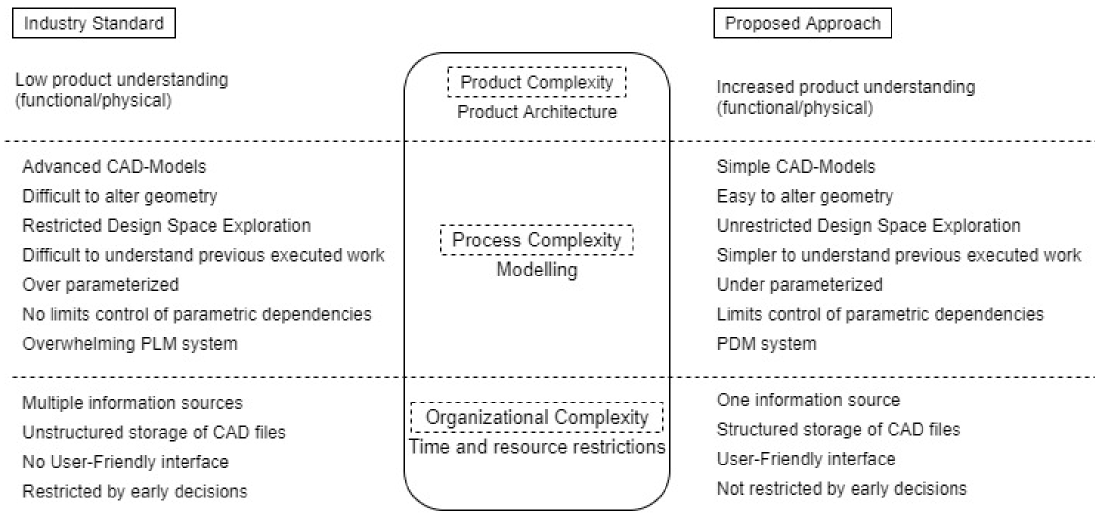

Figure 59 Comparison between the Industry Standard and the Proposed Approach

As can be seen from the figure the Proposed approach presents a solution to the problem presented in chapter 1.2 which is created by the current state of the Industry Standard (see chapter 4.6).

The Library System (Proposed Approach in Figure 59), illustrated by the Proof-Of-Concept Demonstration (see chapter 8) on a Case product, presents a possible approach to increase the design freedom for a

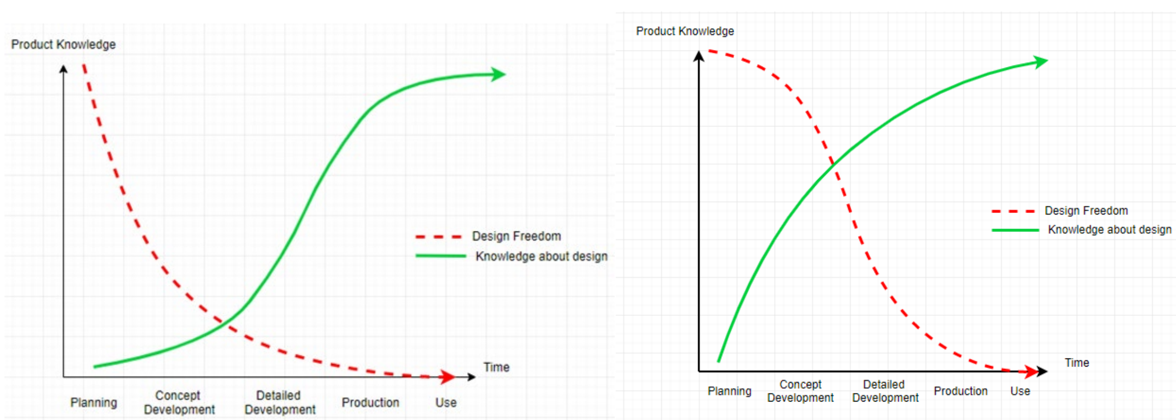

Figure 60 Illustration of the differences between the Industry Standard and the Proposed Approach

product developer during the early concept within the CAD environment, thereby answering the second

Research Question: "***What is a possible solution for increasing the design freedom for a product developer during early concept development within the CAD environment?"***

The early decisions made, by following the Industry Standard (see chapter 4.6), significantly restricts the design freedom. This results in that novel concepts are not explored due to lack of information regarding their performance compared to the existing solution due to the needed time-consuming rework activities. This results in the design paradox (see chapter 2.1.1 and left graph in Figure 60) where when the knowledge of the product increases the possibility to alter the design is restricted due to previous made decisions.

The advantage of using a realized library system following the Proposed Approach implies that it is possible to reduce the impact of early decisions on the design freedom. This is done due to the possibility to quickly create and analyse novel design alternatives through the use of the proposed Library System. This establishes a scenario where the product developers can increase the knowledge about the design and use that new knowledge in their decisions about the geometrical design in the early concept development stages (see right graph in Figure 60).

Even though the results of the potential implementation of the solution suggests that the problem of rigid CAD models can be solved, there is a need to understand the disadvantages of the approach as well. The use of the traditional modelling techniques of heavily parametric CAD models has been done over an extensive period. Therefore, the current industry standard practice is a proven method to achieve the sough for design standard. The over parametric CAD models can be used to create the necessary drawings and added BOM's with the correct dimensions directly after the minor changes. By using Synchronous technology, the accurate dimensions cannot be translated to drawings since these dimensions are not tracked. The primary goal of the more direct modelling is to with the use of synchronous modelling is to explore design at an early concept development stage. This is a limitation since the next stages of the development process cannot be made. The created concepts can then be used as a basis for further developed CAD models that follows the industry standard practices.

8.4. Qualitative Feedback

In this section the qualitative feedback on the created Library System and the usage of the information is presented.

8.4.1. Interview

Two interviews are conducted to gather feedback from practitioners that work following the industry standard presented in chapter 4.6. An additional interview with a database design is conducted to get insights if the proposed architecture of the PDM setup can be recreated when developing the Library system. The interview and the purpose of the method can be seen in chapter 3.7.1.

The results of the feedback can overall be seen as positive as the interviewees expressed that the proposed solution could act as a solution for the real problem of CAD rigidity. The main concerns of the proposed solution were the subjects of how and to what extent it would be implemented. Another suggestion was finding the optimal compatibility for the created solution.

The feedback, together with personal insights by conducting the project, are used as a basis for the discussions and to present the recommendations for the future development of the approach.

9. Discussion

This chapter provides reflections on the executed project. The potential impact of the proposed solution, the limitations of the project execution and results as well as the recommendations for further development are discussed.

9.1. Impact

Academic It can be argued that the conducted work in this project can have a contribution to knowledge. As there is a real problem regarding the need of more resource and time efficient tools as well as allowing product developers to be able to develop products based on their potential value and not be restricted by the process and the used tools. This project can be treated as a case study for exploring a system that increases the freedom for the developers. As there already is extensive research to optimize the development process the results can serve as a new alternative to explore and further develop.

Practical The largest impact of the conducted work is practical in nature. Even though the solution in this project is not fully developed, it illustrates the potential practical impact that it can reach if done correctly. The current industry standard limits and corners the developers by not allowing the exploration of geometrical design alternatives that are based on the potential value the novel solutions may add. Therefore, the implementation of a system that follows the principles of the proposed approach can eliminate the existing industry standard gaps and introduce a solution. In practice the implementation of the proposed approach can allow the product developers to anchor the development process and decisions in early concept development to a system that allows virtual exploration of geometrical alternative designs in a relatively short time span compared to the industry standard. The solution supports the decisions made in early concept development by providing performance results of the different geometrical design alternatives and therefore allowing the screening process be based on knowledge of the product from data reducing the restrictive impacts of early decisions in the concept development. Therefore, the potential practical impact of the proposed solution can result in a system that reduces the time and resource constrains that exist on companies and at the same time enables the product developers to explore more design alternatives which can result in more value adding work.

Economical The proposed solution, even at an early stage of development, can potentially provide a positive economic impact for companies. The proposed solution is aimed to contribute to an improved capability of using the company's resources to generate increase value adding work of the employees by minimizing unnecessary repetitive and time-consuming work when developing new design alternatives for a product. The possibility to easier reuse both functional and physical element of a new design solution also supports the argument that if implemented correctly the proposed solution could reduce costs due to less time-consuming activities spent when creating new design alternatives.

9.2. Limitations

The conducted work and results are subjected to limitations. The limitations are both created by choice as well as during the development. Even though I am confident in the presented results and the validity of the conducted project work, it is important to acknowledge that there is room for improvement and possibility to increase the quality of the work.

Addressing unresolved needs Based on the initial set limitation on focusing the research exclusively on the geometrical variation aspect, it must be acknowledged that the development process includes e.g. decisions regarding manufacturing, material choice etc. that would expand the needs of the system which has not been considered. This creates the possibility that undiscovered needs, that could be of importance if a company would consider implementation, are not taken into account.

There is also a need to acknowledge that a limitation on the created results, especially the created requirements, are that only a few industrial practitioners were interviewed for the primary data collection. This results in that there is a possibility that there are not only undiscovered important needs but also that the identified needs could be biased to a specific industry and/or application.

A flaw in this argument is that the length of the project has to be taken into account when discussing the scope of the project. If all activities in the product development process together with interviews over several industries would have been investigated, it would have been challenging to present results, since mapping of all the potential needs when developing a product could be a master's thesis project in itself. By limiting the scope, to exclusively considering the geometrical designs space of product, it is possible to suggest and demonstrate a more concrete solution.

Expanding the requirement analysis The development of the requirements was a challenging and time-consuming activity where several iterative processes and method were used to break down the identified needs to more concrete sub-solution requirements. One main contributor for why this activity was challenging is that the initial developed needs were derived primarily from secondary data collection such as literature studies. A closer collaboration with a company and a specific case product or several companies of different sizes and product portfolios could have resulted in more concrete needs that would have been derived directly from primary sources. Even tough primary data collection has been conducted in this project, due to circumstances they were conducted not at an early stage of the project resulting in that the statements collected from the interviews served as a support for the findings of the literature rather than the literature being the support for collected needs from primary sources. I acknowledge that there is an argument that by relying more on primary data collection, than the secondary data collection, it would have increased the chances of creating a more advanced solution that would have been more product centric.

You could also argue for that if a more specified system would have been proposed it could limit the potential impact of use as each company and their respective product is heavily individualized. The counter argument is that by presenting a more open-ended system that is general, there is more room for potentially interested stakeholders of the proposed approach to adapt the implementation of the proposed solution based on their respective needs.

Development of the Proposed Approach In conducting the thesis work I have presented a User perspective flowchart that illustrates the activities needed for both the preparation of the Library system as well as a suggestion on the Library system functions when used. Even though I'm proud of the results created during this project there is room for improvement.

The developed flowchart is created by my gathered knowledge and the complete flowchart was created after consultation with the supervisor of the thesis project. If more consultation by practitioners would have been included, when creating the user perspective flowchart, it would have been possible to create a more qualitative flowchart. But as there was no concrete stakeholder, these activities would have required time-consuming search of consultants that have valuable experience and knowledge to give input. This project was as an exploratory research project and even tough primary feedback on the developed flowchart does not exist, the set goals for this project have been achieved based on the time restrictions and the scope that exists on a master's thesis project.

The created CAD models represented a simpler geometry setup of the Case Product. There would have been a possibility to develop the models further during set up in order to mimic the case product geometry as precise as possible. Due to the time restrictions that exists on the master's thesis project I decided that by using a simpler representation it would be possible to develop more concrete results and demonstrations on the proposed solution.

9.3. Recommendations on future work

It important to clarify that the work conducted in this master's thesis project represents the early stages of creating a library system that can offer both modular geometrical design alternatives that can be reused as well as guidelines to create new concepts in an controlled geometrical design space. Therefore, there is a lot of room for further development.

As can be seen in chapter 8.4.1 the feedback from practitioners in the industry suggested some of the decisions and developments that need to be considered in the future in order to successfully realize a library system that follows the proposed solution.

Further development is needed to investigate the interactions between the agents of the proposed solution. There are several interacting systems in the proposed Library system. The scope of this project was to demonstrate a potential solution but in order to create a fully functional Library system, these interactions has to be further investigated.

Further development is needed to determine how an implementation of a library system would be carried out. Two suggested implementation strategies from the feedback was presented. The first suggestion is that the library system can be seen as a separate development hub for users where the different design alternatives could be explored, created and analysed to create a foundation for the detailed design in the PDP. The second suggested implementation strategy is to incorporate the created Library system in already existing database systems used in the industries today.

One other main aspects of further development are to find an interested stakeholder that uses Additive manufacturing to produce products. By involving a stakeholder to the project, the proposed solutions can be further developed to suit a specific problem and therefore more developed results can be created.

Another suggestion from the feedback was to involve database and UX designers to create the actual Library system. The presented results for this master's thesis project consist of a suggestion on the database architecture illustrated by mock-ups. Therefore, there is a need to further develop and realize the Library system

The recommendations for the future work are to involve a stakeholder that work with additive manufactured products/components and create a new project with at least a database designer and a UX designer who further develops and realizes the proposed solution for the Library system. The competence of a database designer can result in the creation of the database. By creating the proposed solution, it is possible to analyse if the interaction between the agents of the system achieve the expected results. The involvement of a UX designer allows the possibility to create a user-friendly interface that follows the principles in the proposed solution. This can either be done by creating a continuation of this project as a new master's thesis project or and independent project within research for design space exploration in the concept development process.

I also recommend that further work regarding the implementations should be conducted in order to be able to create a fully functional Library System that follows the principles in the proposed solution. This due to the fact that the implementation strategy for the proposed Library system has not been investigated in this project.

10. Conclusion

In this project, an exploratory research has been conducted in order to present a possible solution on how the design freedom for developers could be increased through the proposal of a module-based Library System consisting of flexible CAD-models.

The requirements for the proposed Library System were created using a modified QFD. The content of the HoQ were created by a systematically breaking down the collected needs, which were developed through a literature study, interviews, and an observation at a leading aircraft engine manufacturing company. The second phase of the QFD resulted in a Sub-Solution Requirement List that was used to find suitable methods and approaches for the Library system. The project resulted in a proposed User perspective flowchart that illustrated the actions, decision and interacting agents in a Library System that increases the possibility to explore design alternatives within a CAD environment.

Further, a demonstration of the Library System was developed by creating CAD-models using Parametric, Synchronous and Subtraction modelling techniques. A Library System structure was proposed and the activities from the User Perspective Flowchart was created with visual mock-ups that illustrated the Library System interface during usage.

The feedback on the proposed Library system were positive and interest was shown for a continuation of this project through further development. The reasoning being that it was acknowledge that this is a real problem throughout the industry where a current gap exists and is not addressed by the practices used. The comparison between the currently used Industry Standard and the initial results of the proposed Library System through the demonstration showcased that the proposed solution could potentially solve the existing issues of rigid CAD models if further developed and realized.

The overall goal is to create an implementable Library System that follows the principles demonstrated by the results of this project. In order to achieve this, the work conducted in this project can serve as a foundation for further development. It is recommended that the further development should be done with additional collaboration with practitioners and companies in the industry, in order to obtain the best possible outcome.

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Appendix A. Interview Questions

Q: Many companies have different approaches on how the process for new development looks like. Could you just briefly explain how the product development process is conducted in the company (from idea to detailed CAD prototype)? Allocated time for thinking new ideas? Or each 3 months you sit down and think together.

Q: When working on a new product the literature suggests that there is an issue where the CAD models limits the developers. Therefore, when you want to create new models you have to start from scratch. Do these issues exist in your company or do you have the resources to reuse already existing CAD models?

Q: Are you working with simpler CAD models in order to use simpler analyses?

Q: How do you work with flexible models when creating different variants of a product and can the flexible models be used when trying out more drastic variations of a product?

Q: Research suggest that a method to reduce product complexity is to work with functional decomposition to better understand the product. At the same time when creating a modular product, you want to isolate few functions to a specific feature of a part. I would assume that that's quite difficult to achieve when working with complex products?

Q: You mention that you have files that you can upload. But do you work with a library or what does your system look like to find these files?

Q: Research suggests that these databases can be very unstructured and that there can be many variants and files of a component that many developers do not know about as they do not know how to find them. Do these issues exist with your database?

Q: Lack of standardised work methods and gaps in knowledge between colleagues are some reasons suggested in the research for why reuse can be difficult, therefore many companies train their employees. What aspect do you teach to your developers?

Appendix B. Statement List

Statement list	
Challenge 1 Product Complexity Statements - Product Understanding	
PS 1	Its not that common that we create an entirely new product.
PS 2	Usually we work with a derivative of a previous model
PS 3	There can be a need for a larger variant of an engine model and then a lot of the design content of the product remains the same, the functionality is the same.
PS 4	we work with development its either that there is a need to try a new manufacturing method or a new variant of an existing product that we want to test.
PS 5	A component/part fulfils many functions and it is usually a goal to integrate many functions because in some cases it can lead to e.g. reduces weight.
PS 6	in the concept phase you want to understand your product and see what the alternatives could be
PS 7	you have to do a functional decomposition
PS 8	these functional decompositions do exist from previous work.
Challenge 2 Process Complexity Statement - CAD	
CS 1	In some cases, we use parameterized CAD models that can adapt to the other geometry to a certain degree
CS 2	we reuse some of the previous models
CS 3	The bottleneck of creating new models from scratch does exist
CS 4	it takes a lot of time to set up new parametric models that can be reused
CS 5	How smooth this process of reuse is dependent on how the new geometry looks eg. it needs to fit in with the other components
CS 6	We have parametric CAD models that we use so we don't have to start over from scratch
CS 7	On the other hand, we must adjust the models a little so that it fits together.
CS 8	In most cases you have to manually adjust the interface
CS 9	we primarily work with CAD models as a basis for all or analyses, especially when we look at different variants of a product
CS 10	You always want to be able to compare a model with something that's why we usually have a baseline based on a previous model
CS 11	you usually have an idea of what could be done better and then you want to compare the new variant against the baseline
CS 12	you can't really escape the idea of the need for a baseline to compare against
CS 13	But then if you want to model a whole new part or product, you have to model it from scratch
Challenge 3 Organizational Complexity Statement - Information/PLM	
IS 1	Another important aspect of which is reusing the working methods
IS 2	All our CAD files are in a system called TeamCenter, which is a large database of e.g. CAD files.
IS 3	The database also contains a lot of reports and documents that belong to the product, requirements lists and other things that are related
IS 4	The CAD models are only part of what is in the database.
IS 5	We have lots of models in the database that not everyone knows about
IS 6	We at the company have a standardized way of doing our CAD structures as well as how to store in the database which all developers learn
IS 7	And a part of this idea is that if you have to go in and help, then you should have a similar way of thinking about how to model
IS 8	It can also be seen as a way of assuring quality through the work that we create.

Appendix C. Needs List

	Needs list	Sources
1	Reduces the amount of sources	Observation, (Lundin, 2015), (Camba et al, 2014)
2	Preserves the reliability of the information	IS 7, (Lundin, 2015)
3	Presents the availiability of the information	IS 5, (Lundin, 2015), (Kim et al, 2007)
4	Prevents duplicates of documents	Observation
5	Enlightens the need of information	(Lundin, 2015), (Kim et al, 2007)
6	Provides clarity on previously executed work	IS 5, (Camba et al, 2014), (Kim et al, 2007)
7	Allows reuse	CS 2, CS 3, (Camba et al, 2014), (Heikkinen et al, 2018), (Lindemann, 2009), (Gero and Kannengiesser, 2004), (Simpson, 2001)
8	Provides suport for developers decision	IS 6, IS 8, (Lundin, 2015),
9	Provides understanding on existing CAD Models	CS 8, (Heikkinen et al, 2018)
10	provides a standarized work method	IS 6, IS 8, (Heikkinen et al, 2018), Kasik (2015), (Lindemann, 2009)
11	Provides understanding on the modeling tree	Observation, (Heikkinen et al, 2018)
12	Provides understanding on parametric dependencies	Observation, (Heikkinen et al, 2018), (Cheng and Ma, 2017), Kasik (2015)
13	Preserves the robusntess of CAD models	CS 4, (Cheng and Ma, 2017), (Heikkinen et al, 2018)
14	Enlightens the critical parametric dependencies	Observation, (Heikkinen et al, 2018), (Cheng and Ma, 2017), Kasik (2015)
15	Presents the optimal manipulation seequence of dependencies	Observation, (Cheng and Ma, 2017), Kasik (2015)
16	Allows adaptable CAD models	CS 1, CS 4, CS 6, (Heikkinen et al, 2018), Kasik (2015)
17	Reduces the product Complexity	PS 6, (Lindemann, 2009), (Baldwin & Clark, 2000)
18	Increases the product understanding	PS 6, (Lindemann, 2009), (Gero and Kannengiesser, 2004), (Baldwin & Clark, 2000)
19	Provides support for the concept development process	CS 10, CS 11, CS 12, (Cheng and Ma, 2017), (Lindemann, 2009), (Baldwin & Clark, 2000)
20	Reduces rework	CS 4, PS 8, (Camba et al, 2014), (Kim et al, 2007), (Heikkinen et al, 2018), (Gero and Kannengiesser, 2004), (Simpson, 2001)
21	Allows overall adaptability	Observation, (Simpson, 2001)
22	Allows ineractions with the developer	Kasik (2015)
23	Enables the "fun-part" of designing	La Rocca (2017)
24	Is easy to use	(Camba et al, 2014)
25	Allows capture of design intent	PS 5, (Heikkinen et al, 2018)
26	Allows project documentation	Observation
27	Has to manage previous versions of CAD Models	Observation
28	Allows retrival of previous versions	Observation
29	Allows individualization	Observation
30	Prevents disruption of work	(Lundin, 2015), (Camba et al, 2014)
31	Provides simplicity	(Heikkinen *et al*, 2018), (Lundin, 2015), (Camba et al, 2014)
32	Increases the design freedom	Saxenna and Karsai (2010), (La Rocca, 2017)
33	Allows simultanious creation of concepts	(Sobek, 1999), Raudberget (2010)

Appendix D. Pairwise Comparison Part 1

		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	Aa	Ab	Ac	Ad	Ae	Af	Ag
		Reduces the amount of sources	Preserves the reliability of the information	Presents the availability of the information	Prevents duplicates of documents	Enlightens the need of information	Provides clarity on previously executed work	Allows reuse	Provides suport for developers decision	Provides understanding on existing CAD Models	Provides a standarized work method	Provides understanding on the modeling tree	Provides understanding on parametric dependencies	Preserves the robustness of CAD models	Enlightens the critical parametric dependencies	Presents the optimal manipulation seequence of dependencies	Allows adaptable CAD models	Reduces the product Complexity	Increases the product understanding	Provides support for the concept development process	Reduces rework	Allows overall adaptability	Allows interactions with the developer	Enables the "fun-part" of designing	Is easy to use	Allows capture of design intent	Allows project documentation	Has to manage previous versions of CAD Models	Allows retrival of previous versions	Allows individualization	Prevents disruption of work	Provides simplicity	Increases the design freedom	Allows simultanious creation of concepts
A	Reduces the amount of sources	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
B	Preserves the reliability of the information	A	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
C	Presents the availiability of the information	A	B	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
D	Prevents duplicates of documents	AD	BD	CD	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
E	Enlightens the need of information	A	B	CE	D	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
F	Provides clarity on previously executed work	A	BF	F	DF	EF	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
G	Allows reuse	G	G	G	G	EG	FG	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
H	Provides suport for developers decision	AH	H	H	DH	EH	FH	G	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
I	Provides understanding on existing CAD Models	A	BI	I	DI	I	FI	GI	H	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
J	Provides a standarized work method	AJ	B	J	DJ	J	F	G	HJ	IJ	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
K	Provides understanding on the modeling tree	A	B	K	DK	K	FK	G	H	IK	J	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
L	Provides understanding on parametric dependencies	A	B	CL	L	L	FL	G	H	IL	J	KL	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
M	Preserves the robustness of CAD models	AM	M	M	M	M	FM	G	H	M	M	M	M	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
N	Enlightens the critical parametric dependencies	A	B	CN	DN	N	FN	G	H	IN	JN	N	LN	M	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
O	Presents the optimal manipulation seequence of dependencies	A	B	O	DO	O	FO	G	H	IO	JO	O	LO	M	NO	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
P	Allows adaptable CAD models	P	P	P	P	P	P	GP	HP	P	P	KP	P	MP	P	P	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

– Pairwise Comparison Part 2 and the calculated weighted percentages

Q	R	S	T	U	V	W	X	Y	Z	Aa	Ab	Ac	Ad	Ae	Af	Ag
Reduces the product Complexity	Increases the product understanding	Provides support for the concept development process	Reduces rework	Allows overall adaptability	Allows ineractions with the developer	Enables the "fun-part" of designing	Is easy to use	Allows capture of design intent	Allows project documentation	Has to manage previous versions of CAD Models	Allows retrival of previous versions	Allows individualization	Prevents disruption of work	Provides simplicity	Increases the design freedom	Allows simultanious creation of concepts
Q	R	S	T	AU	V	AW	AX	AY	AZ	Aa	Ab	A-Ac	Ad	Ae	Af	Ag
Q	BR	BS	T	U	B	B	BX	Y	Z	B-Aa	B-Ab	B	Ad	B-Ae	Af	B-Ag
Q	R	S	T	U	V	CW	X	Y	Z	Aa	Ab	Ac	Ad	Ae	Af	Ag
Q	R	S	T	U	V	DW	X	Y	DZ	D-Aa	D-Ab	Ac	Ad	Ae	Af	Ag
Q	R	S	T	U	V	W	X	Y	Z	Aa	Ab	Ac	Ad	Ae	Af	Ag
Q	FR	S	FT	U	V	FW	X	Y	FZ	Aa	Ab	Ac	Ad	Ae	Af	Ag
GQ	G	GS	GT	GU	G	G	GX	G	G	G-Aa	G-Ab	G	G-Ad	G-Ae	G-Af	G-Ag
H	H	HS	HT	H	HV	HW	HX	H	H	H	H	H-Ac	H-Ad	H	H-Af	H-Ag
Q	R	S	T	U	I	I	X	Y	IZ	I-Aa	I-Ab	I	Ad	Ae	Af	Ag
Q	R	JS	T	U	JV	J	X	JY	JZ	Aa	Ab	Ac	Ad	Ae	Af	Ag
Q	R	S	T	U	KV	W	X	Y	Z	Aa	Ab	Ac	Ad	Ae	Af	Ag
Q	R	S	T	U	V	W	X	Y	Z	Aa	Ab	Ac	Ad	Ae	Af	Ag
MQ	MR	MS	T	MU	M	M	MX	MY	MZ	M-Aa	M-Ab	M-Ac	M-Ad	M-Ae	Af	M-Ag
Q	NR	S	NT	U	NV	NW	X	NY	Z	Aa	Ab	Ac	N-Ad	N-Ae	Af	Ag
Q	R	S	T	U	OV	OW	X	OY	Z	Aa	Ab	Ac	Ad	Ae	Af	Ag
PQ	PR	PS	PT	PU	PV	P	X	PY	P	P-Aa	P-Ab	P	Ad	P-Ae	Af	Ag
X	QR	Q	QT	Q	Q	Q	QX	QY	Q	Q	Q	Ac	Ad	Q-Ae	Af	Q-Ag
X	X	R	RT	R	R	R	RX	RY	R	R	R	R-Ac	R-Ad	R-Ae	Af	R-Ag
X	X	X	ST	S	S	S	X	SY	S	S-Aa	S	S-Ac	Ad	Ae	Af	Ag
X	X	X	X	T	T	T	T	T	T	T	T	T	T	T-Ae	T	T
X	X	X	X	X	U	U	X	Y	U	U-Aa	U-Ab	U-Ac	Ad	Ae	Af	Ag
X	X	X	X	X	X	V	X	VY	VZ	Aa	Ab	V-Ac	Ad	Ae	Af	Ag
X	X	X	X	X	X	X	X	Y	Z	Aa	Ab	W-Ac	Ad	W-Ae	Af	Ag
X	X	X	X	X	X	X	X	XY	X	X-Aa	X	X-Ac	X-Ad	X-Ae	X-Af	X
X	X	X	X	X	X	X	X	X	Y	Y	Y	Y-Ac	Ad	Ae	Y-Af	Y
X	X	X	X	X	X	X	X	X	X	Aa	Z-Ab	Z-Ac	Ad	Ae	Af	Ag
X	X	X	X	X	X	X	X	X	X	X	Aa-Ab	Aa-Ac	Aa-Ad	Ae	Af	Aa-Ag
X	X	X	X	X	X	X	X	X	X	X	X	Ab	Ad	Ab-Ae	Ab-Af	Ag
X	X	X	X	X	X	X	X	X	X	X	X	X	Ad	Ac-Ae	Ac-Af	Ac-Ag
X	X	X	X	X	X	X	X	X	X	X	X	X	X	Ad	Ad-Af	Ad
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Af	Ae
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	Af
X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

A	19	0.027536232	2.75
B	19	0.027536232	2.75
C	5	0.007246377	0.72
D	15	0.02173913	2.17
E	4	0.005797101	0.58
F	6	0.008695652	0.87
G	32	0.046376812	4.64
H	31	0.044927536	4.49
I	17	0.024637681	2.46
J	14	0.020289855	2.03
K	8	0.011594203	1.16
L	8	0.011594203	1.16
M	28	0.04057971	4.06
N	16	0.023188406	2.32
O	12	0.017391304	1.74
P	28	0.04057971	4.06
Q	28	0.04057971	4.06
R	29	0.042028986	4.20
S	25	0.036231884	3.62
T	32	0.046376812	4.64
U	21	0.030434783	3.04
V	16	0.023188406	2.32
W	12	0.017391304	1.74
X	31	0.044927536	4.49
Y	27	0.039130435	3.91
Z	17	0.024637681	2.46
Aa	25	0.036231884	3.62
Ab	23	0.033333333	3.33
Ac	25	0.036231884	3.62
Ad	31	0.044927536	4.49
Ae	29	0.042028986	4.20
Af	31	0.044927536	4.49
Ag	26	0.037681159	3.77
Sum	690	1	100

Appendix E. QFD 1 Mapping of System of Systems Part 1

			Information Handling											CAD						
		Importance divided in percentageout of 100	Centralize information	Identify relevant information surrounding the product	Distribute information surrounding the product	Highlight available information regarding the product	Organize information in a structured way	Suggest relevant information for the developer	Detect duplicate documents	Detect duplicate partfiles	Remove dublicates	Store relevant information regarding the product	Communicate previous executed work to the developer	Communicate existing CAD-Models	Create workguidlines for the developer	Structure modeling tree	Create robust models	Map parametric dependencies	Highlight critical parameters	Establish flexible CAD Models
1	Reduces the amount of sources	2.75	9	3	9	3	3		1	1	1	9	3		1					
2	Preserves the reliability of the information	2.75	3	9			3		3	3	3	3		3	9	1	3	1		1
3	Presents the availiability of the information	0.72	3	3		9	3	1				1	1	9	1			3	3	
4	Prevents duplicates of documents	2.17	1	3	1				9	9	9	3		3	1					
5	Enlightens the need of information	0.58	1		1	3		9	1			3	9	3	1			1	9	
6	Provides clarity on previously executed work	0.87		3	3	3		3				9	9	9	1			1	1	
7	Allows reuse	4.64	3	1	9		3					3	9	9	9		9	3	1	9
8	Provides suport for developers decision	4.49		1		1	3	1				3	3	3	9	1		3	3	3
9	Provides understanding on existing CAD Models	2.46		3			9			1	1			9	1	1		3	1	
10	provides a standarized work method	2.03	9	3	3		1					3			9		1			
11	Provides understanding on the modeling tree	1.16										3	3	1		9		1	1	
12	Provides understanding on parametric dependencies	1.16		3			1						3					9	3	1
13	Preserves the robustness of CAD models	4.06															9			3
14	Enlightens the critical parametric dependencies	2.32				3		3				3							9	1
15	Presents the optimal manipulation seequence of dependencies	1.74						9				3						3	9	1
16	Allows adaptable CAD models	4.06	3	1	1		3					3	1				3			9
17	Reduces the product Complexity	4.06	3	3			3					3								
18	Increases the product understanding	4.20	3	3			3					3	3							
19	Provides support for the concept development process	3.62	3				3	3				3	3							
20	Reduces rework	4.64	3			1	3						3	9	9			3	1	9
21	Allows overall adaptability	3.04	3				9								3					
22	Allows interactions with the developer	2.32					3					1	9	1						
23	Enables the "fun-part" of designing	1.74	1	3		1	3						3	3	3			3	1	3
24	Is easy to use	4.49	9	3	1	1	9		3	3	3	3	3	9	9	3	3	3	3	3
25	Allows capture of design intent	3.91		1		3						1		1						9
26	Allows project documentation	2.46	3	1								3			1					
27	Has to manage previous versions of CAD Models	3.62		3								3		9						
28	Allows retrival of previous versions	3.33		3	3		3					3								
29	Allows individualization	3.62					3					3								
30	Prevents disruption of work	4.49	9	3	1	3	1					3	3	3	3		3	3	3	3
31	Provides simplicity	4.20	9	1	1	3	1					3	3	9	9		9	3	3	9
32	Increases the design freedom	4.49	3			3		3	1	1	1	3	3	1	1			1		9
33	Allows simultanious creation of concepts	3.77					3													
		Importance of Functional requirement	281.63	162.78	105.19	104.85	253.92	59.99	49.07	50.95	50.95	243.75	165.19	291.3	289.47	33.61	165.5	121.12	115.92	299.24
		Rank of Improtance	4	14	21	22	5	28	31	29	29	6	13	2	3	31	12	17	18	1

- QFD 1 Mapping of System of Systems Part 2

15	128.27										3				3	1	3	9	3			1						3	3		3			1		Organize product dependencies	Product
8	240.32	3	3	9	3					9	3	3		3	3	1	9	3	1										3	3	1	1	3	3		Generate produt understanding	
9	236.77	9	1	3	3					1				3		9	1											3				1		9		Follow concept development principles	
7	240.81		3		3		1	1							9			1	3	3	3	1	3	3	9	3	3	9	3	3	3	9	1	9	Reduce wasteful work for the developers	Library
26	80.25													9					3						3		3	3			3	1			Adapt the application	
24	96.83											3	9	1	3					3	3		1	3	3		3	1	3	9	1			1	Communicate with developer through interface	
16	122.98		3								1	9			1			1	3		1	1	1					3		1	9	3	9		Enjoy the design activity	
19	110.67	1	3		1			1			9		3	1									1	1	9	3			3	1	9	3		3	Provide simplicity for the developer when navigating the system	
25	84.48		1							9					3			3	3		1		3									1			Capture the intention of design	
20	105.71		1				3	3	9					1	3										3	3	3	1	3		1	3		1	Store project progress	
11	181.04	1	3				9	9	3						1				3	3		1		3	3	9	3	3			3	3			Store CAD-Model files	
27	77.34			1		9					3	1	3	3											3	1						1			Customize interface environment base on developers needs	
10	211.74	3	3	9	9	3	3		1		1	1			1									1	3	3		3	3	3	3	3	3	9	Control the system environment	
23	99.69	9	1	3			1				1			3				1	1						1		3		3				1	1	Comply with development method	

Appendix F. Outcome of QFD 2

											Individual sum for parts of System A & C
281.63	104.85	253.92	59.99	243.75	165.19	240.81	122.98	181.04	211.74	99.69	1965.59
14.34	5.33	12.92	3.05	12.4	8.4	12.25	6.26	9.21	10.77	5.07	100
											Individual percentage of sum of System A & C

SYSTEM A & C - QFD 2

Organizational Complexity and Database additions

Sub-system solutions for - Information Handling and Library functionalities

	Importance weight in precentage for System AA & CC	Create a single interface platform for the user	Base the system architecture on the product architecture	Create a system that visually supports the developer in the development process	Create a system interface that supports the developer with both functional and physical knowledge reuse	Create a system interface that is user friendly	Store CAD-files in an organized and accessible manner	Create a system that allows the user to individually control aspects of the interface layout	Illustrate the role of the proposed approach in the development process
Centralize information	14.34	9	3	1	1	9	3	3	
Highlight available information regarding the product	5.33	3		9	1	3	3	3	
Organize information in a structured way	12.92	1	9	3	9	1	1	1	
Suggest relevant information for the developer	3.05		1	1	9		1		
Store relevant information regarding the product	12.4		3	3			3		
Communicate previous executed work to the developer	8.4		1	3			3	3	1
Reduce wasteful work for developers	12.25	9	9	9	3	3	3	3	
Enjoy the design activity	6.26	9	1	1	1	9		9	9
Store CAD-Model files	9.21				1	1	9	1	
Control the system environment	10.77	9	1	1	3			9	3
Comply with development method	5.07	1	1						9
Importance of Sub-Solution Requirement		426.56	340.3	293.8	247.93	260.27	257.02	296.36	142.68
Rank Importance of Sub-Solutions		1	2	4	7	5	6	3	8

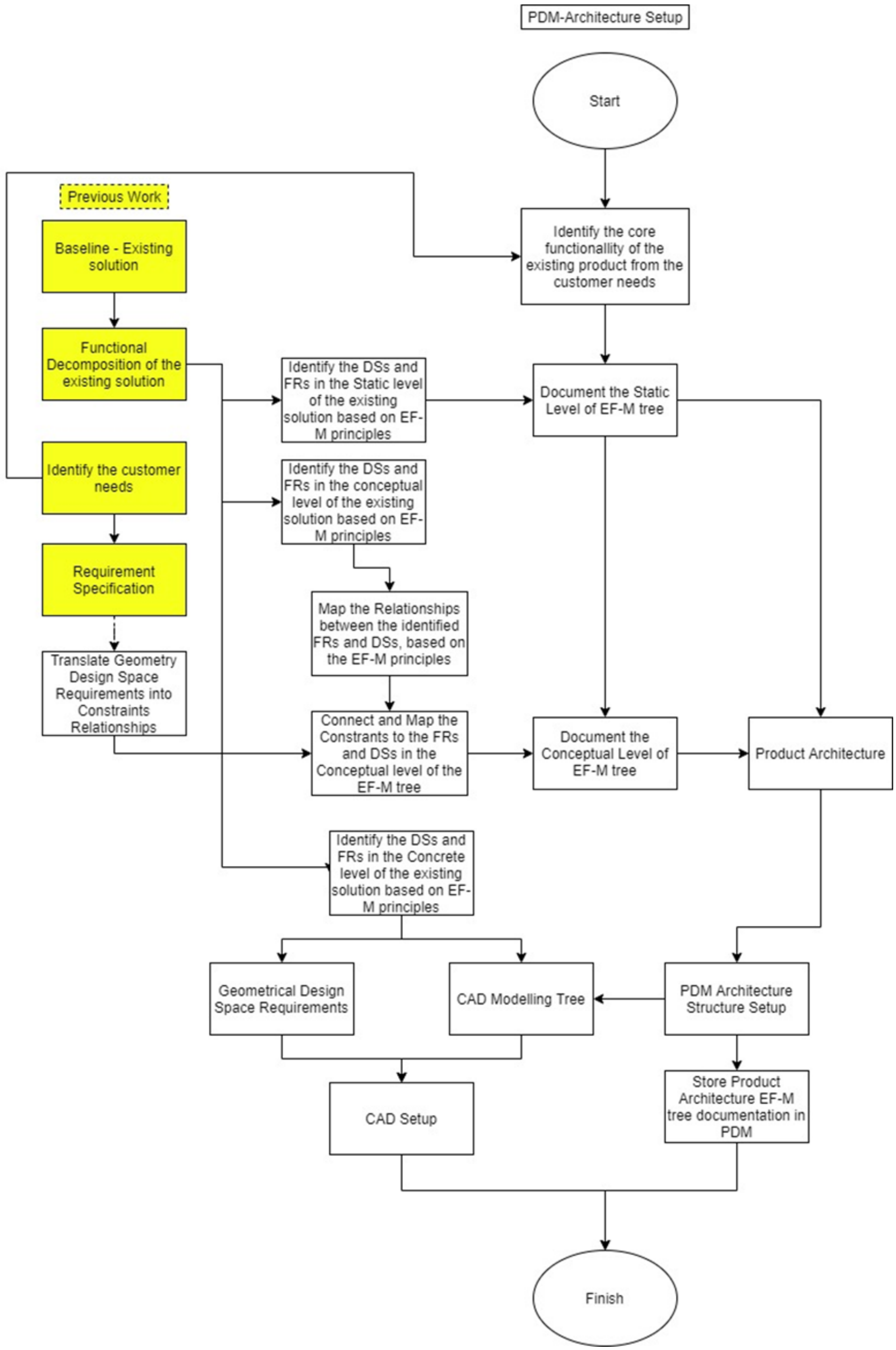
QFD 2 for System B

291.3	289.47	33.61	165.5	121.12	115.92	299.24	128.27	240.32	236.77	1921.52	Individual sum of System B
15.16	15.06	1.75	8.62	6.3	6.03	15.57	6.68	12.51	12.32	100	Individual percentage of sum of System B

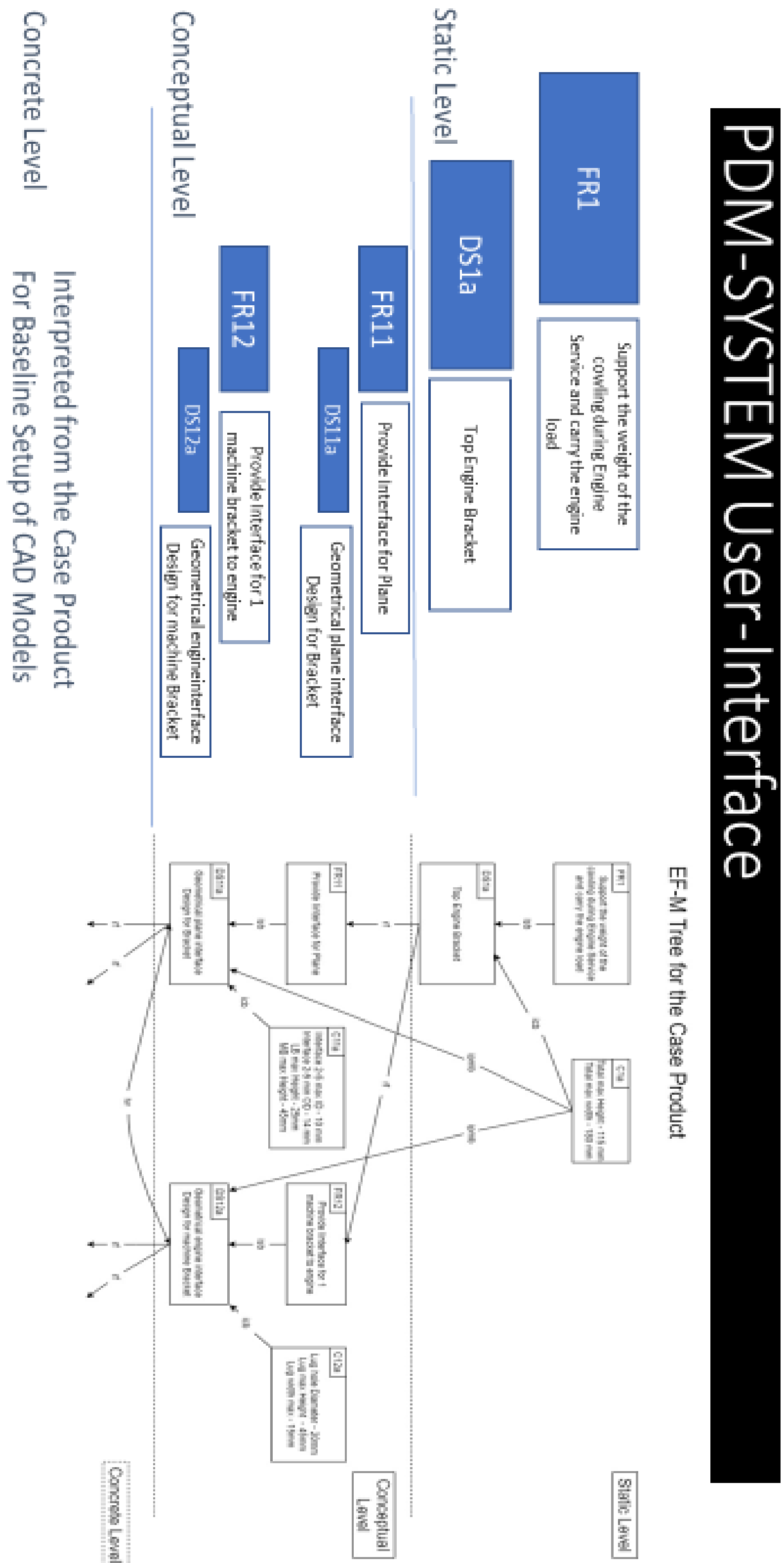
QFD 2: Sub-Solutions for System B Process and Product Complexity

Rank Importance of Sub-Solutions	Importance of Sub-Solution	Follow concept development principles	Generate produt understanding	Organize product dependencies	Establish flexible CAD Models	Highlight critical parameters	Map parametric dependencies	Create robust models	Structure modeling tree	Create workguidlines for the developer	Communicate existing CAD-Models	
		12.32	12.51	6.68	15.57	6.03	6.3	8.62	1.75	15.06	15.16	Importance weight in precentage for System BB
9	148.76	1									9	Create a system interface that structurally presents available CAD Models
11	135.54									9		Create a sequential guidelines for development team
13	100.64	1			3			3	9			Create the structure of the modeling tree based on a Top-Down approach
3	279.96	3		3	9			9	3			Create models parallelly with increasingproduct understanding through the mapping of Product architecture
2	285.8		9	1	9	3	3	9	3			Create a CAD model that is geometrically adaptable
7	217.71				9			9				Create CAD models that are scalable
7	217.71				9			9				Create CAD models that allow modularity
10	146.07			3		9	9			1		Translate critical parametric dependencies to an applicable worksheet
6	222.01		9	3	3			3	1	1		Create control of the paramteric dependencies with value limits
4	262.09		9	9	3			3	1	1		Map Functional and Physical Elements of the product
5	225.51		9	3	3			3	3	1		Include the effects of requirement constraints between Functional and Physical Elements
1	287.52		9	9	3	3	3	3	3			Map the relationships between the Functional and Physical Elements and the relation constraints
12	125.94	9								1		Show applicability to the generally accepted development process

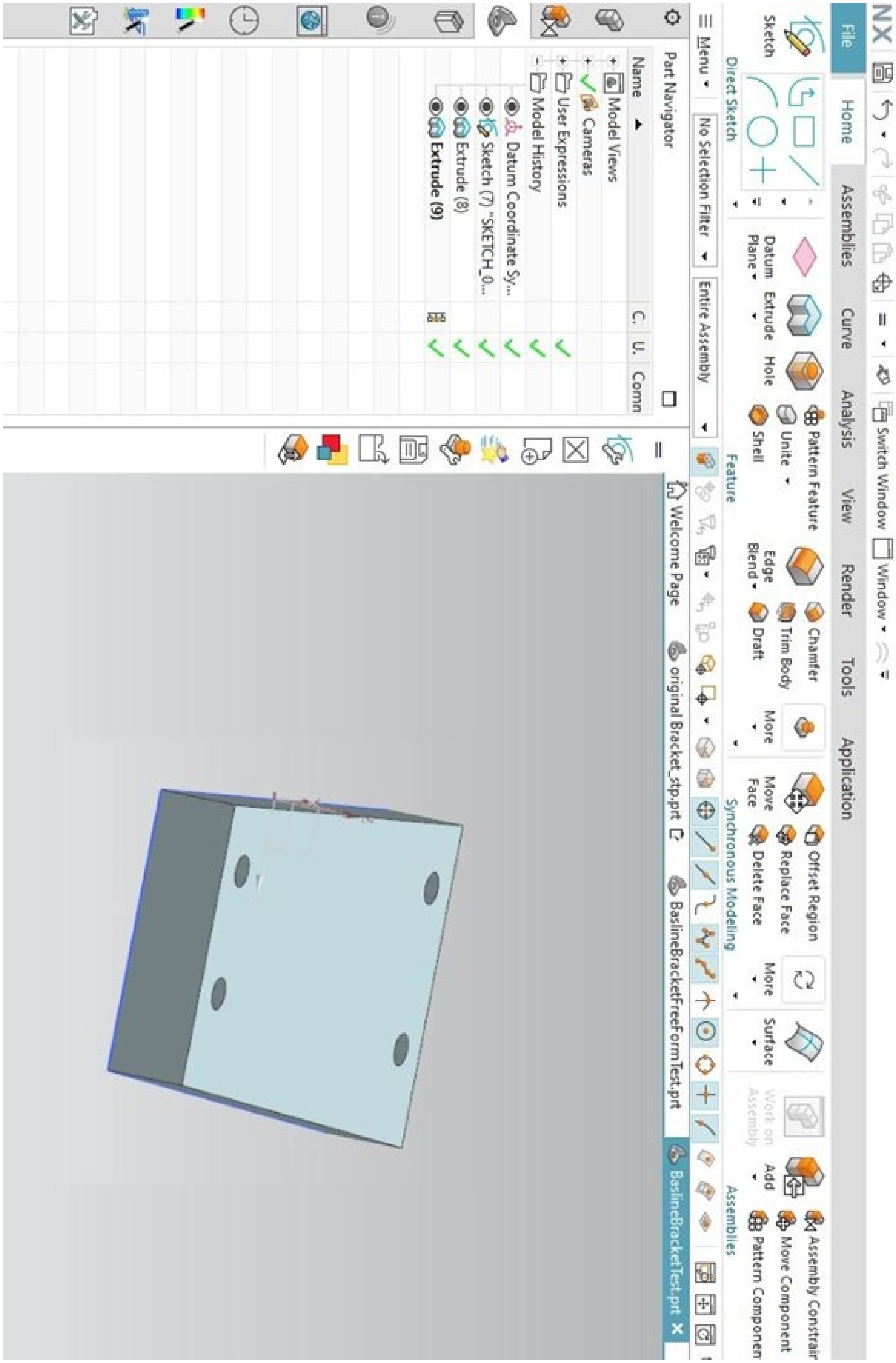
Appendix G. PDM structure set-up activities



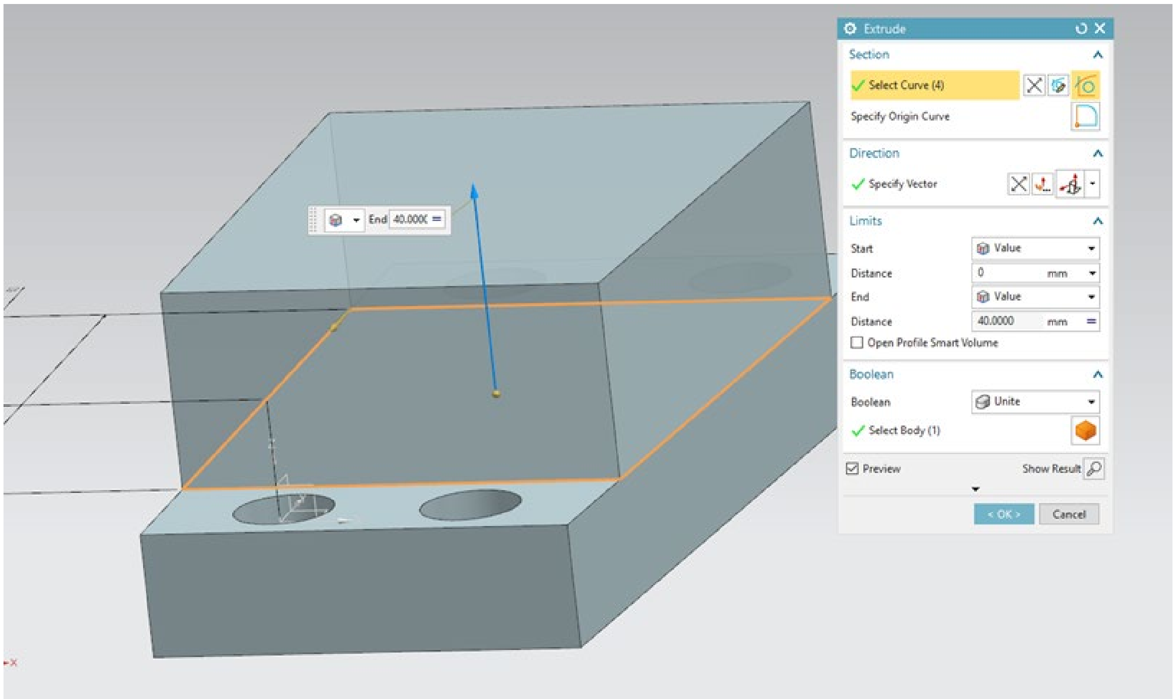
Appendix H. PDM Structure – User Interface

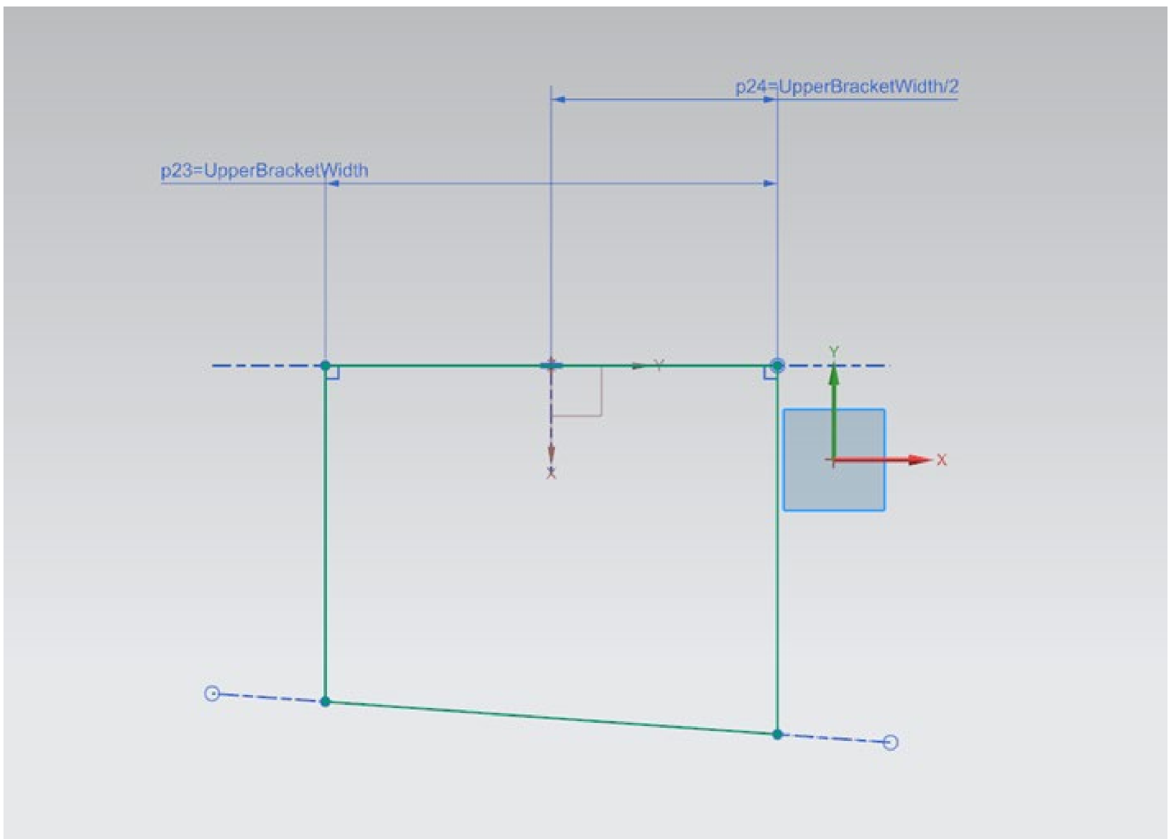


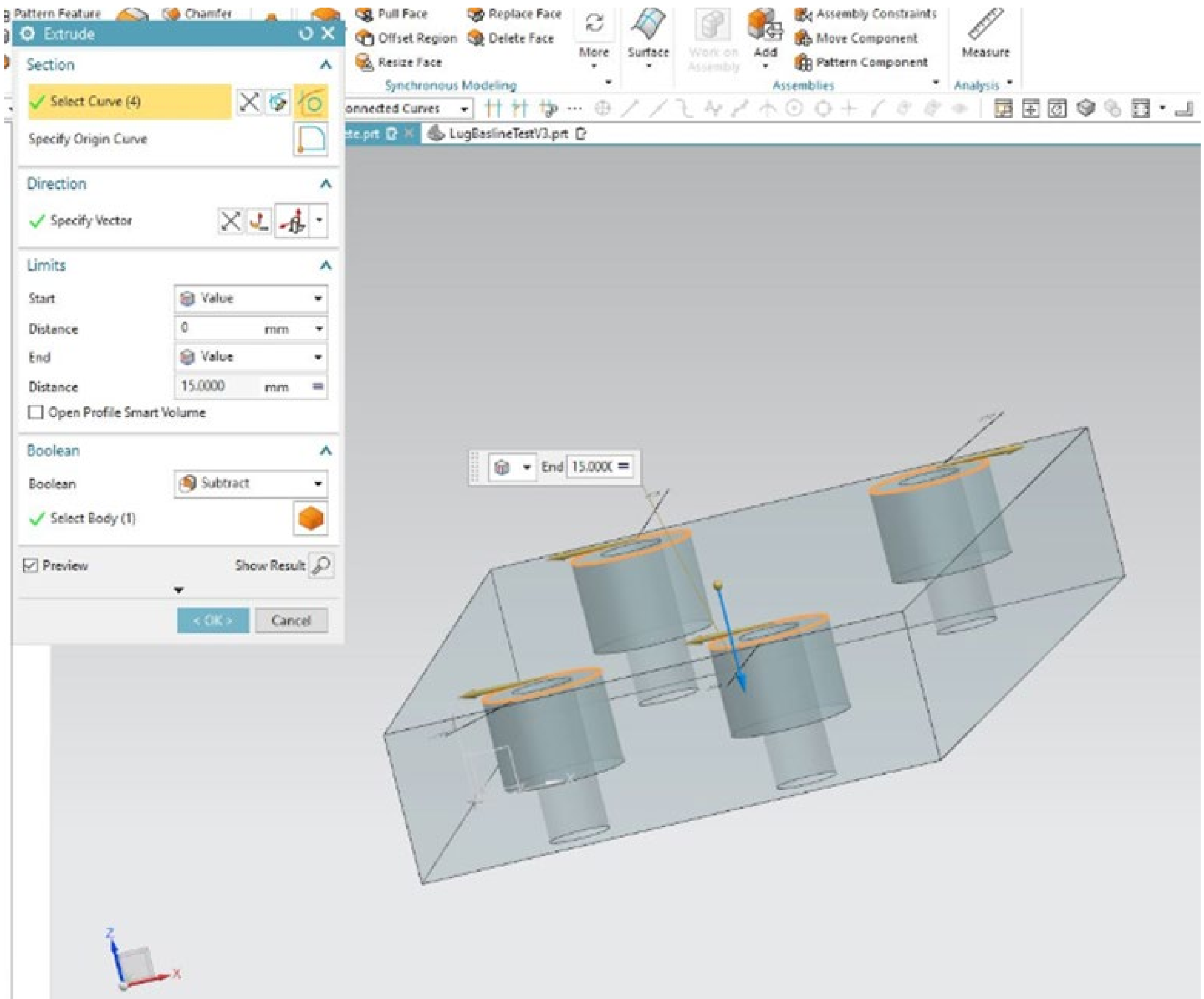
Appendix H. First sketch extrude and subtraction operations



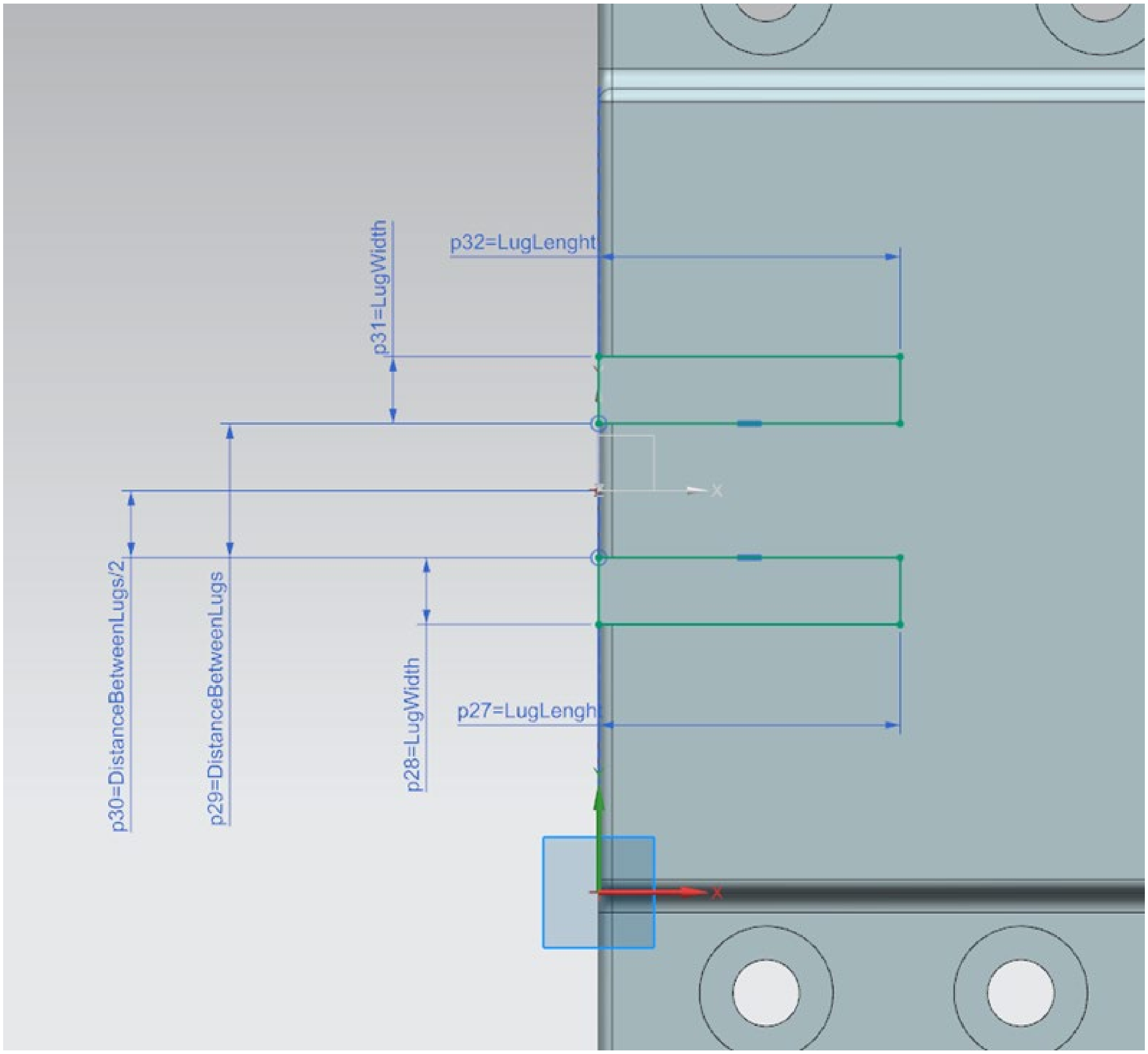
Appendix I.Second Sketch



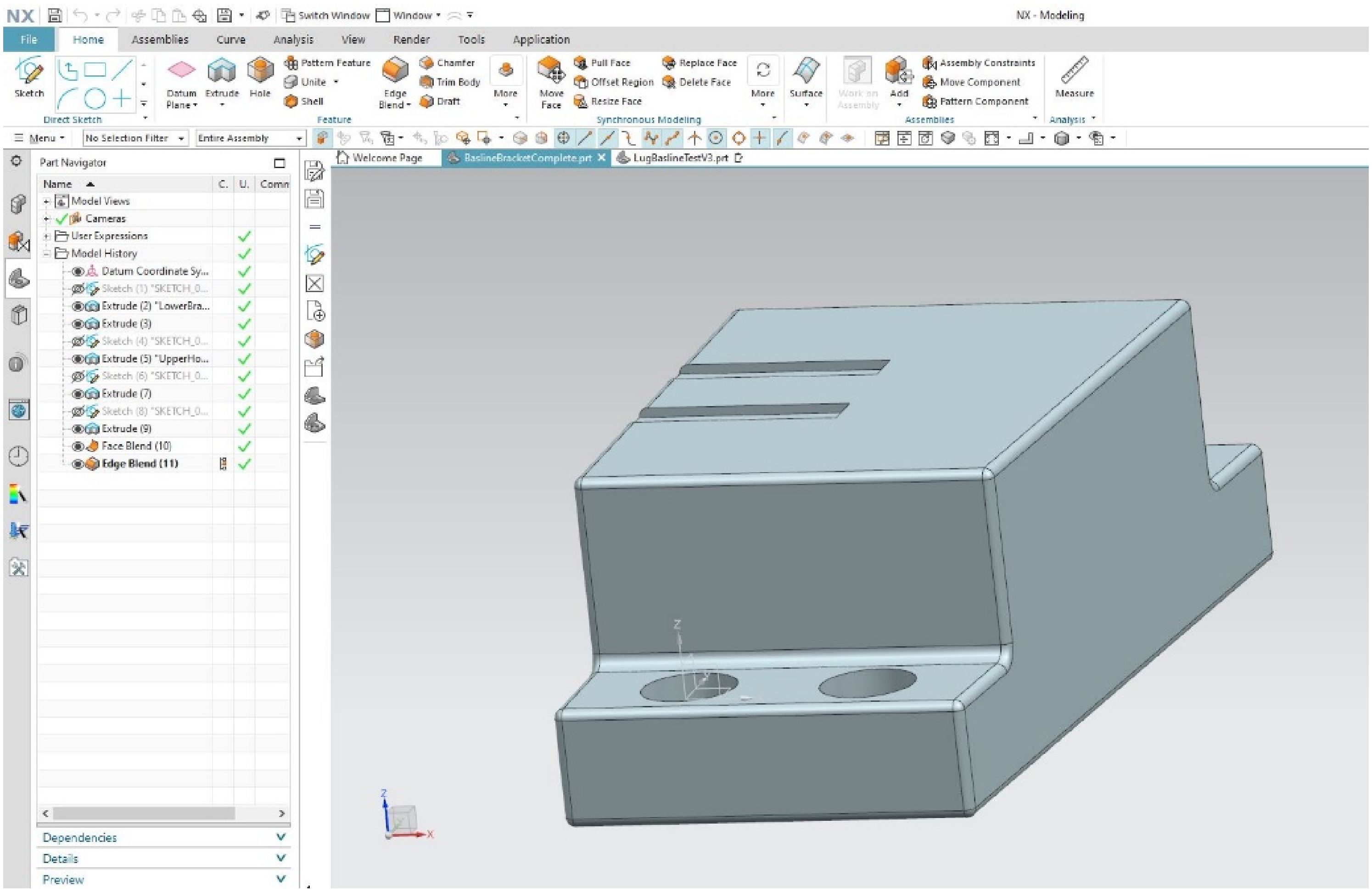



Extrude
Section
Select Curve (4)
Specify Origin Curve
Direction
Specify Vector
Limits
Start
Value
Distance
0
mm
End
Value
Distance
15.0000
mm
Open Profile Smart Volume
Boolean
Boolean
Subtract
Select Body (1)
Preview
Show Result
< OK >
Cancel
Pull Face
Replace Face
Offset Region
Delete Face
Resize Face
Synchronous Modeling
More
Surface
Add
Assembly Constraints
Move Component
Pattern Component
Assemblies
Measure
Analysis
Pattern Feature
Chamfer
LugBaslineTestV3.prt
End
15.000(

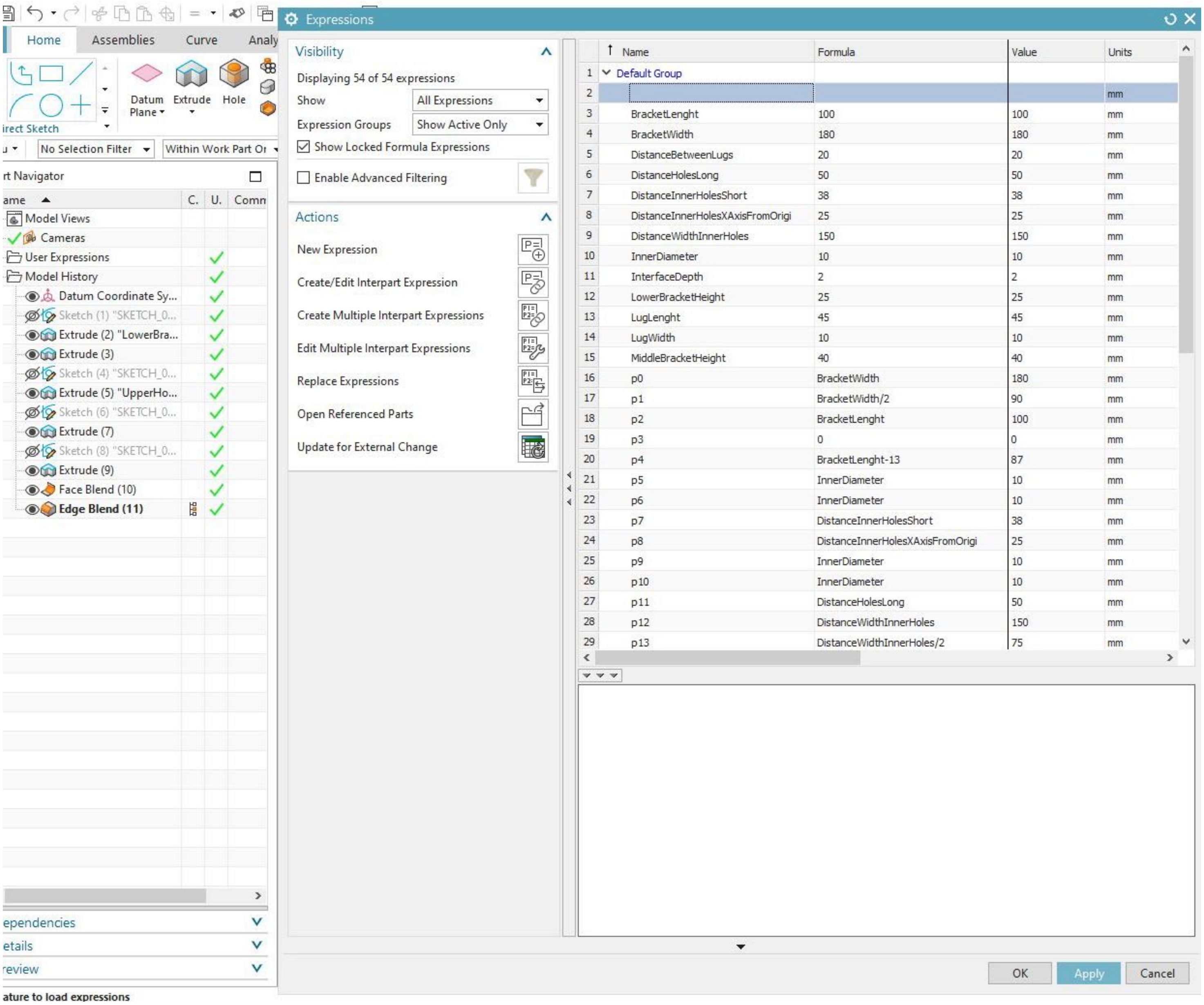
Appendix J. Universal interface

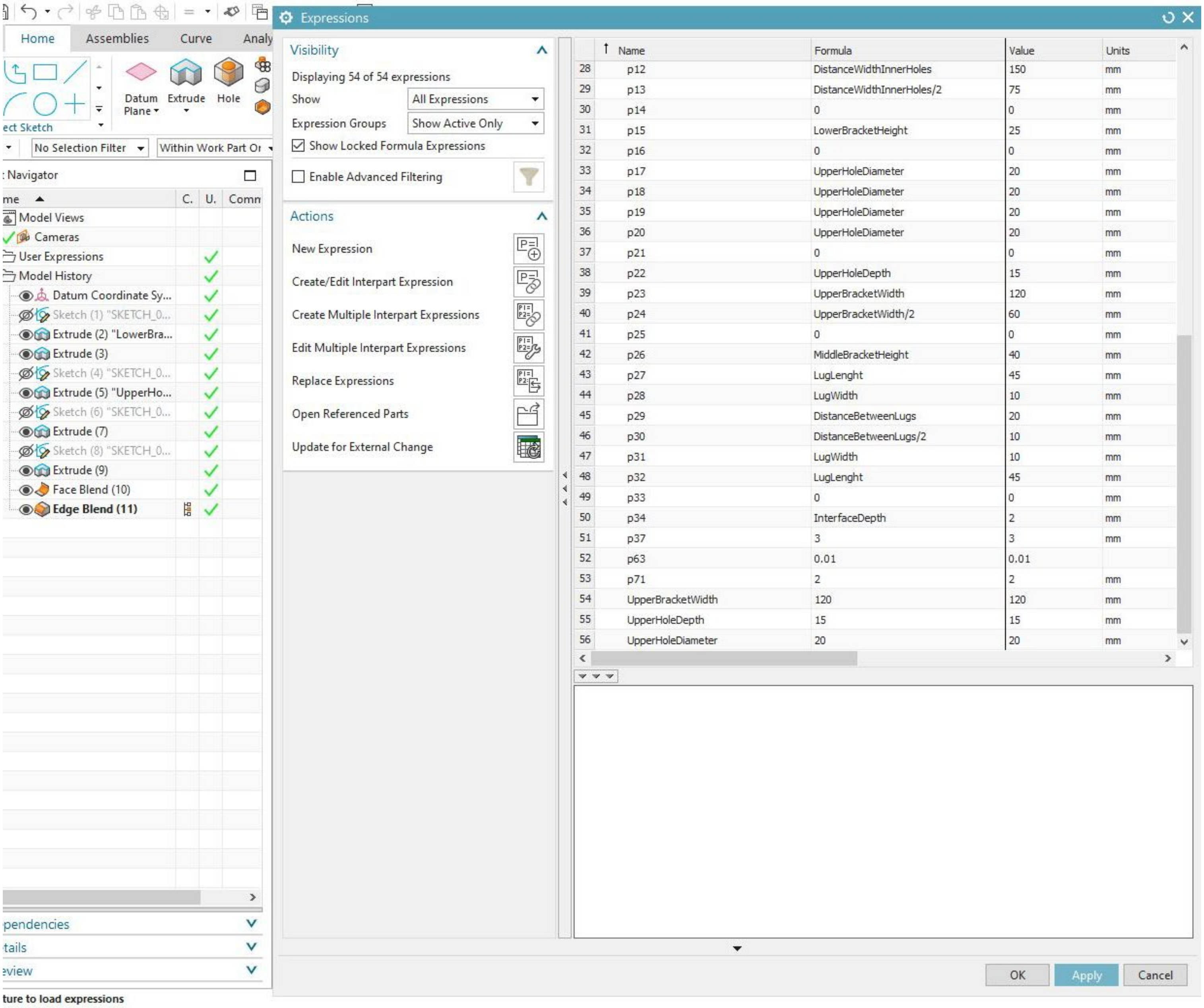


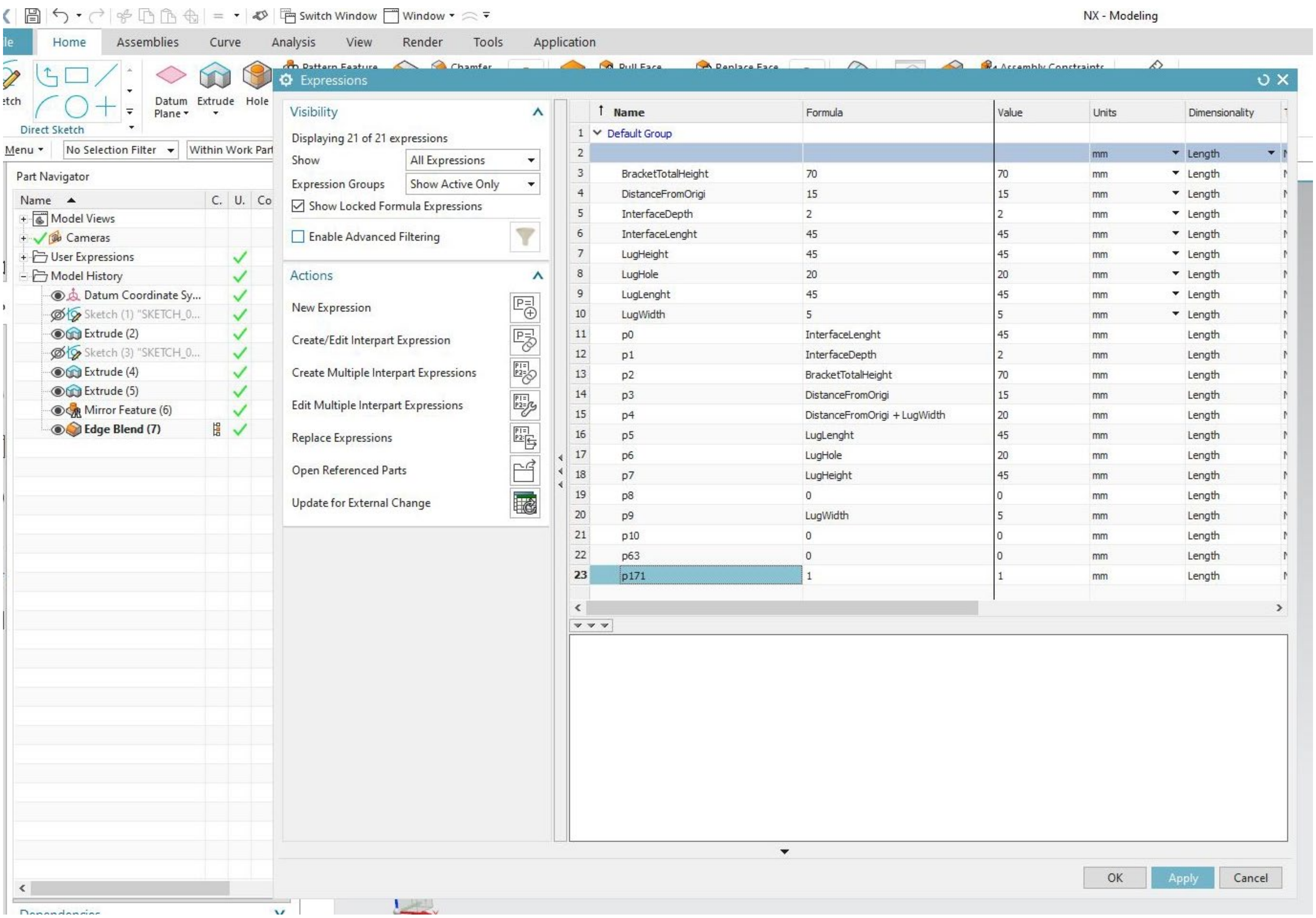
Appendix K. Complete Baseline for fulfilment of FR12 based on the Case Product



Appendix L. Parametric dependencies for the bracket and lug




Expressions
Home
Assemblies
Curve
Datum Plane
Extrude
Hole
No Selection Filter
Within Work Part Or
Navigator
Model Views
Cameras
User Expressions
Model History
Datum Coordinate Sy...
Sketch (1) "SKETCH_0...
Extrude (2) "LowerBra...
Extrude (3)
Sketch (4) "SKETCH_0...
Extrude (5) "UpperHo...
Sketch (6) "SKETCH_0...
Extrude (7)
Sketch (8) "SKETCH_0...
Extrude (9)
Face Blend (10)
Edge Blend (11)
Visibility
Displaying 54 of 54 expressions
Show All Expressions
Expression Groups Show Active Only
Show Locked Formula Expressions
Enable Advanced Filtering
Actions
New Expression
Create/Edit Interpart Expression
Create Multiple Interpart Expressions
Edit Multiple Interpart Expressions
Replace Expressions
Open Referenced Parts
Update for External Change
Name Formula Value Units
28 p12 DistanceWidthInnerHoles 150 mm
29 p13 DistanceWidthInnerHoles/2 75 mm
30 p14 0 0 mm
31 p15 LowerBracketHeight 25 mm
32 p16 0 0 mm
33 p17 UpperHoleDiameter 20 mm
34 p18 UpperHoleDiameter 20 mm
35 p19 UpperHoleDiameter 20 mm
36 p20 UpperHoleDiameter 20 mm
37 p21 0 0 mm
38 p22 UpperHoleDepth 15 mm
39 p23 UpperBracketWidth 120 mm
40 p24 UpperBracketWidth/2 60 mm
41 p25 0 0 mm
42 p26 MiddleBracketHeight 40 mm
43 p27 LugLenght 45 mm
44 p28 LugWidth 10 mm
45 p29 DistanceBetweenLugs 20 mm
46 p30 DistanceBetweenLugs/2 10 mm
47 p31 LugWidth 10 mm
48 p32 LugLenght 45 mm
49 p33 0 0 mm
50 p34 InterfaceDepth 2 mm
51 p37 3 3 mm
52 p63 0.01 0.01
53 p71 2 2 mm
54 UpperBracketWidth 120 120 mm
55 UpperHoleDepth 15 15 mm
56 UpperHoleDiameter 20 20 mm
OK
Apply
Cancel



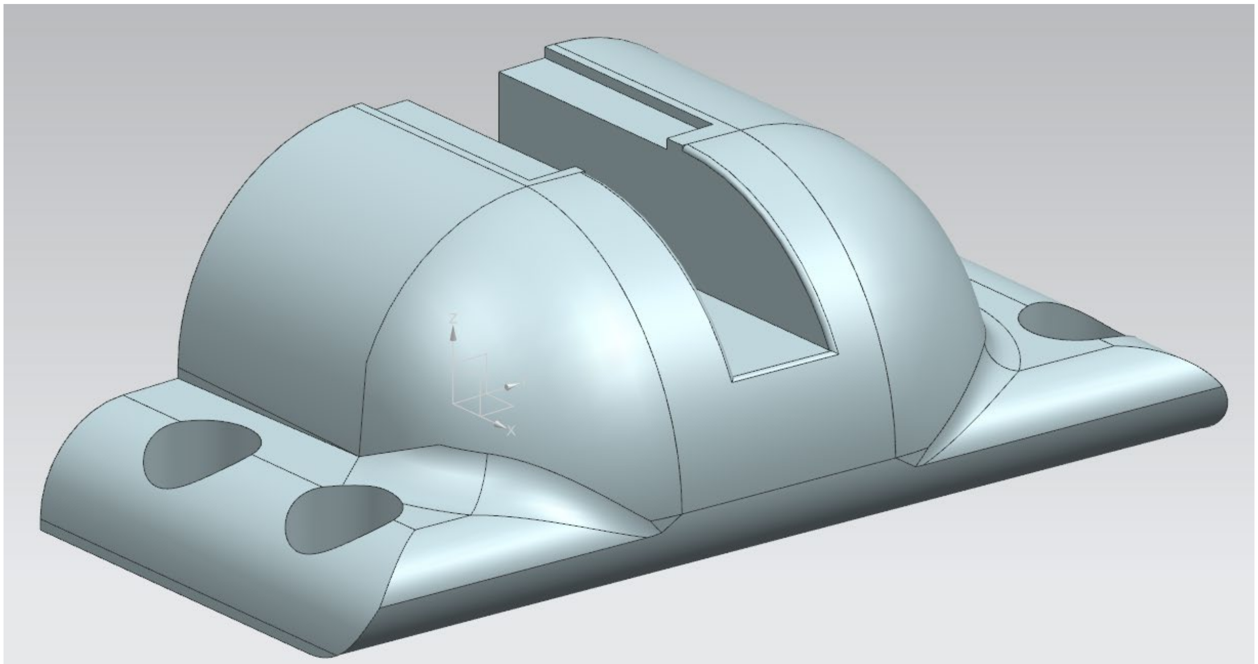
Appendix M. C source code for sequential Geometry Design Space Limits

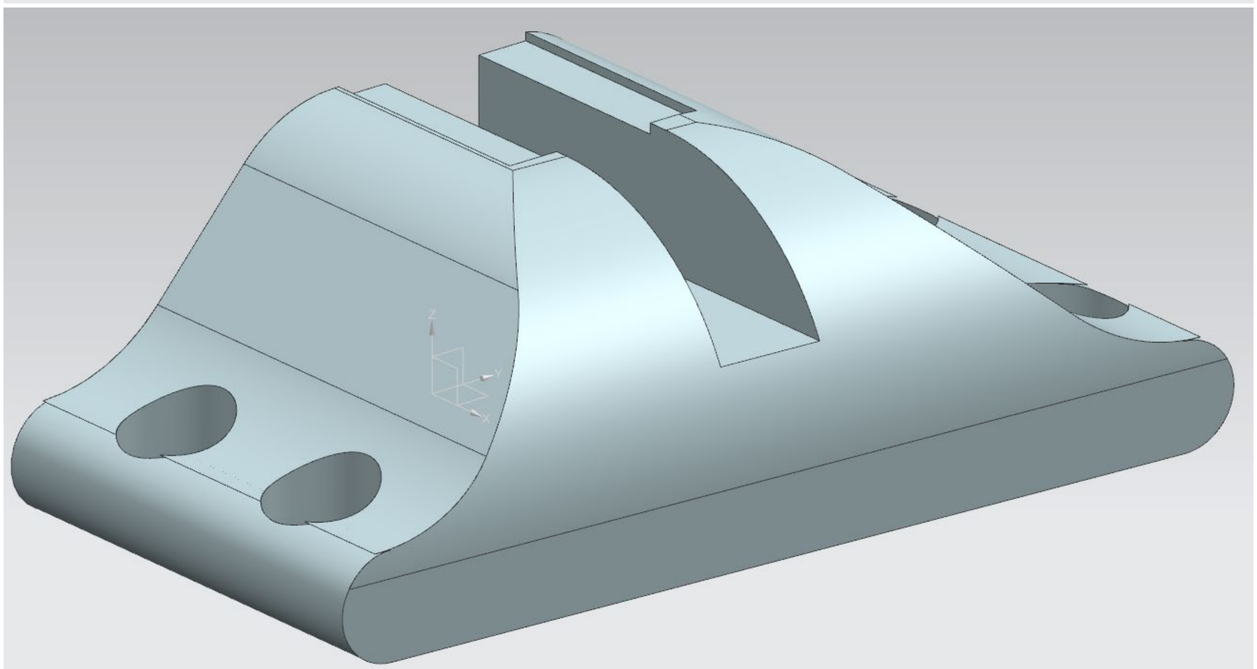
```
#include <stdio.h>

double distanceHolesLong = 50;
double distanceHolesShort = 38;
double distanceWidthInnerHoles = 150;
double interfaceLength = 45;
double interfaceDepth = 2;
double distanceBetweenLugs = 20;
int main() {
  double UpperHoleDiameter;
  printf("Choose UpperHoleDiameter ranging between 14mm and 25mm \n");
  scanf("%lf",&UpperHoleDiameter);
  if(UpperHoleDiameter < 14 || UpperHoleDiameter > 25){
    printf("Value outside of specified range \n");
    return 0;
  }
  double minDistanceX = UpperHoleDiameter / 2 + 2;
  double minBracketLength = minDistanceX + distanceHolesLong + UpperHoleDiameter / 2 + 2;

  double BracketLength;
  printf("Choose BracketLength ranging between %0.2lf mm and 100mm  \n", minBracketLength);
  scanf("%lf",&BracketLength);

  if(BracketLength < minBracketLength || BracketLength > 100){
    printf("Value outside of specified range \n");
    return 0;
  }
  //printf("%lf\n",BracketLength );

  double DistanceX = 0;
  double maxDistanceX = BracketLength - 2 - UpperHoleDiameter / 2 - distanceHolesLong;
  printf("Choose inner holes distance from Xaxis Origi ranging between %0.2lf mm and %0.2lf mm  \n",
minDistanceX, maxDistanceX);
  scanf("%lf",&DistanceX);

    if (DistanceX < minDistanceX || DistanceX > maxDistanceX){
    printf("Value outside of specified range \n");
    return 0;
  }
```

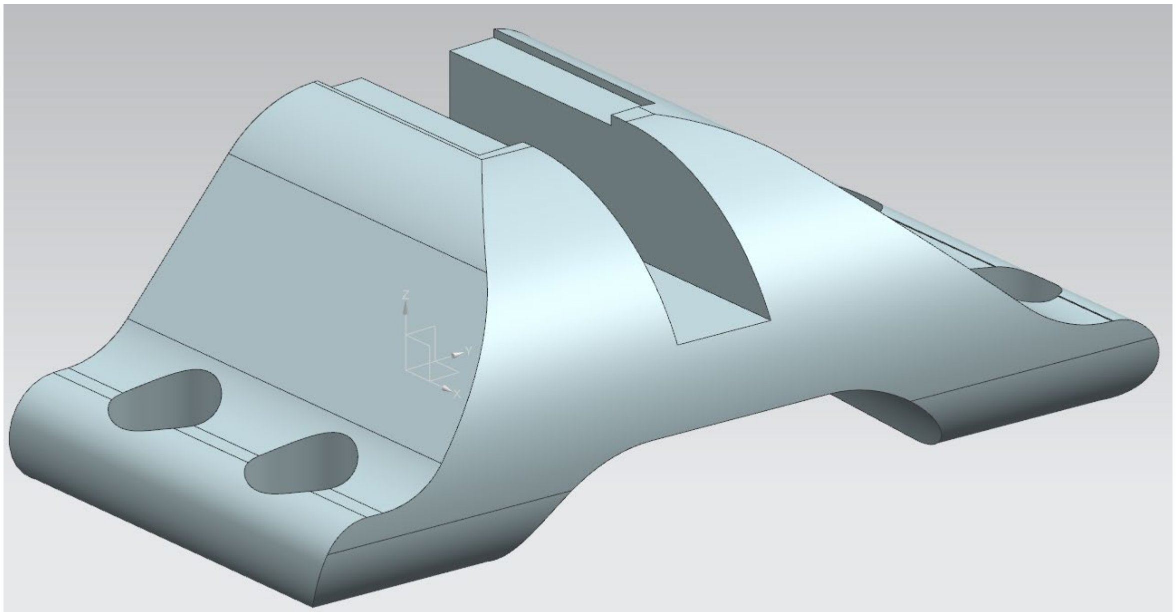
```
double BracketWidth;
double minBracketWidth = 2 + UpperHoleDiameter + distanceWidthInnerHoles + 2;
printf("Choose Bracket Width ranging between %0.2lf mm and 180 mm  \n", minBracketWidth);
scanf("%lf",&BracketWidth);

if (BracketWidth < minBracketWidth || BracketWidth > 180){
  printf("Value outside of specified range \n");
  return 0;
}

double LowerBracketHeight;
printf("Choose a Lower Bracket Height raging between 4 mm and 25 mm \n");
scanf("%lf", &LowerBracketHeight);

if (LowerBracketHeight < 4 || LowerBracketHeight > 25){
  printf("Value outside of specified range \n");
  return 0;
}

double UpperHoleDepth;
double maxUpperHoleDepth = LowerBracketHeight - 2;
printf("Choose a upper Hole Depth raging between 2 mm and %0.2lf mm \n", maxUpperHoleDepth);
scanf("%lf", &UpperHoleDepth);

if (UpperHoleDepth < 2 || UpperHoleDepth > maxUpperHoleDepth){
  printf("Value outside of specified range \n");
  return 0;
}

double LugInterfaceWidth;
printf("Choose a Lug Interface Width raging between 5 mm and 15 mm \n");
scanf("%lf", &LugInterfaceWidth);

if (LugInterfaceWidth < 5 || LugInterfaceWidth > 15){
  printf("Value outside of specified range \n");
  return 0;
}

double UpperBracketWidth;
double minUpperBracketWidth = distanceBetweenLugs + (LugInterfaceWidth * 2);
printf("Choose a width for rthe upper Bracket raging between %0.2lf mm and 120 mm \n",
minUpperBracketWidth);
scanf("%lf", &UpperBracketWidth);
```

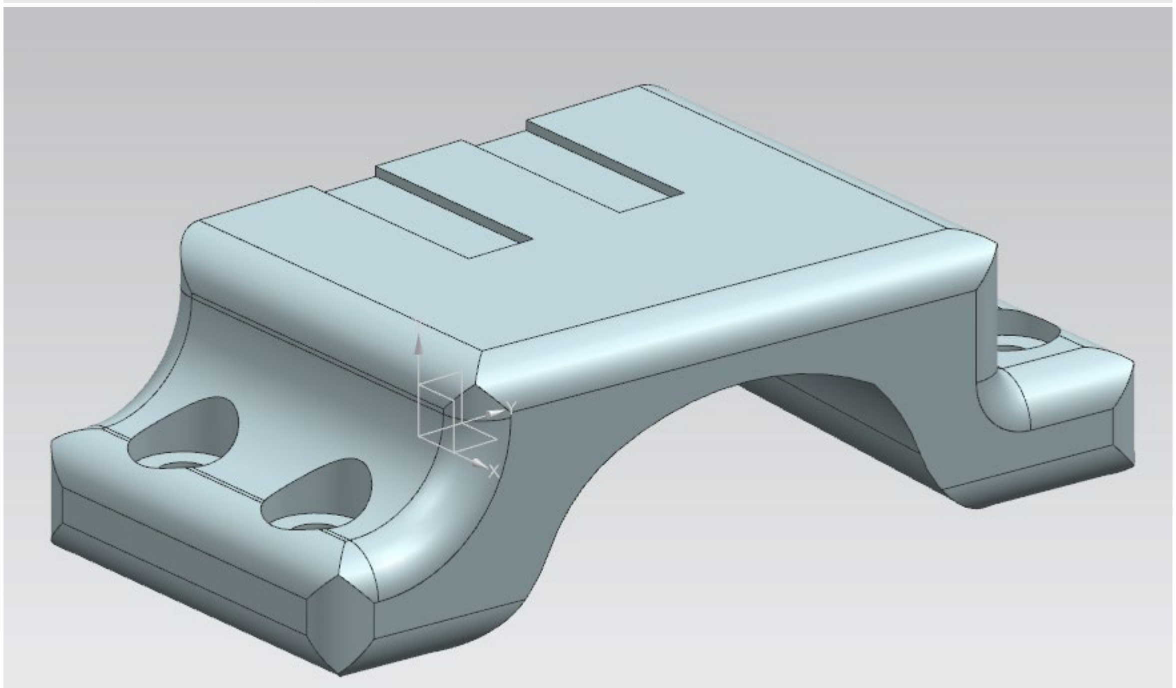
```
  if (UpperBracketWidth < minUpperBracketWidth || UpperBracketWidth > 120){
   printf("Value outside of specified range \n");
   return 0;
  }

  double UpperBracketHeight;
  printf("Choose a Upper Bracket Height raging between 4 mm and 40 mm \n");
  scanf("%lf", &UpperBracketHeight);

  if (UpperBracketHeight < 4 || UpperBracketHeight > 40){
   printf("Value outside of specified range \n");
   return 0;
  }

}
```

Appendix N. Design Alternatives for FR12

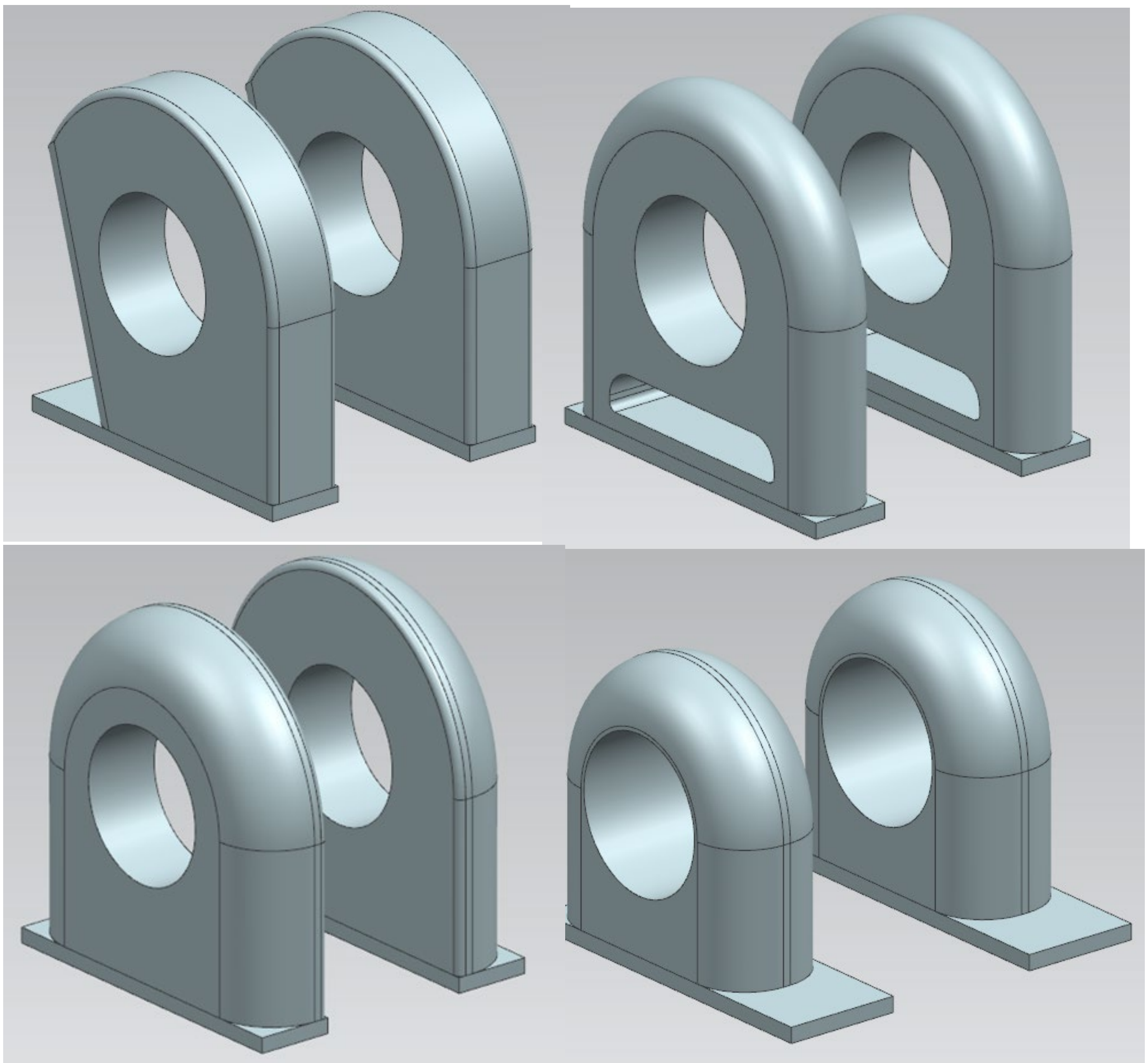






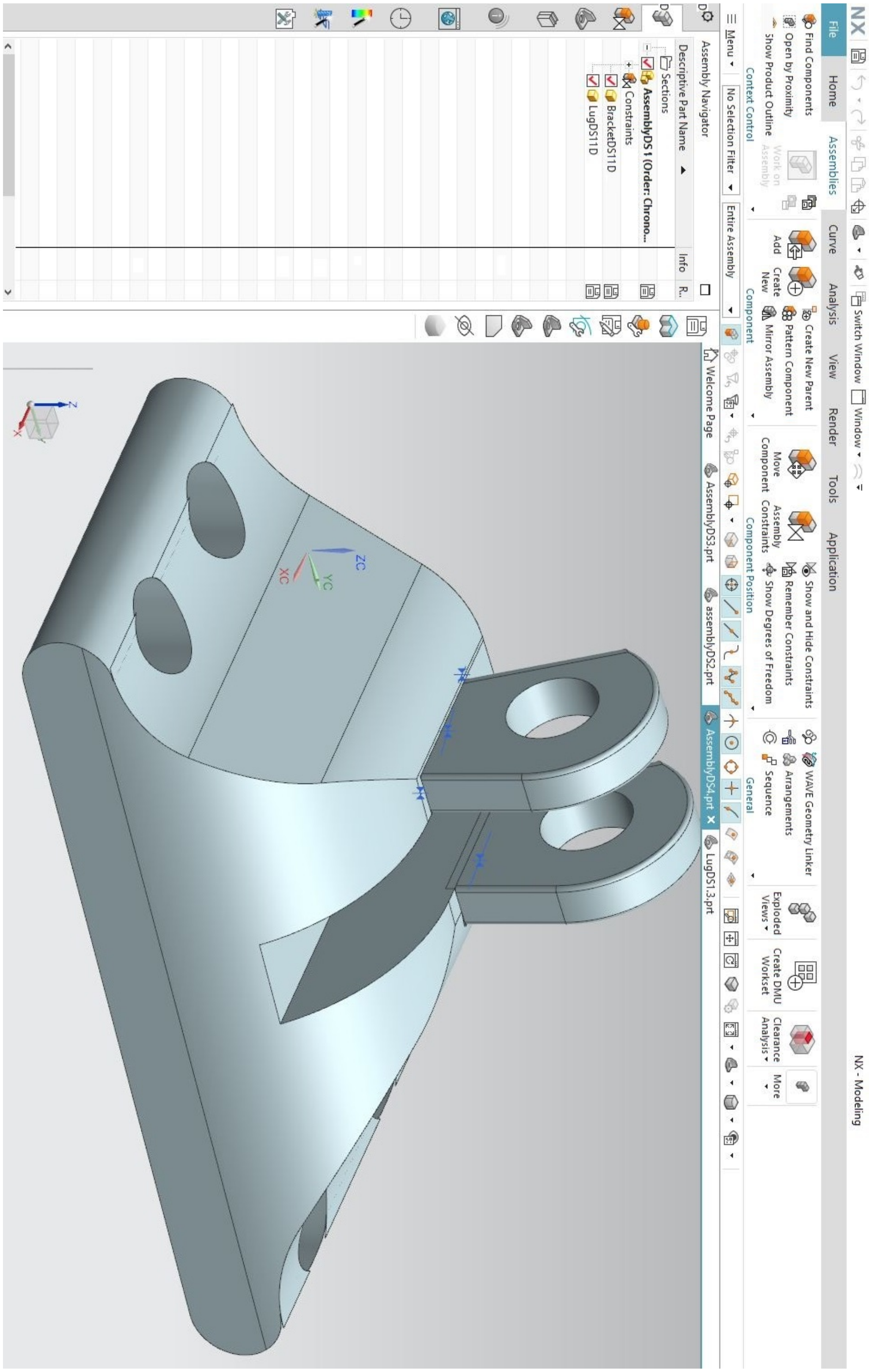


Appendix O. Design Alternatives for FR11

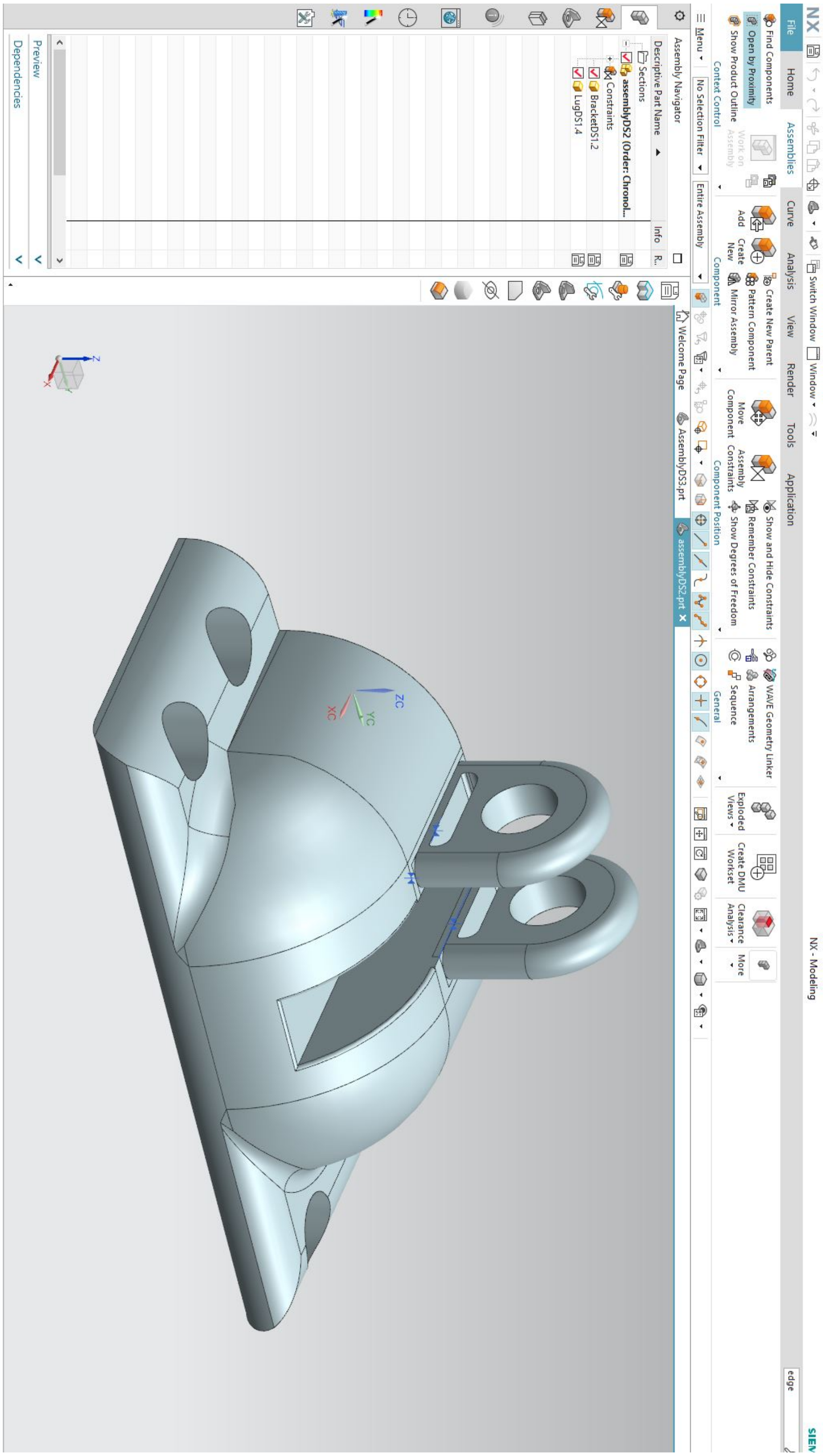


Appendix P. Generated Concepts

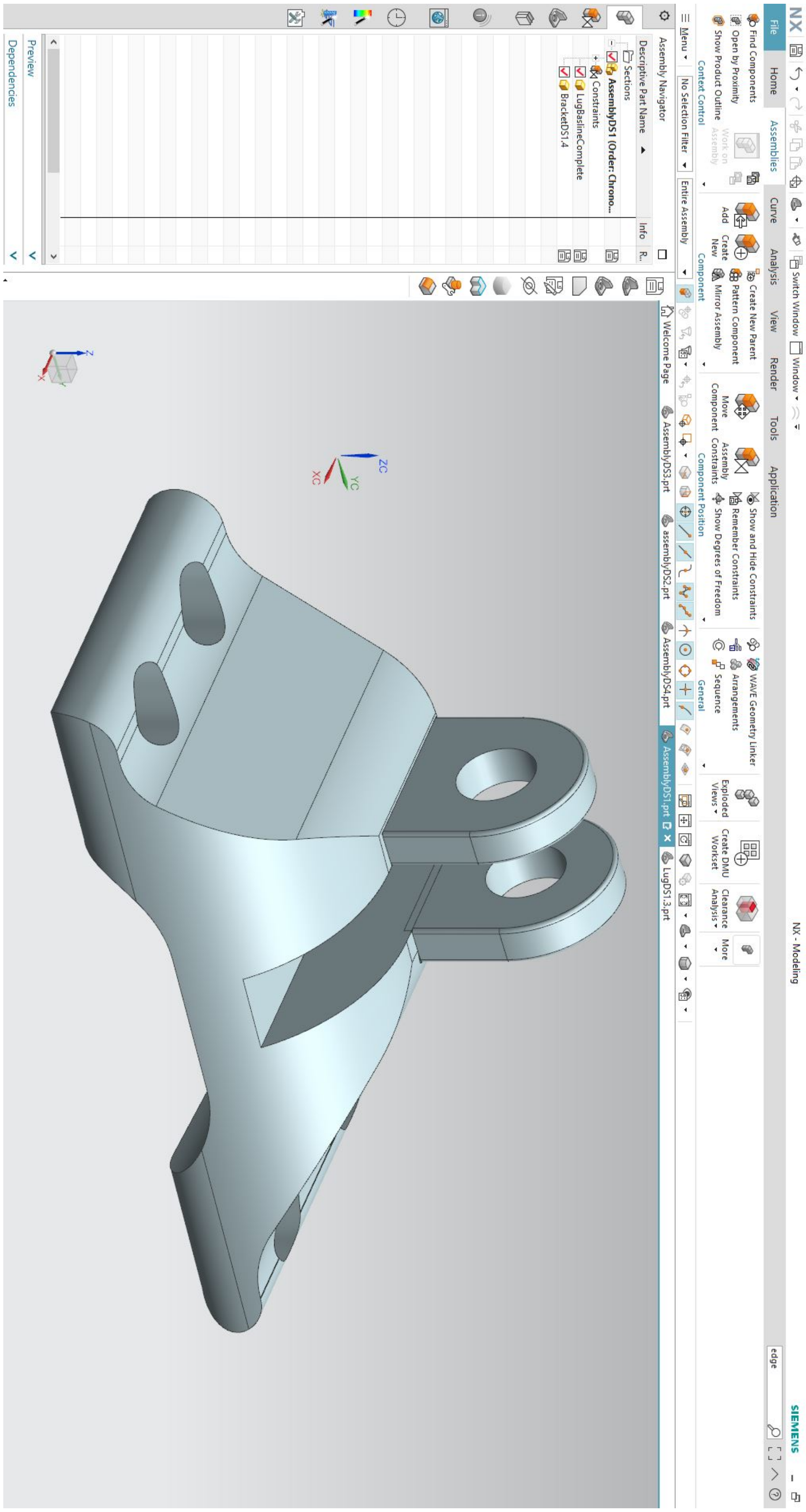
DS1b = DS11D+DS12D



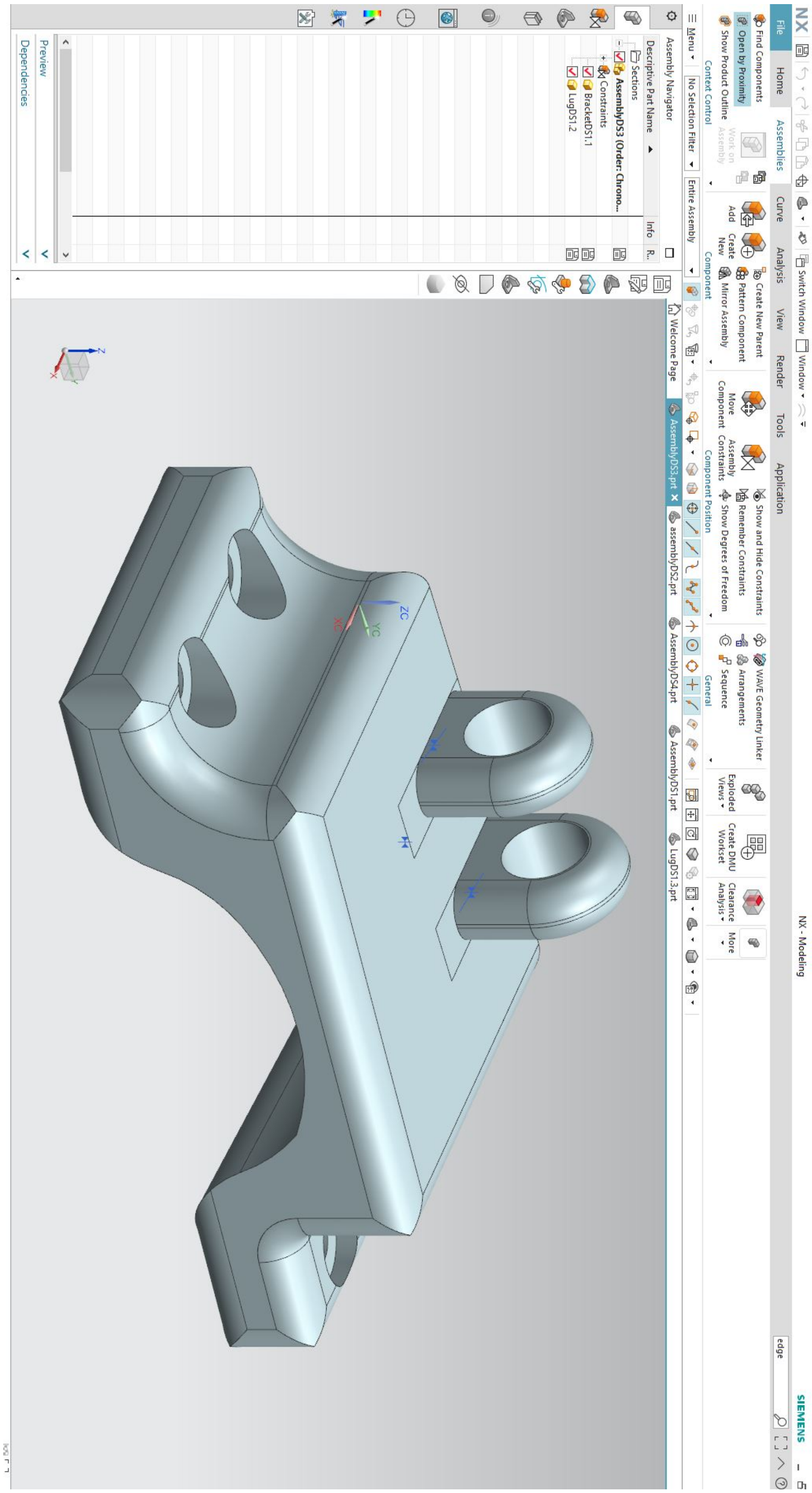
DS1c = DS11E & DS12C



DS1e = DS11a & DS12E



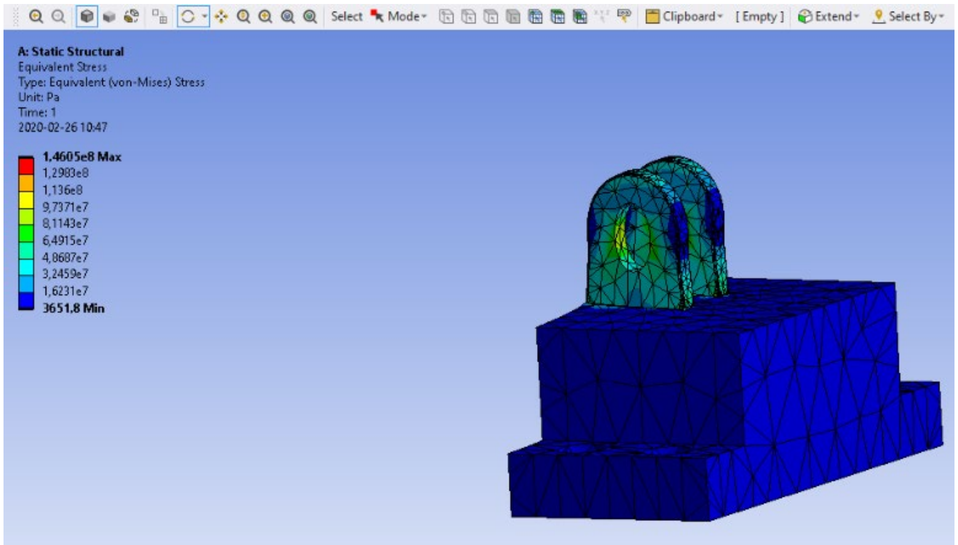
DS1d = DS11C & DS12B

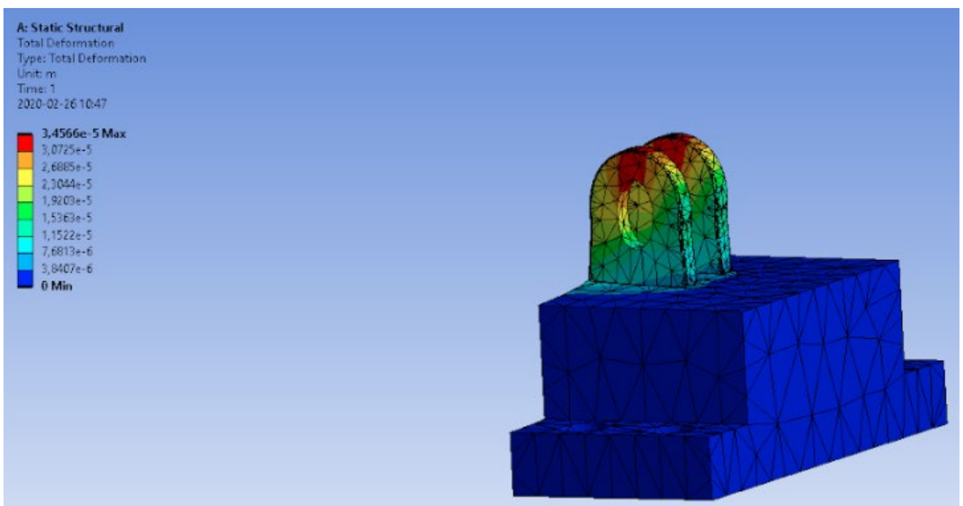


Appendix Q. Ansys Results

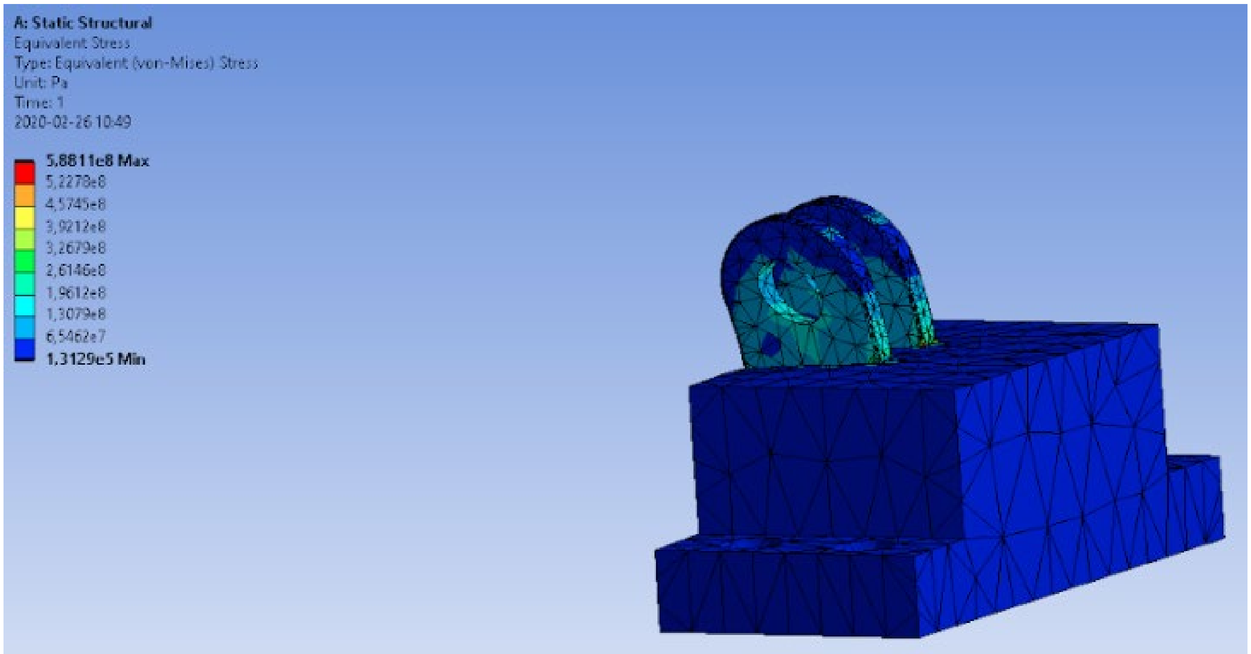
Concept DS1a – Created Baseline for the jet engine bracket

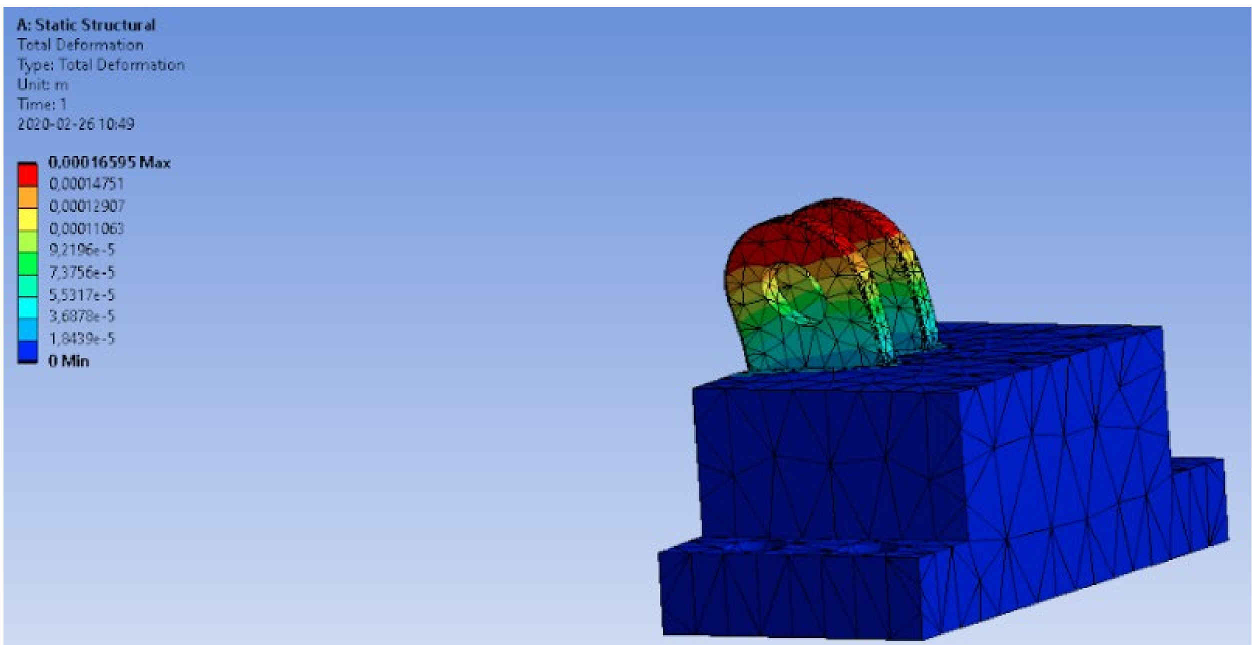
Load Case 1 –



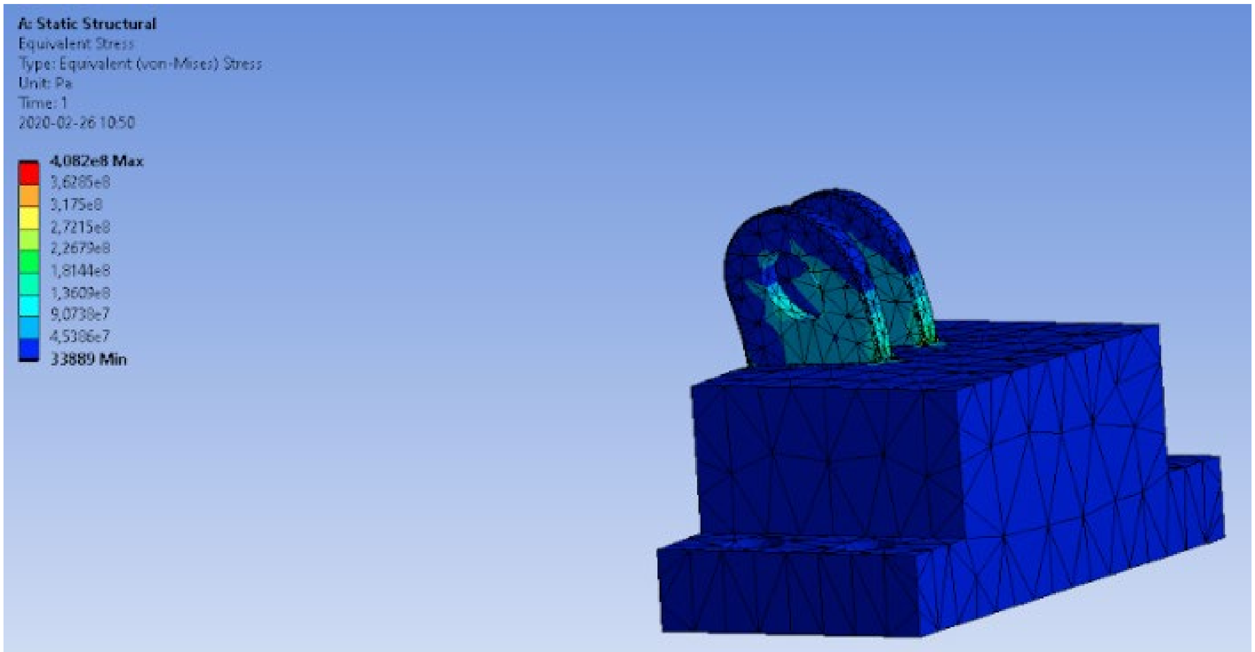


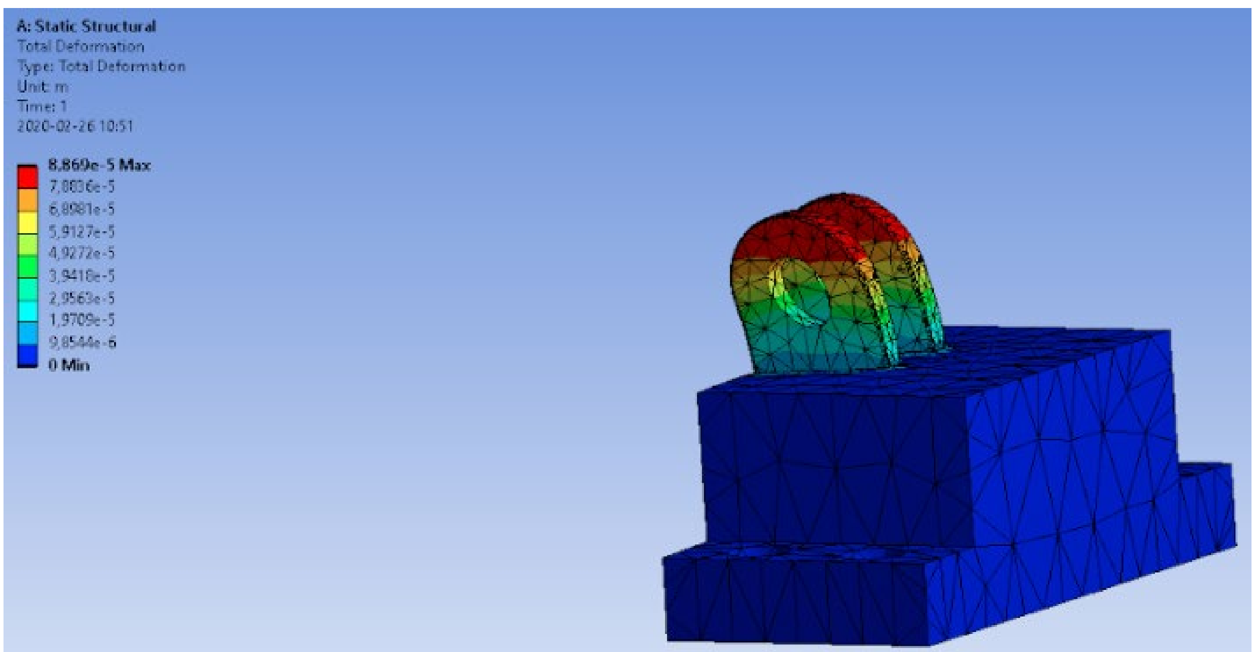
Load Case 2 –


A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1
2020-02-26 10:49
5,8811e8 Max
5,2278e8
4,5745e8
3,9212e8
3,2679e8
2,6146e8
1,9612e8
1,3079e8
6,5462e7
1,3129e5 Min

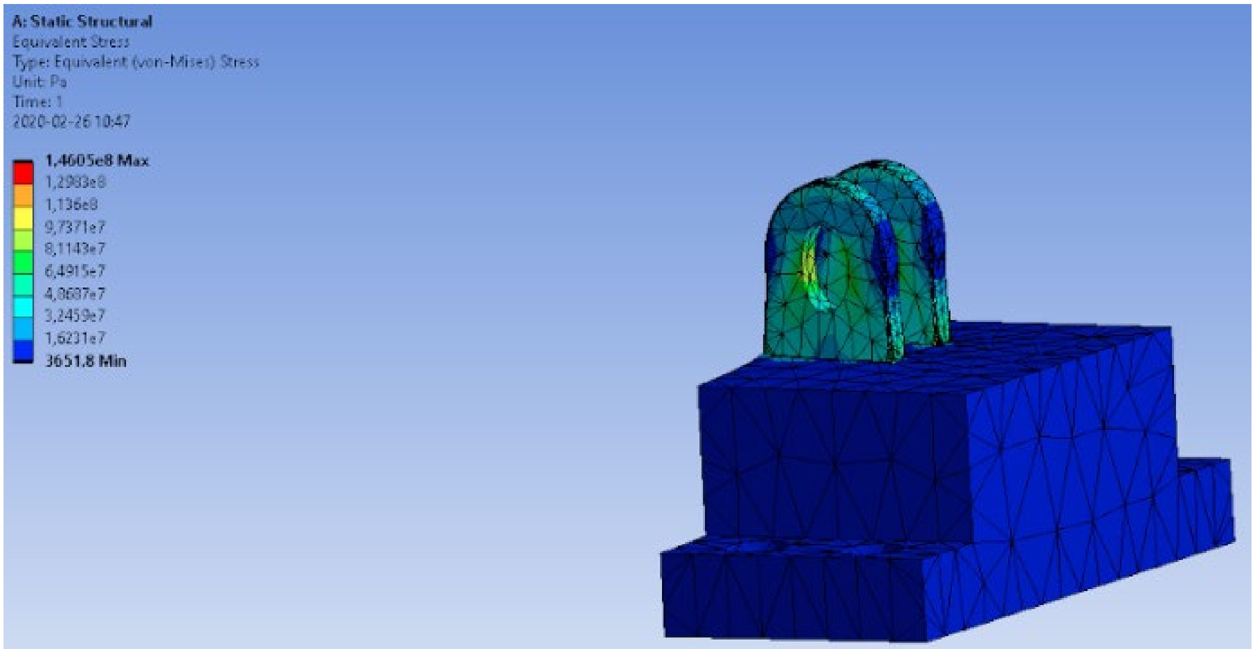

A: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
2020-02-26 10:49
0,00016595 Max
0,00014751
0,00012907
0,00011063
9,2196e-5
7,3756e-5
5,5317e-5
3,6878e-5
1,8439e-5
0 Min

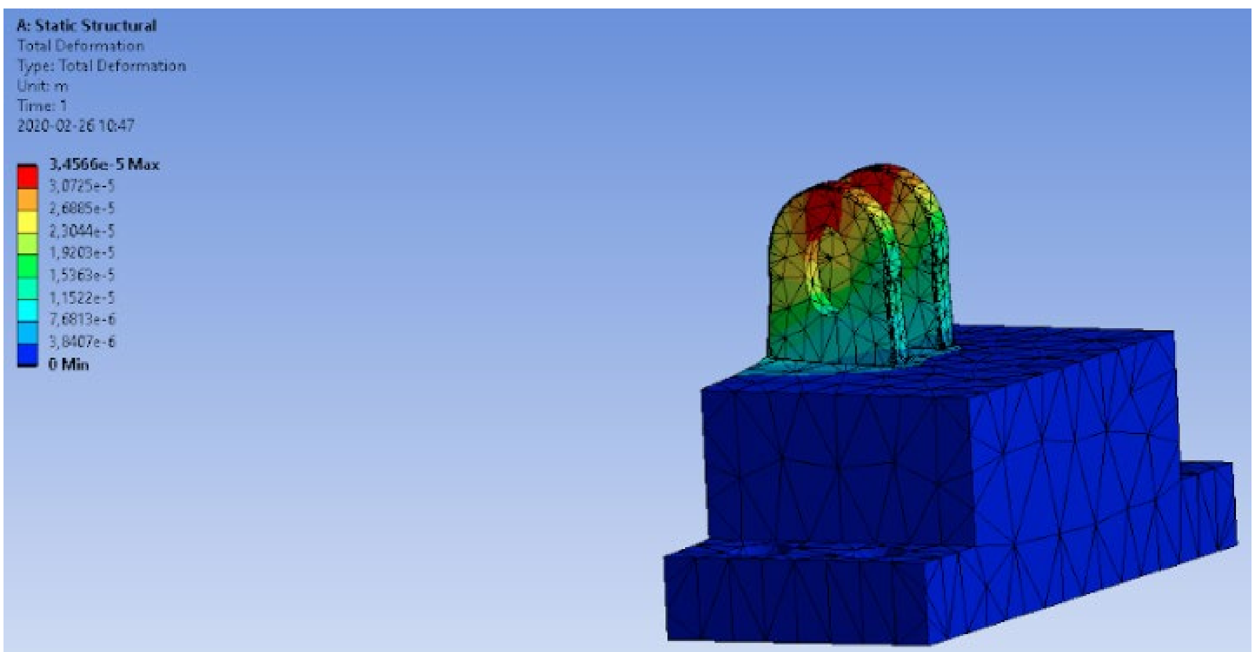
Load Case 3 –


A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1
2020-02-26 10:50
4,082e8 Max
3,6285e8
3,175e8
2,7215e8
2,2679e8
1,8144e8
1,3609e8
9,0738e7
4,5386e7
33889 Min


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
2020-02-26 10:51
8,869e-5 Max
7,8836e-5
6,8981e-5
5,9127e-5
4,9272e-5
3,9418e-5
2,9563e-5
1,9709e-5
9,8544e-6
0 Min

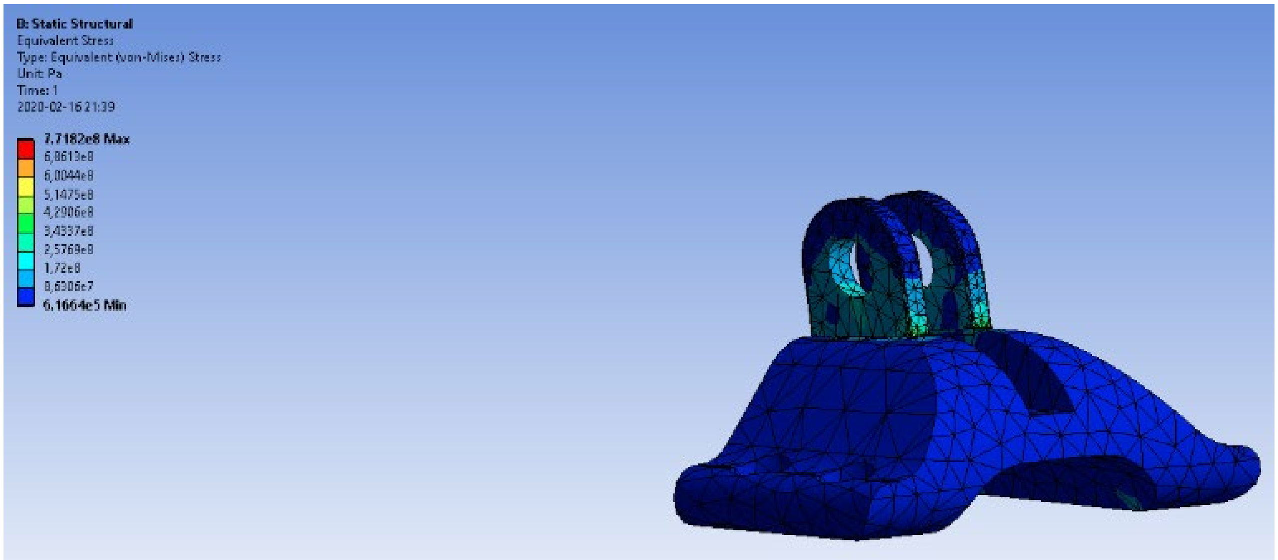
Load Case 4 –

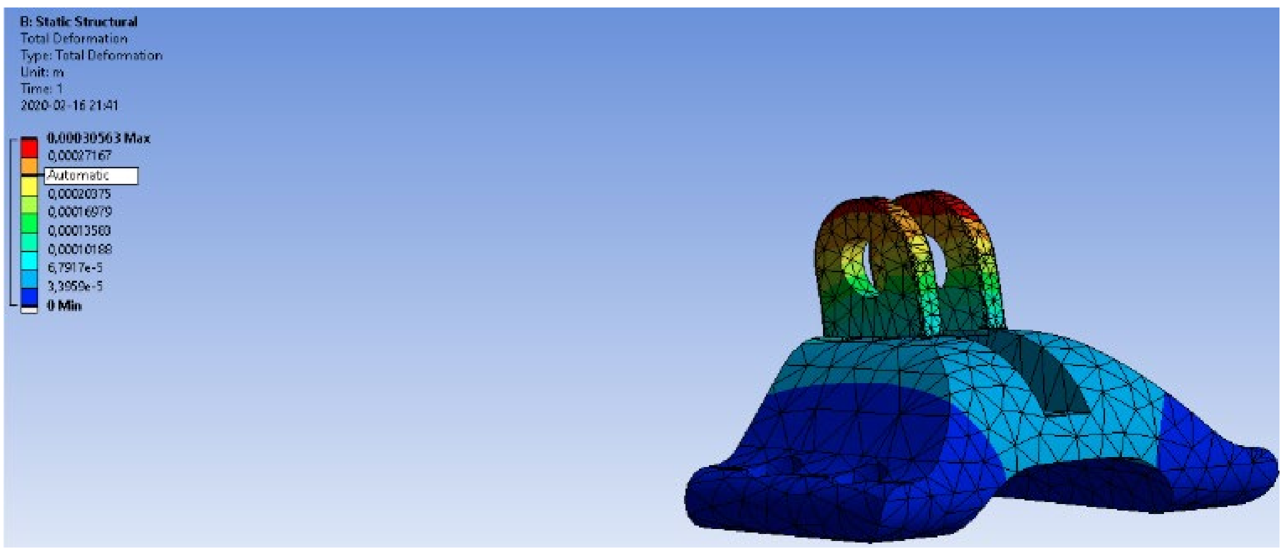

A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1
2020-02-26 10:47
1,4605e8 Max
1,2983e8
1,136e8
9,7371e7
8,1143e7
6,4915e7
4,8687e7
3,2459e7
1,6231e7
3651,8 Min


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
2020-02-26 10:47
3,4566e-5 Max
3,0725e-5
2,6885e-5
2,3044e-5
1,9203e-5
1,5363e-5
1,1522e-5
7,6813e-6
3,8407e-6
0 Min

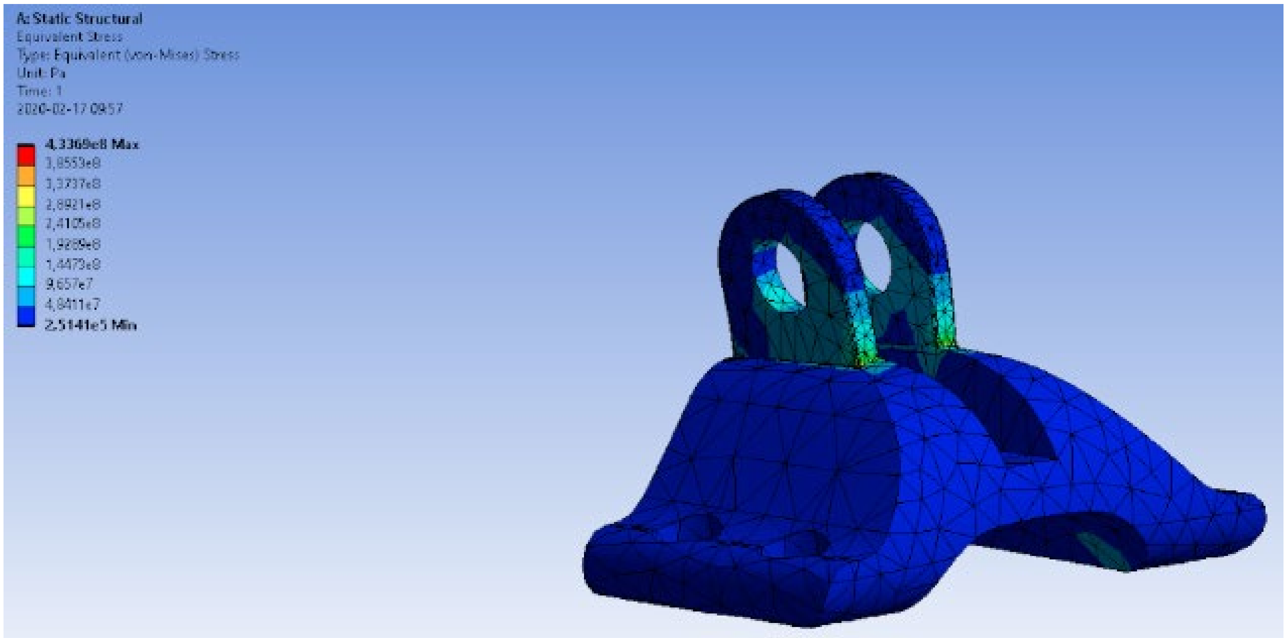
Concept DS1e

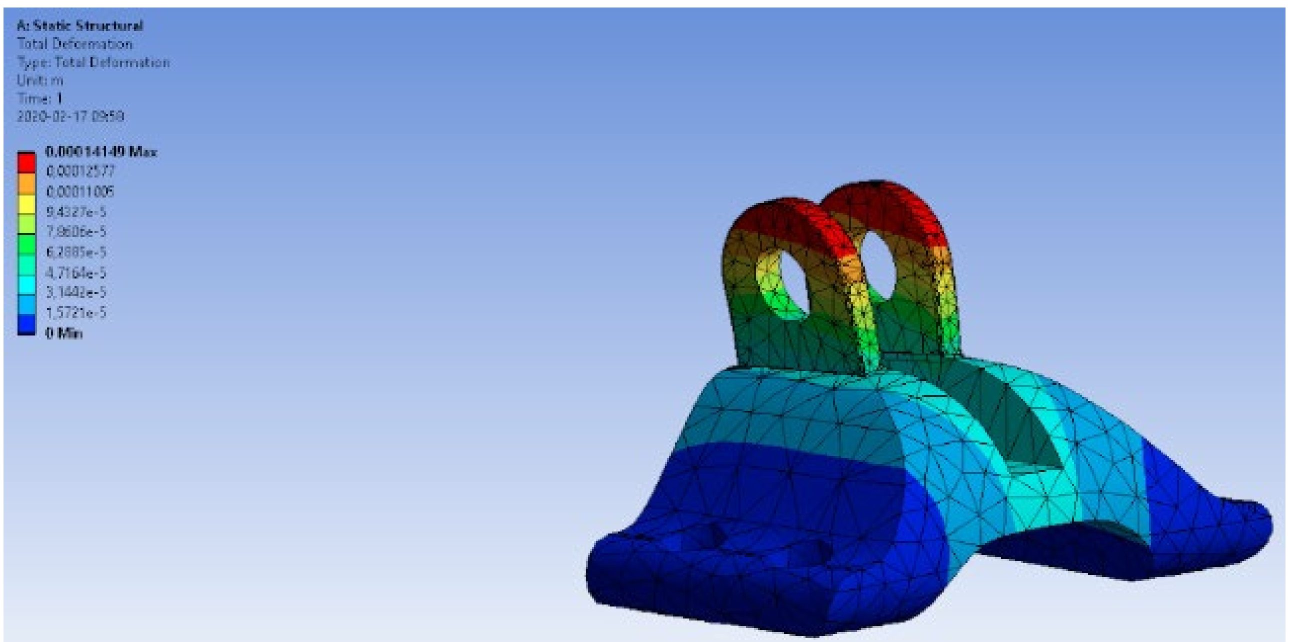
Load Case 2 –



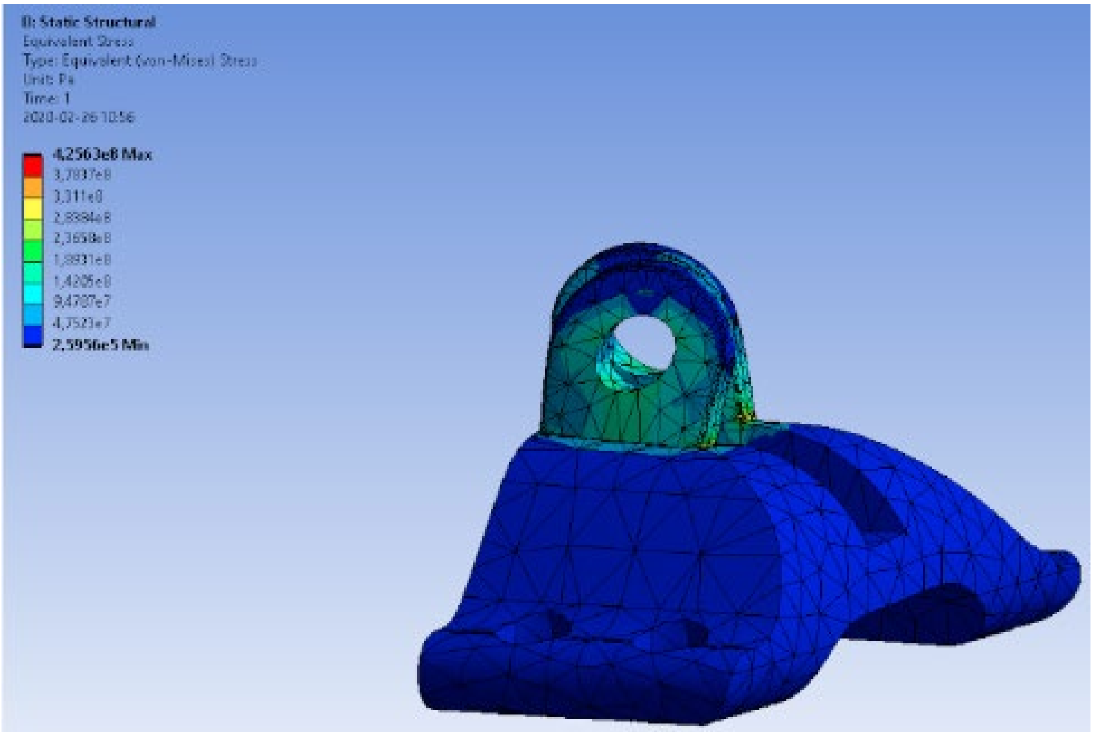


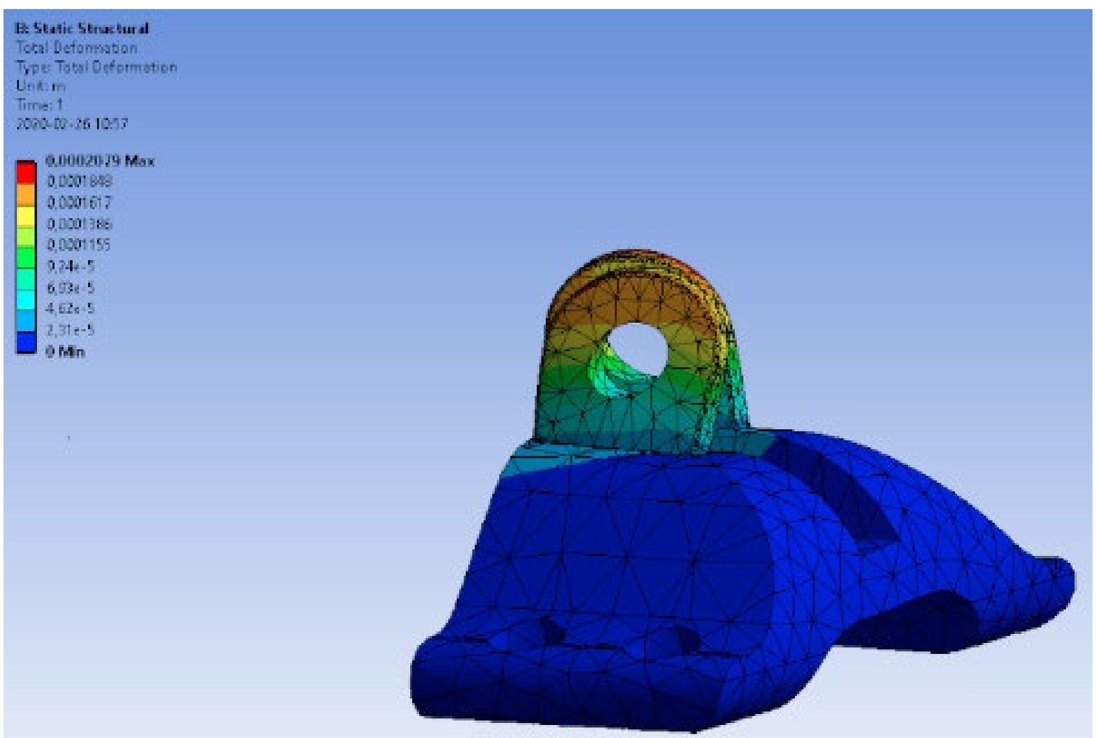
Load Case 3 –


A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1
2020-02-17 09:57
4,3369e8 Max
3,8553e8
3,3737e8
2,8921e8
2,4105e8
1,9289e8
1,4473e8
9,657e7
4,8411e7
2,5141e5 Min


A: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
2020-02-17 09:58
0,00014149 Max
0,00012577
0,00011005
9,4327e-5
7,8606e-5
6,2885e-5
4,7164e-5
3,1442e-5
1,5721e-5
0 Min

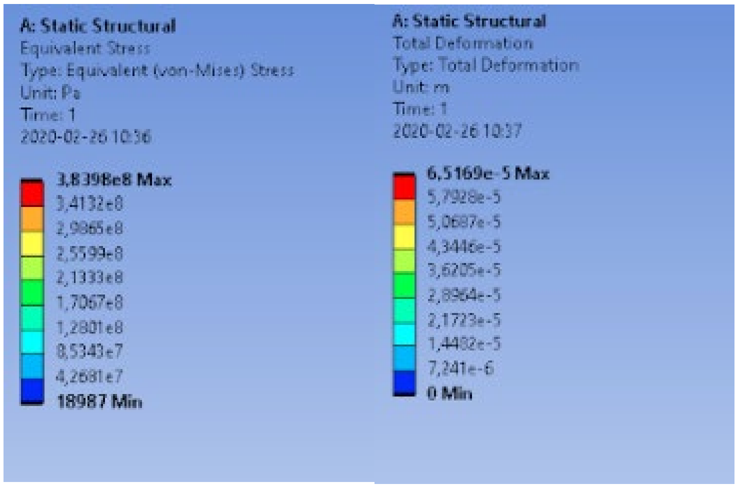
Load Case – 4


B: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1
2020-02-26 10:56
4,2563e8 Max
3,7837e8
3,311e8
2,8384e8
2,3658e8
1,8931e8
1,4205e8
9,4787e7
4,7523e7
2,5956e5 Min

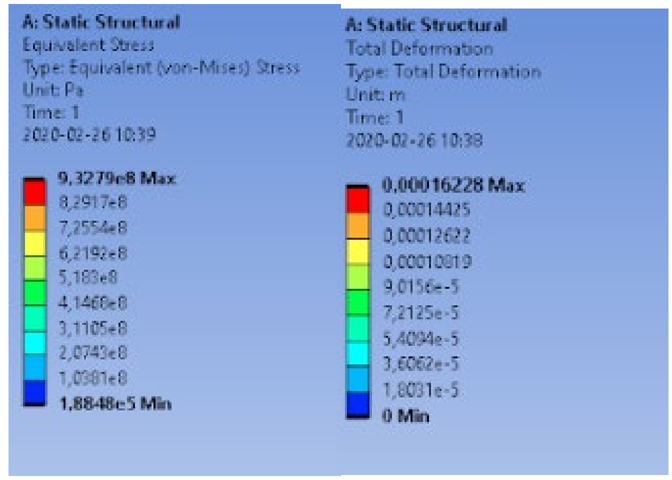

B: Static Structural
Total Deformation
Type: Total Deformation
Unit: m
Time: 1
2020-02-26 10:57
0,0002079 Max
0,0001848
0,0001617
0,0001386
0,0001155
9,24e-5
6,93e-5
4,62e-5
2,31e-5
0 Min

CONCEPT DS1c = DS11E & DS12C

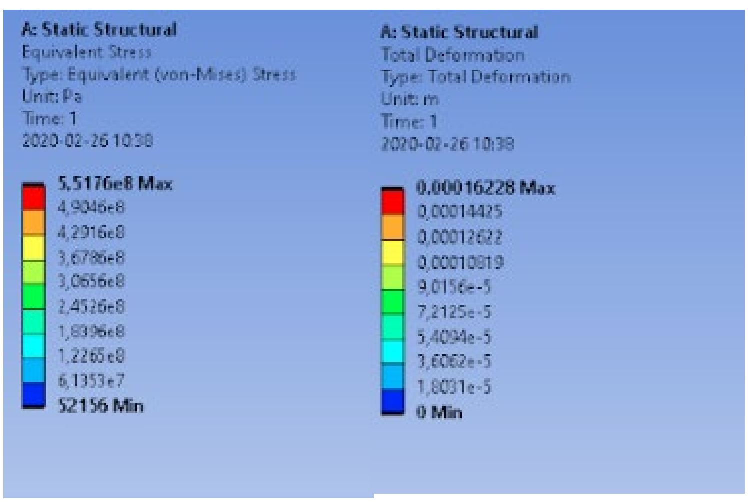
Load case 1



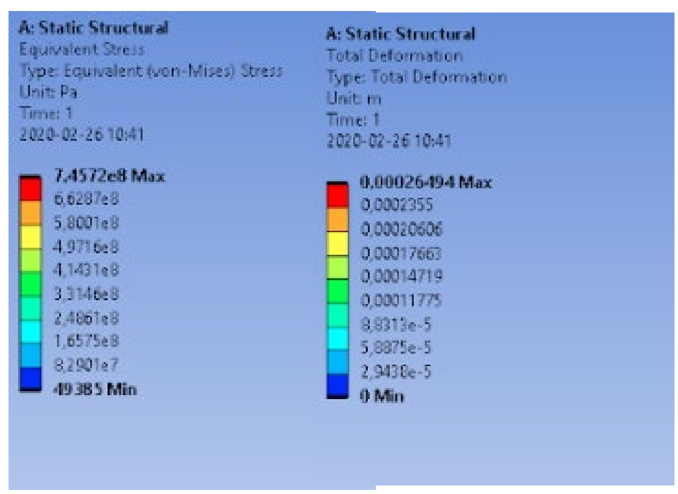
Load Case 2



Load case 3

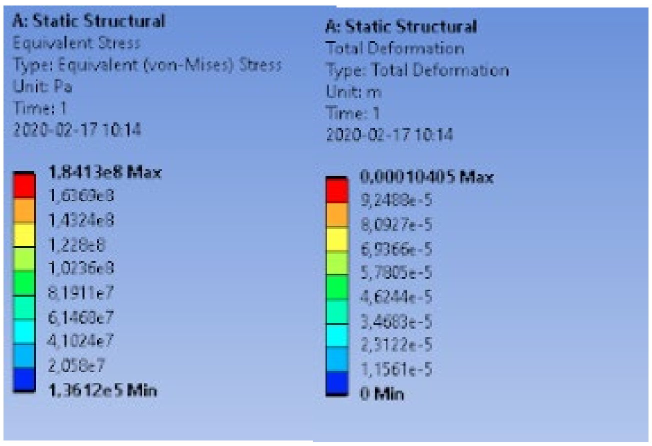


Load case 4

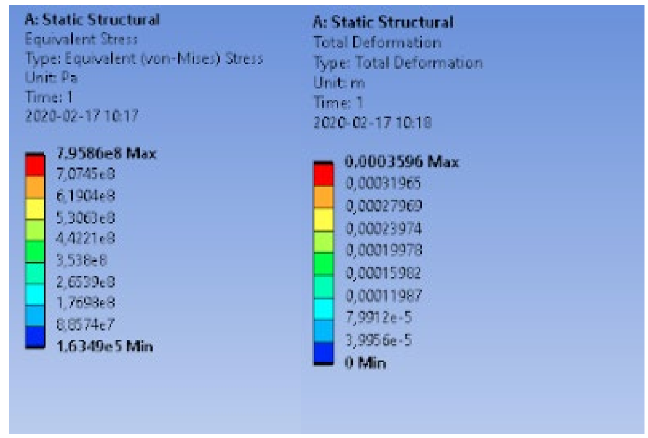


Concept DS1d = DS11C & DS12B

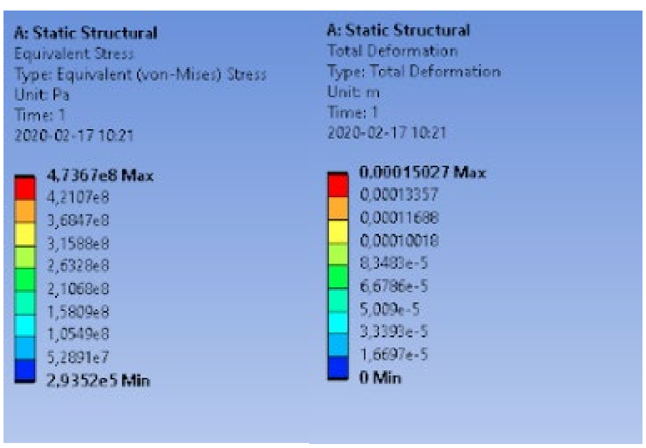
Load case 1



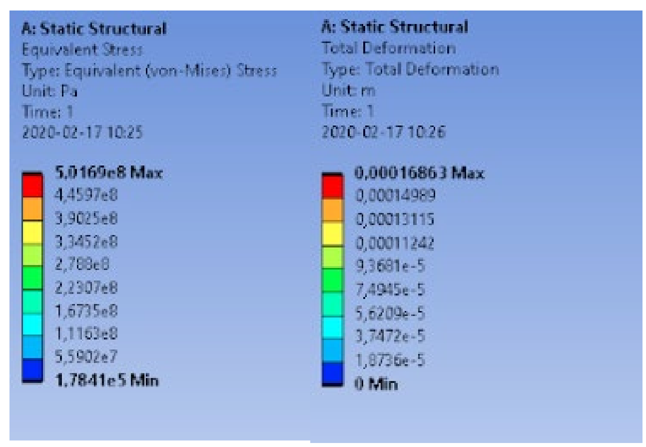
Load Case 2



Load Case 3

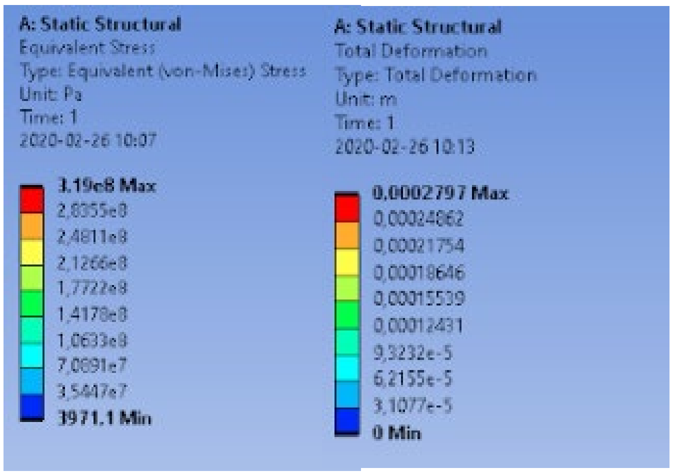


Load Case 4

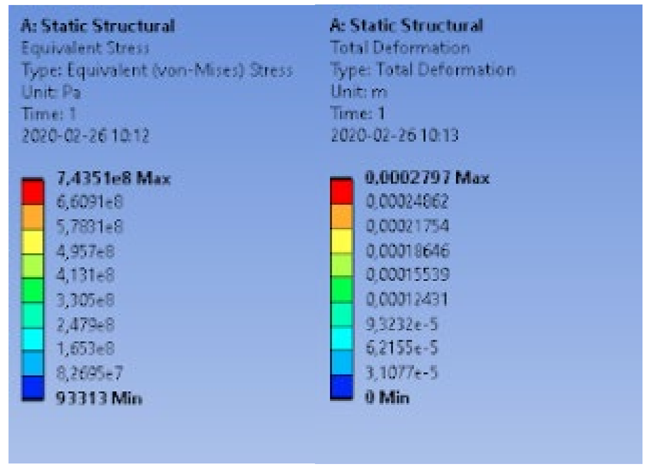


Concept DS1b

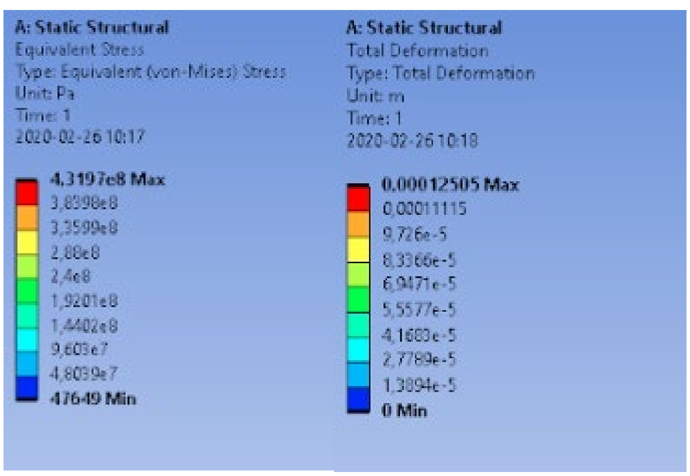
Load Case 1



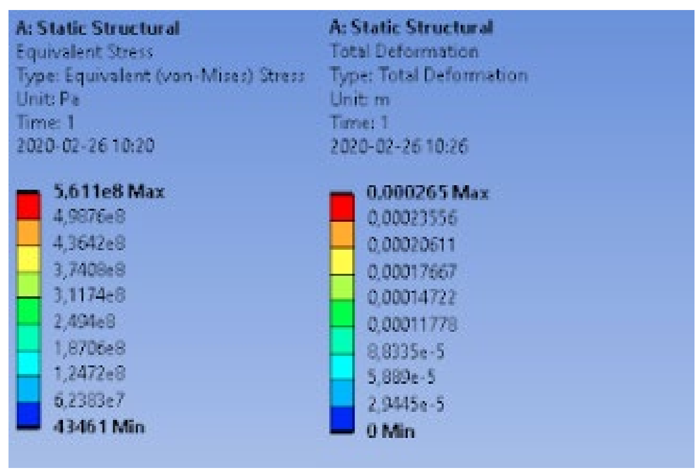
Load Case 2



Load Case 3

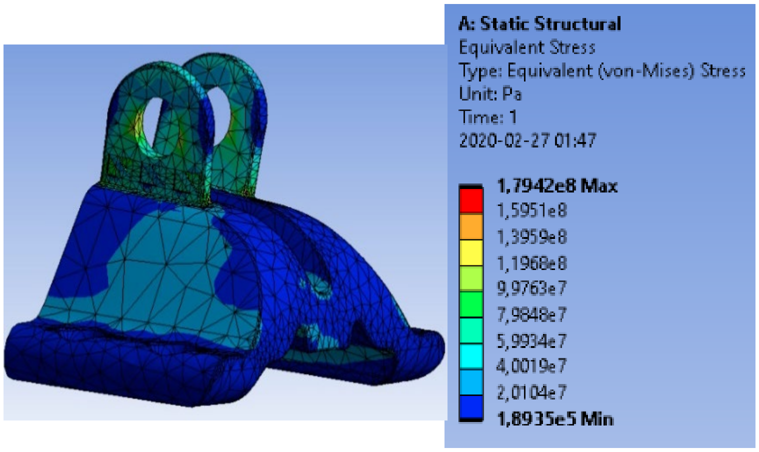


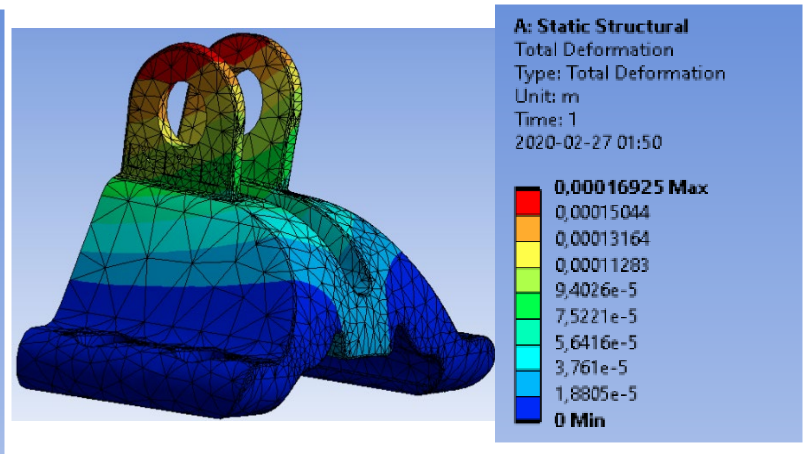
Load Case 4



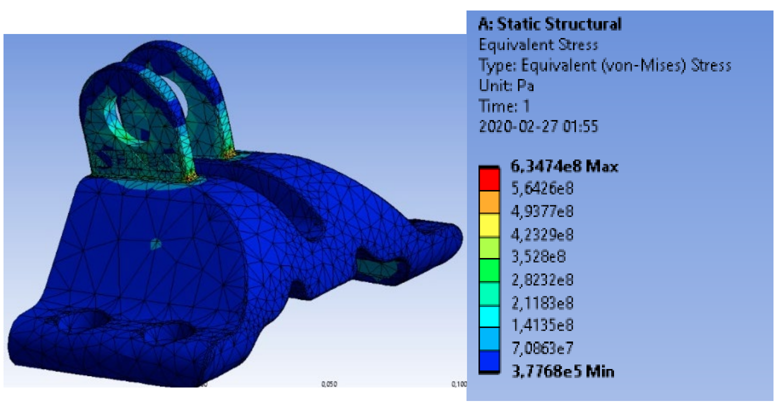
Appendix R. Ansys results Concept DS1F

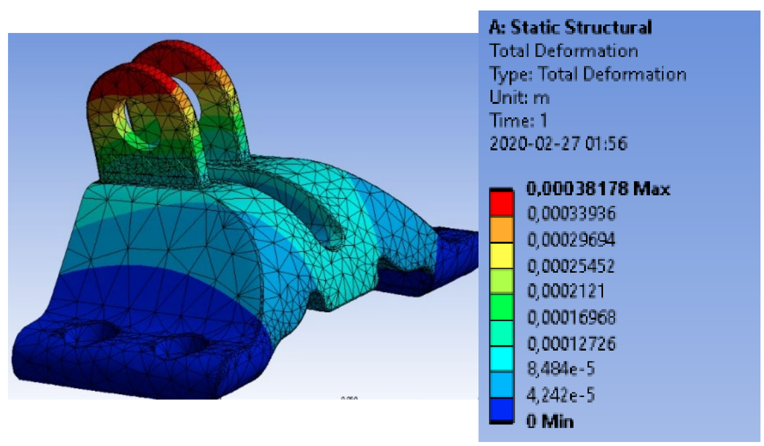
Load Case 1



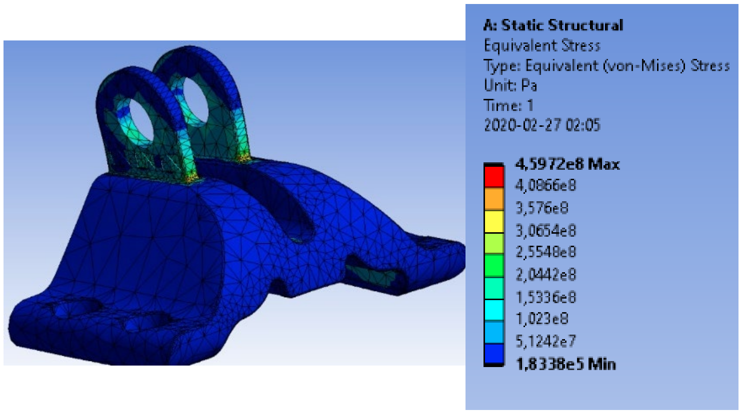


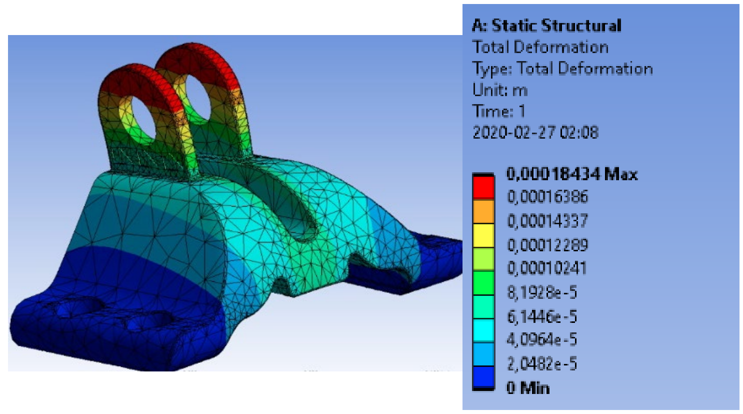
Load Case 2





Load Case 3





Load Case 4