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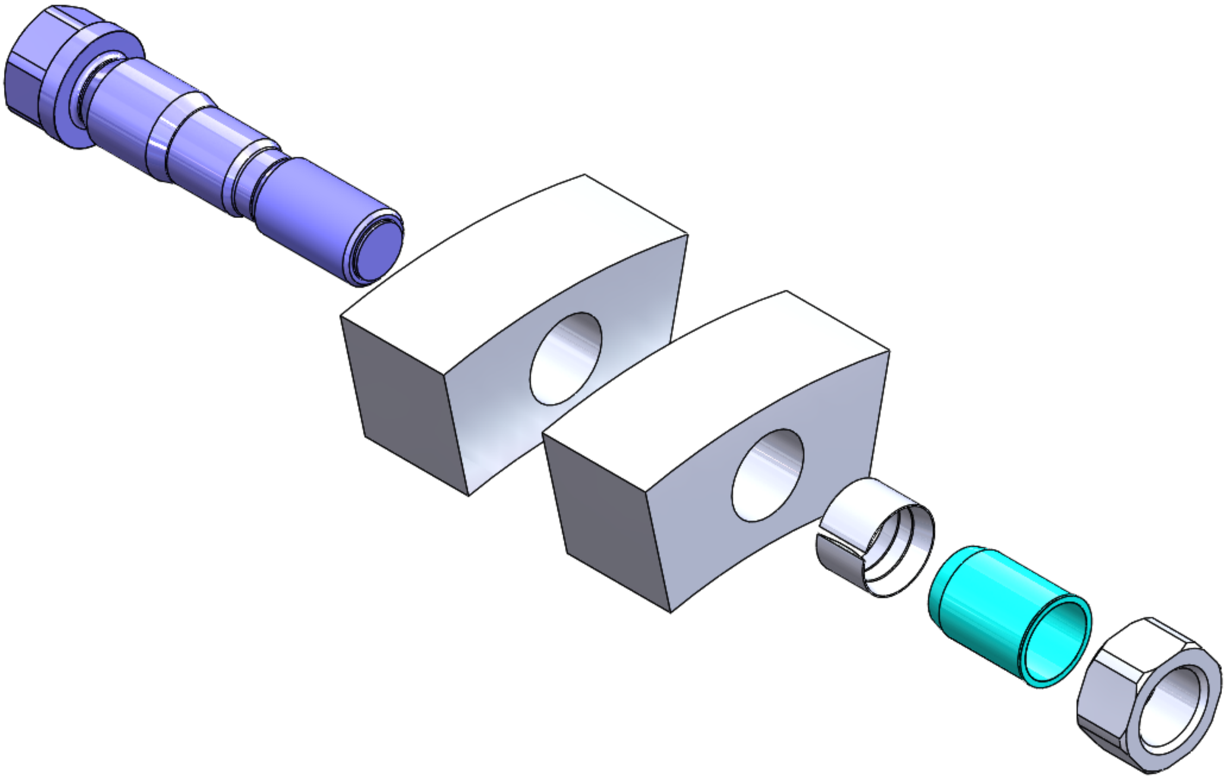

Design & Development of Flange Connection for Robust Torque Transfer in Marine Propulsion System

Master's thesis in Product Development

SHIYAM SUBBURAMAN

Department of Industrial and Material Science
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

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Supervisor: Samuel Ottosson, Caterpillar Propulsions AB
Examiner: Gauti Asbjörnsson, Department of Industrial and Material Science

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Department of Industrial and Mateial Science
Chalmers University of Technology
SE-412 96 Gothenburg
Telephone +46 31 772 1000

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Shiyam Subburaman
Department of Industrial and Material Science
Chalmers University of Technology

Abstract

Marine propulsion systems undergo a multitude of varying loads, which can be due to resonances, engine torque peaks, ice propeller impacts and marine propulsion itself. The stresses experienced by the propeller are propagated throughout the length of the shaft.

The flange faces, connecting the propeller to the engine gearbox, is subjected to both axial and shear forces. Caterpillar propulsion utilizes a combination of bolts and expansion dowels at the flange faces to absorb these forces. The focus of the project was to develop an improved design for the expansion dowels, in terms of manufacturability and cost. The Product development methodology and Advanced Product Quality Planning Framework were followed for developing a new concept. The developed solution works on the principle of 'wedge effect' to achieve the required interference fit. The final solution is designed for ease of manufacturing and also enables ease of assembly.

The final product was simulated in virtual conditions. Static analysis was done so as to fulfill all the requirements from the classification societies. Virtual Prototyping was done to simulate the worst-case conditions, like the peak transient torque acting on the flange faces, to validate the robustness of the solution. Attempts were made to answer the research questions in the end. The final product was also checked for fulfillment of target specifications to see if the project has achieved the purpose it had set out for.

Keywords: Advanced Product Quality Planning, Product Development, Quality Function Deployment, static design analysis, Virtual prototyping, expansion dowel, interference pin, flange connection, shear pin.

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Shiyam Subburaman, Göteborg, August 2020

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1
Introduction

The chapter provides an overall understanding of the purpose and direction of the thesis. It also attempts to define the goals and deliverables for the project considering the scope.

1.1 Background

Caterpillar Propulsion Production AB is part of Caterpillar Inc., which is working with the development, manufacture and sale of propulsion systems and other marine accessories that includes contract manufacturing in the mechanics and manufacture of electronic control systems and related operations. The company also acts as a one-stop solution provider for the entire propulsion system(Swedish Companies Registration Office, 2020). A schematic of the marine propulsion system is shown in figure 1.1(de Mello, 2018).

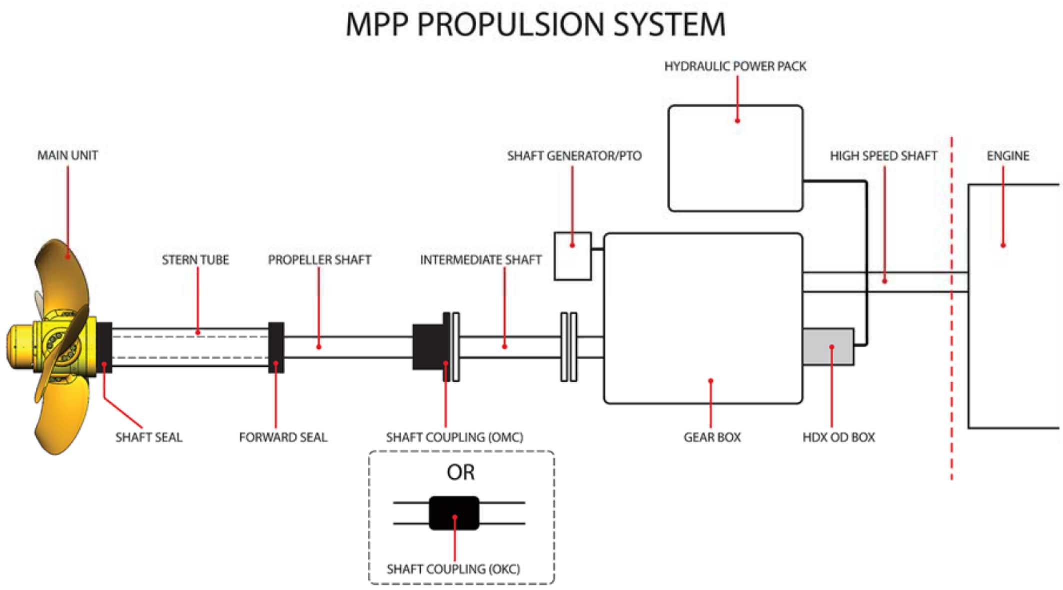

Figure 1.1: Functional Schematic of Marine Propulsion System

The thesis deals within the area of diesel-driven marine propulsion systems of ships, driven by mechanically integrated components right from the propeller to the engine. During propulsion, the propeller would be subjected to a multitude of forces and torsional loads that are propagated throughout the shaft line. The resilience of the components in the system to withstand the loads determines the 'sea-worthiness' of the vessel. Also, the design of these components depend on the region for which it would be designed for.

The thesis aims at developing a suitable flange connection for a certain 'Ice class' ships. Ships are classified as 'Ice class' when ships operate in extremely cold conditions. The 'Ice class' ships then have to fulfil some stringent safety regulations in addition to the existing regulations stipulated by the classification societies. It is also important to note that the design of the propulsion system is unique for every ship. So, the project deals with the optimization of one particular component, expansion dowel, that is used, in combination with the pre-tensioned bolts to secure the flanges connecting propeller shaft and the engine for '1A' Ice class ships. The purpose of this expansion dowel is to primarily withstand the shear forces acting on the flanges. The improvement of this existing flange connection was the central part of the thesis.

1.2 Aim

The thesis aims to

- Analyse the varying loads experienced in different parts of the system.
- Design and develop an optimized concept for the flange connection that withstands the robust torque transfer during propulsion from the engine to the propeller.

If optimized, the benefits can be in the form of reduced operational downtime and reduced cost of manufacturing, which may contribute to a positive dealer experience and better customer satisfaction.

1.3 Research Questions

The propulsion system experiences a multitude of forces due to resonances, engine torque peaks and ice impacts that pushes the capabilities of all the components to their limits. The thesis intends to answer the following questions.

- Do opportunities exist for designing a bolt that improves the power train resilience while also keeping the manufacturing cost low?
- Is there any alternate type of interference fit that does not use lubricant for mounting and dismounting?
- Does the designed concept withstand the peak transient torque experienced by the system?

The thesis will delve deep into this design space to find the root cause of the problem and develop a solution.

1.4 Limitations

The scope of the project is to explore optimal concepts of torque bolts and flanges for high vibratory torque applications within the regulatory playing field. So,

- The success of the project is not dependant entirely on the creation of a completely new and revolutionizing concept, but, rather on the methods and the results that lead up to the creation of the conceptual flange connection.
- Analysis will not be carried out on the physical models to ascertain the results.
- There are two types of flange connections used to arrest the axial and torsional forces acting on the coupling joints. The project aims at developing a solution for the flange connection that arrests the torsional forces and not primarily the axial forces.
- The thesis is not focused on the entire marine propulsion system, but, rather on the flange connection between the engine and the propeller of Ice class 'A' ships. Depending on the success of the application, the solution can be used for other systems as well.

2

Theory

The design of a marine propulsion system is unique for every ship as it primarily depends on the region it is planned for operation. The safety is high for the ships that operate in cold climates and are, therefore, classified as 'Ice class' ships, since these ships operate in extreme conditions and experience high stresses on the propulsion shaft due to ice impacts. The classification societies that govern every part of a marine propulsion system was discussed here and the design of the current solution was also detailed.

2.1 Regulations from Marine Classification Societies

The main purpose of any classification society is to provide assistance to the marine industry with regards to maritime safety, verification of structural integrity for the essential parts in a ship's hull and its appendages. It also ensures the reliability of the propulsion systems and other auxiliary systems that are built into the ship. The Classification society should act in compliance with international and/or national statutory regulations on behalf of the flag Administrations. It is an independent, self-regulating, externally audited body. (IACS, 2020).

A list of all the classification societies are:
- International Association of Classification Societies (IACS)
- Det Norske Veritas and Germanischer Lloyd (DNV GL)
- American Bureau of Shipping (ABS)
- Bureau Veritas (BV)
- Lloyd's Register (LR)
- Nippon Kaiji Kyokai (ClassNK)
- Registro Italiano Navale
- Russian Maritime Register of Shipping
- China Classification Society (CCS)
- Croatian Register of Shipping/ Austrian Veritas
- Polish Register of Shipping
- Bulgarian Register of Shipping
- Korean Register of Shipping
- Indian Register of Shipping
- Hellenic Register of Shipping
- Shipping Register of Ukraine

- Dromon Bureau of Shipping
- Maritime Bureau of Africa
- International Register of Shipping
- Registro Internacional Naval
- Overseas Marine Certification Services

A vast majority of commercial ships are built and surveyed in compliance with the standards laid down by these Classification Societies. The standards are issued by a society as published Rules, though the rules are not intended to be a design code as such. A ship is primarily designed based on the requirements laid out by the customer, and the requirements stipulate the classification society the ship design has to follow. The classification society, that needs to be followed, usually depends on the region the ship is intended to be operated in. Caterpillar Propulsion primarily follows the regulations laid out by IACS by default. Other classification societies that are usually requested at Caterpillar Propulsion by customers are DNVGL, ABS, BV, LR and CCS.

2.2 Propulsion System Design

The thesis mainly deals with the diesel driven marine propulsion systems. The marine propulsion system comprises of a propeller, a propeller shaft, one or more flange couplings and coupling bolts. The robust design of these components contribute towards the effective torque transmission from the gearbox to the propeller. A discussion in brief about each one of the systems influencing the optimum design of the flange connection were detailed.

Torque acting on the system

The torsional loads acting on the propulsion system can propagate from the propeller blades or from the engine gearbox. It can be in the form of propeller/ice interaction, applied loads, both static and dynamic. The various torque acting on the system were as follows(DNVGL, 2018).

- Mean torque.
- Maximum torque range for repetitive loads.
- Maximum torque for rare occasional peak loads.
- Vibratory torque for continuous operation.

Mean torque

It is the nominal torque experienced by the system, corresponding to the highest nominal shear stress and bending stress of the components in the system.

Maximum Torque for repetitive loads

This type of stress would be typically experienced by the system during clutching when the torque experienced by the system is maximum when overcoming inertia. The plot of maximum torque for repetitive loads as transient vibrations is shown in figure 2.1(DNVGL, 2018).

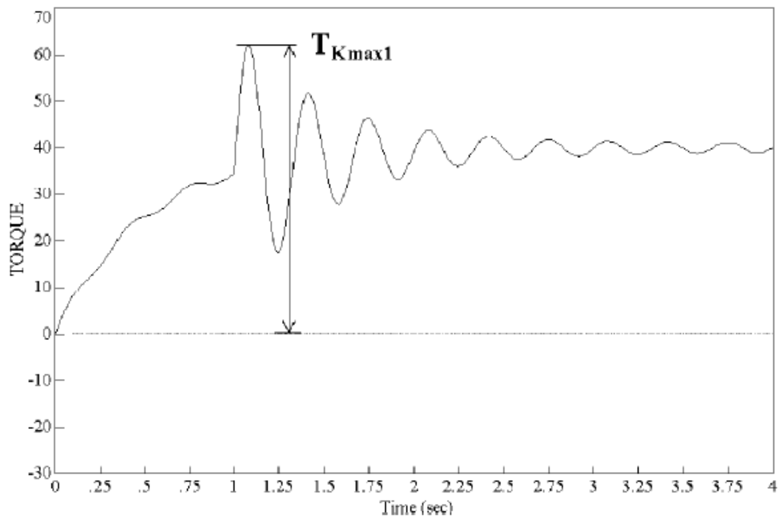

Figure 2.1: Maximum Torque for repetitive loads as transient vibrations

Maximum Torque Range for repetitive loads

The difference in torque is most typically experienced by the system when passing through a major resonance, either during start or stop. The plot of maximum range of torque for repetitive loads as transient vibrations is shown in figure 2.2(DNVGL, 2018).

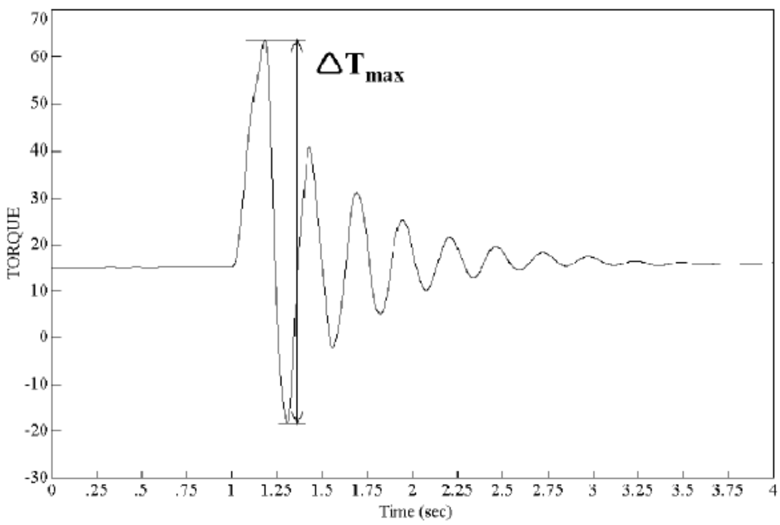

Figure 2.2: Maximum Torque Range for repetitive loads as transient vibrations

Vibratory torque for continuous operations

The nominal positive vibrations experienced by the system about the mean torque is plotted as a function of time as below. The plot of maximum torque for repetitive loads as transient vibrations is shown in figure 2.3(DNVGL, 2018).

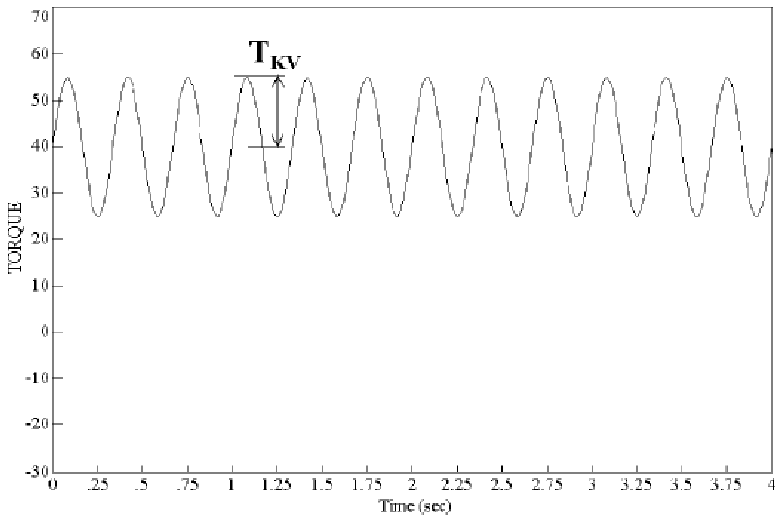

Figure 2.3: Vibratory torque for continuous operations

Permissible maximum torque for rare occasional peak loads

The peak loads can be caused by propeller-ice impact. This can be studied by analysing the different propeller-ice torque excitation cases for a combination of

- Specific number of ice loads(single or multiple ice blocks) and the corresponding load parameters(DNVGL, 2015).
- Duration of propeller blade/ice interaction expressed in propeller rotation angle(DNVGL, 2015).

The parameters vary as per the class requirements. The transient torsional vibration analysis shall be described as a sequence of blade impacts which are of a half-sine shape. This analysis results vary for every ship and can be reported using the Torsional Vibration Calculation(TVC) Report. The propeller-ice interaction for the various cases of load and the rotation angle of the propeller were studied. The maximum of the three cases outlined in figures 2.4,2.5 and 2.6 were taken to be the peak torque experienced by the propulsion system.(DNVGL, 2015).

For the thesis, a specific customer order, 7219M, was taken as the target propulsion system for which the new solution was intended for. The peak torque for the system from the TVC Report of the order was found to be 1350kNm and the final concept was analysed using this value of peak torque.

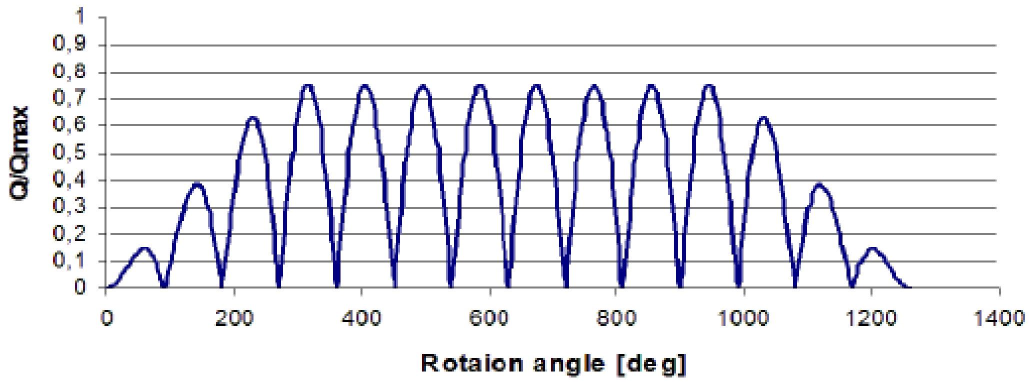

Figure 2.4: The 90° single blade impact sequence of propeller-ice interaction

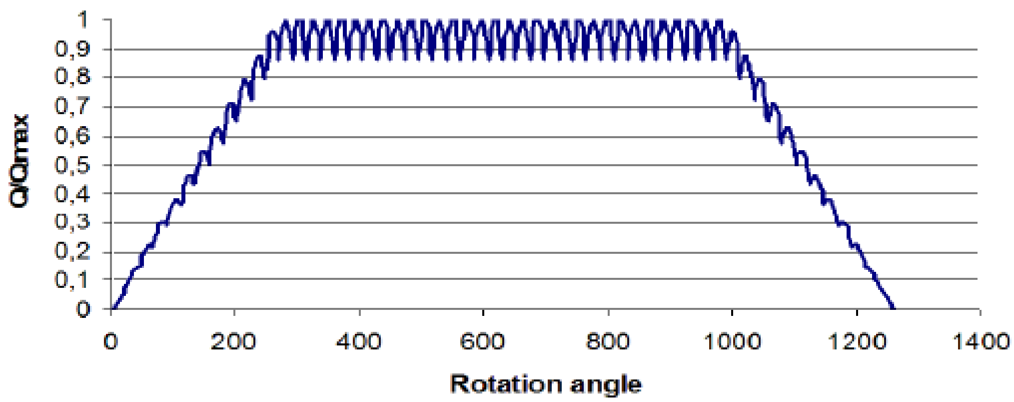

Figure 2.5: The 135° single blade impact sequence of propeller-ice interaction

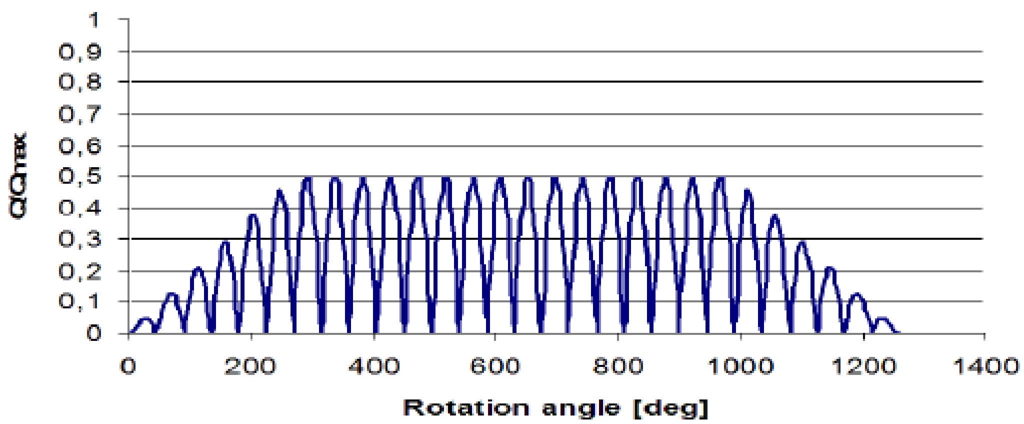

Figure 2.6: The 45° double blade impact sequence of propeller-ice interaction

Shafting Design

The shafting elements connect the propeller to the engine. The shaft arrangement typically includes:

- Shafts
- Flange couplings
- Bearings and seals

The loads experienced by the propulsion systems under various conditions were listed in section 2.2. The stresses caused by the thrust on the propeller blades were transmitted over the length of the shaft, which is shown in figure 2.7. The loads experienced by the shaft was maximum at the propeller end and decreases as the distance between the shaft and the propeller increases. Hence, the diameters at different points in the shaft were varied depending on the total stress experienced at that point. Different classification societies demand similar requirements. So, the shaft design was standardised to have a set design for a given set of torque requirements.(de Mello, 2018).

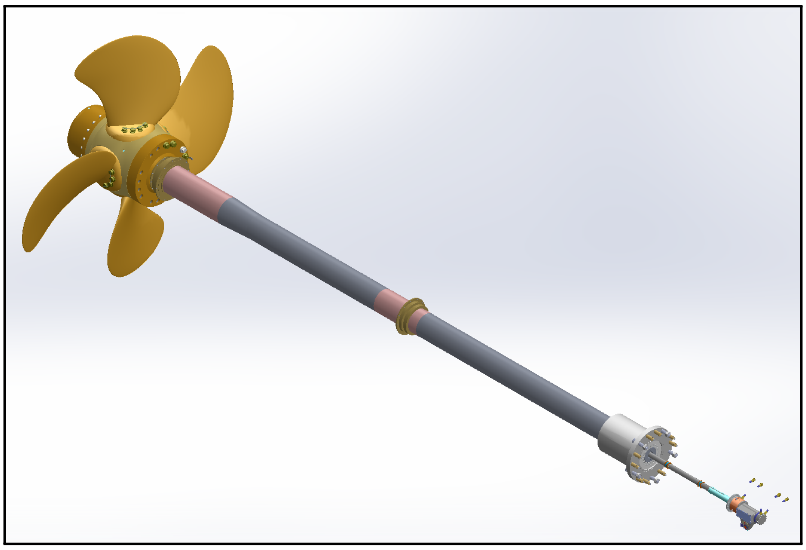

Figure 2.7: A 3D model of Shaft Arrangement

In addition to the class regulations, there were also rules internal to Caterpillar propulsion for manufacturability. Since the thesis was focused on the flange connection of the shaft arrangement, a brief on the components relevant to the thesis were given.

Flange joint

A flange joint acts as an interface that connects the propeller shaft from the propeller to the engine shaft from the gearbox. Unlike a typical shaft connection, the shaft and the flange joints can be assembled or disassembled when needed. There are two common types of flange joints used at Caterpillar Propulsions: Sleeve couplings and

Oil mounted couplings(OMC). For the given propulsion system, an OMC was used as the preferred flange joint, which shown in figure 2.8.

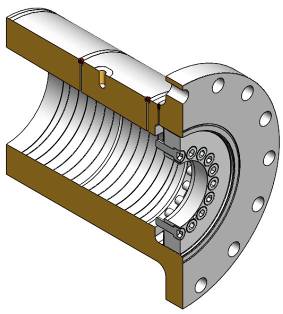

Figure 2.8: A 3D Model cut-section of an OMC Flange

When the OMC has driven up the conical propeller shaft, a pressure is created that makes it possible to transfer the torque. The size of the flange coupling depends on the size of the propeller shaft and the transmitted torque. It also depends on the size of the coupling bolts used. Since the flange coupling is subject to both shear and axial forces, the flange requires a combination of clearance type bolts and interference type dowels. The classification regulations stipulate that the force offered by the bolts and dowels should overcome the mean torque experienced by the shaft and also the peak torque experienced by the system in transient conditions. The classification rules expect, in the worst case, the flange coupling on the propeller end to fail before the flange coupling bolts fail, to ensure better serviceability of ships(de Mello, 2018).

Flange Coupling bolts

The flange coupling intends to transfer torque while holding the components from different systems together. The flange coupling bolts were designed to keep the flanges, which are subject to a combination of axial and shear forces, intact. This can be achieved by using a different combination of bolt types and this also depends on the choice of the manufacturer. Caterpillar propulsion uses a combination of pretensioned bolts, to arrest the axial forces and expansion dowels, to arrest the shear forces acting on the flanges. While the pretensioned bolts were standard bolts, expansion dowels require a special design.

Expansion Dowels

The expansion dowels were specifically designed to provide an interference fit that primarily arrests the shear forces acting on the flanges due to the transmitted torque.

A cut-section of an expansion dowel is shown in figure 2.9. The tapered hole of the outer sleeve and the tapered bolt shank should have a surface contact. The surface pressure on the flange hole increases as the taper of the bolt shank is moved over the sleeve. The movement would be achieved by the tightening of a nut at the thread of the bolt end. The stick and slip motion, that causes ceasing, was avoided by pumping hydraulic oil between the tapered surfaces, as it forms a thin film between the surfaces.

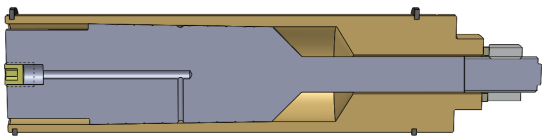

Figure 2.9: A 3D model of the expansion dowel assembly cut section

The count of the total number of parts for the existing design is 6, see figure 2.10. The project intended to arrive at a concept that is easier to manufacture and has a lesser number of parts than the existing solution.

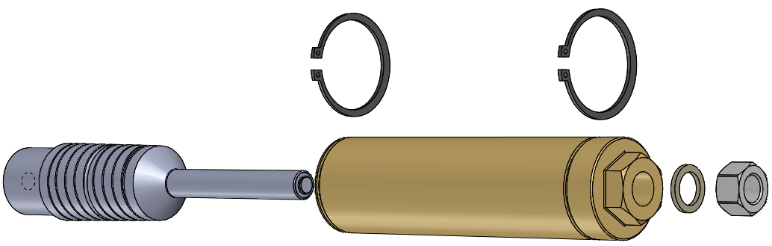

Figure 2.10: An exploded model of the expansion dowel

2.3 Design Setup

The regulations do not have set dimensions for the interference type of bolts. But, it does have certain criteria for a minimum diameter for the interference bolts that need to be fulfilled(DNVGL, 2018).

$$diameter, d_b \geq 66\sqrt{\frac{(2T_{peak} - T_f)}{nD\sigma_y}}$$

where d_b =Diameter of the cylindrical bolt

T_{peak} = Peak Torque experienced by the system

T_f = Frictional torque of the system

n = Number of fitted bolts

D = Pitch Circle Diameter of the flange hole

σ_y = Yield strength of the material

The minimum diameter holds good for a solid shaft and this can be translated to a thickness in a hollow shaft by comparing the equivalent area.

2.4 Simulation Setup

Tests were conducted to ensure the solution fulfils all criteria from a regulatory requirements standpoint. The developed product was tested for two conditions: Static Analysis and Virtual Prototyping.

Static Analysis

Some of the main criteria from the regulations under consideration for static conditions were

- The bolt can to be tightened upto 70% of its yield strength(DNVGL, 2018).
- The system should maintain an interference fit with the flange hole(DNVGL, 2018).

The bolt pretension should be such that the minimum cross-section should experience a maximum of 70% of its yield strength of 650 N/mm^2 ie. $455N/mm^2$.

The interference fit can be ensured by checking for surface pressure acting at the centre of the outer surface of the mid sleeve, supposed to be in contact with the two flange joints.

Virtual Prototyping

The success of the project depends on the ability of the solution to withstand the varying loads during operation. Some of the main criteria that the system should withstand for operational conditions were also given by classification societies(DNVGL, 2018)

- Twice the peak torque minus the friction torque shall not result in shear stresses beyond 0.6 times the yield strength of n expansion devices(DNVGL, 2018).
- The components should be designed for a safety factor of 1.3(DNVGL, 2015).

Loads acting on the system

The peak torque for the propulsion system, T_{peak} = 1350kNm

The frictional torque acting on the propulsion system,T_f = 728kNm.

From the criteria, Twice the peak torque minus the friction torque shall not result in shear stresses beyond 0.6 times the yield strength of n expansion devices.

$2T_{peak}$ - T_f = 1972 kNm for '10' expansion devices.

Therefore, the load acting on a single expansion device for a bolt circle diameter of 970 mm was 406.6kN.

As per the second criteria, the load including the safety factor of 1.3 would be 528.6kN.

So, when a load of 528.6kN is applied, the system should not yield or the shear stresses acting on the expansion device should not be above 0.6 times the yield strength ie. 390MPa.

3
Methods

The Product Development methodology was primarily followed for this thesis. Only the Product Development tools used in this project were detailed below.

3.1 Research and Data collection

To understand the problem better and define the need for the project, a variety of data collection tools were used, as per the Product Development methodology (Karl T.Ulrich, 2012).

Literature Review

The regulations for the design of propulsion machinery, framed by the different Classification societies were studied. The design methodology followed within Caterpillar design teams were also studied to understand their design philosophy. An extensive study on the working of all the propulsion systems right from the propeller to the control systems were reviewed. The drawings of various propulsion systems and their calculations behind the dimensioning of the system were referenced. The classification rules also helped to understand the design thinking behind the existing design of expansion dowels.

Benchmarking

The external solutions offered by third-party suppliers were also studied to derive the desired design criteria for the ideal solution. The data was studied in the form of design principle, technical specifications and request for quotes. The benchmarking increased the cost-consciousness during the concept screening phase when multiple concepts were evaluated.

Patent Search

A patent search was also done to find similar solutions for expansion mechanisms that might have been already patented. This was also done to avoid any patent infringement. The patent databases were region-specific. For this project, the patent databases of USA, Europe and China were primarily looked at.

Interviews

The interviews were conducted in a semi-structured manner, to enable the free flow of ideas. The lead users of the existing product were targeted. Ideally, the end-customers were the preferred choice, but the product under focus was relatively unnoticeable to the customer. Lead users were primarily interviewed to understand the existing product better and relate to the issues faced at the time of assembly/dis-assembly. The interviews lasted about 20-40 minutes. To maintain the consistency of information, the structure of the interviews were maintained in a similar way using an Interview guide, attached in the appendix A.1.

3.2 Data analysis

As one of the first steps in conceptualising a product, data analysis was used to convert the raw data into useful information. The steps involved in analysing data were in the form of

- Interview analysis
- Establishing customer needs
- Deriving design requirements

Interview analysis

The interviews were analysed for extracting important customer statements. The customer statements were listed and they form the basis for extracting the customer needs. Interviews analysis can be done using many methods. Thematic content analysis was done to group the customer statements and elicit customer needs(Terry, Hayfield, Clarke, & Braun, 2017).

Establishing customer needs

The customer statements were translated into customer needs as the Voice of the customer(VOC). The customer statements may lead to one or more customer needs and the customer needs were elicited keeping in mind the functionality of the product. The regulatory requirements for the product were also translated into customer needs as Voice of Regulations(VOR). The needs were then rated, on a scale of '1 to 5', '5' being the highest rated and '1' being the lowest rated, based on the importance perceived from a customer perspective. The field failure report was taken as Voice of Business(VOB) and the corresponding customer needs of the field failure were assigned a high importance rating.

Deriving design requirements

There were multiple ways of converting customer needs into design requirements. In this thesis, the design requirements were derived from customer needs using the Phase 1 Quality Function Deployment(QFD) matrix, also known as 'House of Quality', which ensured the translation of all the customer needs into one or more design requirements. A target value was assigned to each design requirement for setting the target specifications for the intended product.

3.3 Concept generation

The concept generation phase involved the usage of multiple Product development tools to trigger multiple ideas and concepts. All the methods had the potential to be used independently to generate concepts as well(Karl T.Ulrich, 2012).

Function structure

Generating concepts could get complicated for generating complex products. The function structure method was used to break down the intended functions into sub-functions of the product and then concepts were generated for individual sub-functions and later combined. The function structure was created using two methods: Process flow model and Function means tree(Karl T.Ulrich, 2012).

Morphological matrix

In the morphological method, the concept generation activity was divided into two steps: generating concepts for individual sub-functions and later combining the individual concepts to get a whole feasible solution(Karl T.Ulrich, 2012). A total of 9 concepts were generated using this method.

Rapid ideation method

Rapid ideation method involved rapidly generating concepts in a short period, in our case, ten minutes. This simple yet powerful method proved very useful in generating multiple concepts. This brainstorming method was used to generate as many concepts as possible without any restrictions. The idea was not to be critical on any of the ideas conceptualized(Karl T.Ulrich, 2012). A total of 5 working concepts were generated using rapid ideation method.

3.4 Concept Screening

The concept screening method was an effective tool to reduce the number of concepts based on the it's suitability with the criteria. The concept screening stage did not select any concepts. It was just used to eliminate not-so-good concepts.

Elimination method

In the elimination method, concepts were eliminated based on the overall count of the criteria the concept did not satisfy. This matrix just checks the feasibility of the concept with regards to some general criteria like safety, quality, manufacturability and cost. All the concepts were assigned a binary value of whether it fulfils a list of generic criteria or not.

Pugh method

The Pugh matrix was also used as a concept screening tool, where the concepts were scored based on the customer needs criteria. In this stage, the concepts were scored on individual criteria irrespective of the importance attached to the criteria. So, there was always a possibility of losing out on the better concepts that have failed in the less important criteria. To avoid this, multiple iterations were done by changing benchmarked concepts. A '+' sign indicated that the particular concepts performed better than the reference for that particular criterion or '0' indicating that the concept was at the same level with the benchmark or a '-' sign indicating the concept performed worse than the reference. The reference was initially the existing product for the first iteration. In the second iteration, the overall best performing concept is selected as reference(Karl T.Ulrich, 2012).

3.5 Concept Scoring

In the concept scoring phase, the concepts had to be more carefully evaluated to arrive at the right concept. The concepts were scored based on the importance of the criteria involved.

Kesselring method

Kesselring matrix was an ideal method for this project to rate concepts based on the importance attached to each criterion. The highest-ranked concepts were chosen to be the final concepts for contention. The Kesselring matrix was used to qualitatively determine the right concept that fulfils the maximum intent of the criteria. Multiple iterations of Kesselring matrix was done by adding some additional criteria to increase the resolution of the criteria and the concepts were re-evaluated. Though similar to Pugh matrix, a major difference was that the concepts were rated from '1' being the lowest to '5' being the highest score. This score was then multiplied with the importance attached to each criterion and added up to find the highest weighed concept(Karl T.Ulrich, 2012).

3.6 Refining Technical Specifications

The technical specifications were refined using Phase 2 Quality Function Deployment(QFD2). The intention of using QFD2 was to drive down all the design requirements into the parts level design. This was the final step of the design process, that acted as a quality gate to ensure the robustness of the solution and determine if the intention of the design requirements were converted to their respective dimensions. Phase 2 QFD was mainly used to help understand the amount of relevance a dimension has towards achieving the desired result. The dimensions that attach the highest importance could have the potential to be the special characteristics of that part.

4
Data Collection and Analysis

4.1 Literature Review

An extensive study was conducted on the regulations laid down by classification societies on propulsion systems. The specifications for the design of different systems in a ship were limited by constraints, which varied from one classification society to the other. So, the system was designed for the extreme criteria for material selection, design and operational requirement, which were laid out by a combination of classification societies. The intention was to design a universal concept that satisfies all the individual classification societies alike, even when the customer chooses any classification society of his/her choice in the future. An explanation of the critical design parameters that influence the design of the flange coupling connection were detailed in section 2 of the report.

Some of the critical boundary conditions that must be factored in the design of the flange coupling connection were listed below.

- The permissible tensile strength of the material can be a maximum of 1000 MPa(ABS, 2019).
- Shear strength of the material should be 0.6 times the yield strength(DNVGL, 2018).
- The diameter of the expansion dowel is dependant on the pitch circle diameter of the flange and diameter of the shaft(IACS, 2015).
- The friction torque shall be at least twice the repetitive vibratory torque(DNVGL, 2018).
- Twice the peak torque minus the friction torque shall not result in shear stresses beyond 0.6 times the yield strength of n expansion devices(DNVGL, 2018).
- In the case of pretensioned bolts, the upper acceptable material tensile strength is 1350MPa and may have a pre-stress up to 70% at the smallest cross-section(DNVGL, 2018).
- The components should be designed for a safety factor of at least 1.3(DNVGL, 2015).

4.2 Benchmarking

To understand the pulse of the customer and respond to the varying demands from the market, similar products available in the market were studied and compared with the existing solution. The products involved in the benchmarking study were

- SKF Super Grip bolts
- Nord-Lock Superbolt HYFit expansion screws
- Pilgrim Radial Fit Bolts

Customer Needs (VOB, VOC, VOR)	Imp	Cat	SKF	Nord-Lock	Pilgrim
Interference fit type of bolt to be used	5	5	5	5	5
The system to be designed for manufacturability	5	1	2	2	3
The system should be cylindrical	4	3	1	1	1
The system should have low surface finish	1	1	2	5	5
Surface of coupling should withstand shear forces on the pin.	3	4	5	5	5
The system should have a surface contact with flange holes	3	3	5	5	5
The system should have a clearance fit with the flange hole before assembly	3	3	5	4	4
The system should have a controlled assembly/disassembly	2	4	5	5	5
The cost of the system should be less than the existing solution	5	5	1	2	3
The system should have minimum number of components	2	4	3	2	3
Assembly of the system should be deskilled	1	1	4	4	4
Assembly of the system should be simple and easy	2	1	3	3	3
The bolt circle diameter of the flange can be reduced.	1	4	2	2	1
The manufacturing of the system should be de-skilled	4	3	2	2	2
Standard manufacturing techniques to be used.	3	1	1	1	1
The system should work on multiple modes of expansion	1	4	3	3	3

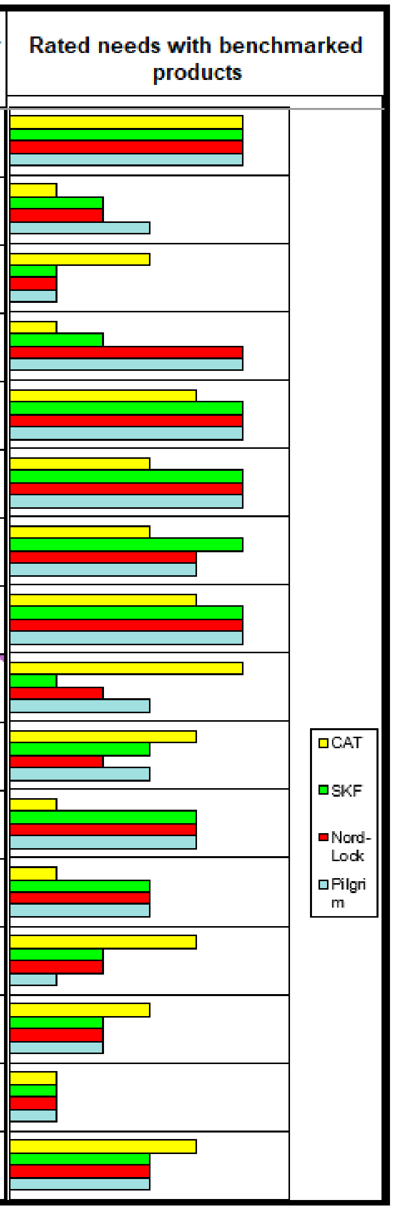

Figure 4.1: A sample of the customer needs comparison based on Benchmarking

SKF Super Grip Bolts

The SKF Super Grip bolt works on the principle of pulling a tapered shank bolt into a matching tapered sleeve, that in turn expands the outer diameter. The tightening mechanism is unique that uses a separate hydraulic tool to achieve the required expansion and a nut is used for retaining the expansion. The SKF bolts were also used as an alternative for the in-house expansion dowels.

Nord-Lock Superbolt HYFit Expansion Screws

The HYFit Expansion screws also follow the same principle of 'tapered surfaces' for expansion and hydraulics to enable tightening. The Nord-Lock is also an active spares supplier in the marine industry.

Pilgrim Radial Fit Bolts

The Radial Fit bolt also follows similar construction with regards to the SKF Super Grip bolts. These bolts are also designed to transmit the Thrust and bending loads and also in maintaining the flange alignment. These bolts can be used in combination with Pilgrim Clamp bolts in a flange connection(International, 2018)

	Expanded Diameter of the bolt	Angle of Taper of the sleeve	Surface Roughness of the sleeve	Surface pressure between surfaces	Clearance diameter of bolt before	Total cost of manufacturing	Part count	Time to assembly	Bolt circle diameter	Number of special operations	Mode of expansion	Number of sides involved in	Number of special charecteristics	Time taken for disassembly	Number of Special tools for assembly	Clear feedback on assembly/disassem
Target	66.06 mm	15°	6.3	28 Mpa	66 mm	≤ 2000 sek	≤ 5 nos.	≤ 10 mins	970 mm	0	Mech anical	1	0	≤ 5 mins	0	NA
CAT	5	1	3	4	5	5	4	3	4	5	5	1	5	5	5	3
SKF	5	5	5	5	5	2	5	5	3	1	5	3	1	5	5	5
Nord-Lock	5	4	5	5	5	1	3	5	1	4	5	3	4	5	5	5
Pilgrim	5	3	4	4	5	3	5	5	4	1	5	3	1	5	5	5

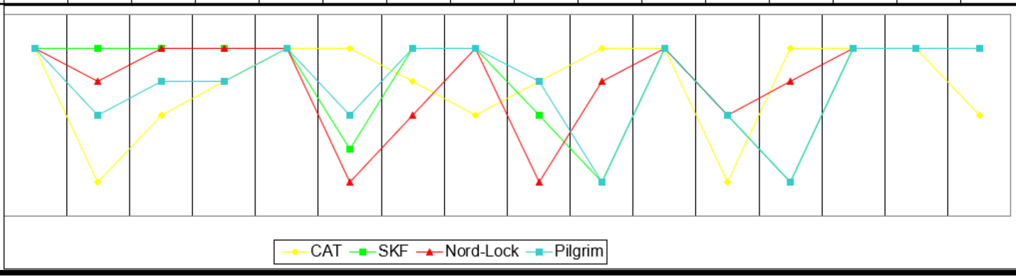

Figure 4.2: Customer requirements comparison based on Benchmarking

The requirements were spelt out and the competitor's technical specifications were studied. The budgetary quote of the benchmarked products was also taken into consideration to conduct a comparison study. The comparison study was done to identify the requirements/needs, for which the existing product fared better and the requirements/needs for which the existing product fell short in comparison with its competition. A sample of the comparison study is shown in figure 4.1 and 4.2. The full list of needs comparison for benchmarking is attached in appendix B.4. The feedback from this study was taken into account while designing the new concept.

Some of the key takeaways compared to the existing in-house solution were listed below.

- The principle of operation for all the products were similar.
- The mode of operation of all the systems utilized hydraulic force to assist expansion.
- The assembly of all the products required accessibility from both ends of the system.
- The price of the competition is at least four to five times higher than the price of manufacturing the product in-house. The intention was to develop a product that should be cheaper than the in-house developed product was felt.

4.3 Past failure report

Field failures in the past served as a strong business case for reinforcing the need for the project and also to mitigate the existing possibility of failure in the future design. The number of field failures relating to the existing design was one, but compared to the number of orders where the product is in use, this number is huge.

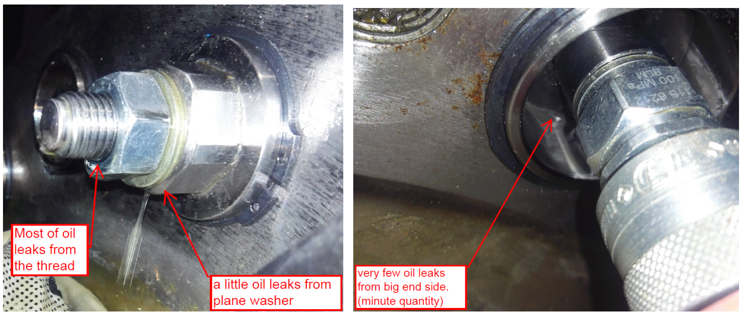

Figure 4.3: Images from the field failure report

The failure had happened onsite and at the time of commissioning the propulsion system. The issue was about the expansion dowel's failure to sustain the required oil pressure at the time of assembly, as shown in figure 4.3. The root cause was due to poor manufacturability of the taper. From this case of field failure, the need for a solution that improves the manufacturability of the part and that reduces the operational downtime was felt.

4.4 Patent Search

Since the project deals with the development of a new solution, the search was not restricted to any specific area of operation. Applicable patents were compared and analysed to better understand the mode of operation and also to ensure the product concepts pertaining to the project were original. Some of the patents, their similarities and differences were listed in the table 4.1.

Patent US2019301507(A1)	**Sections of relevance in prior art**	**Subject features fulfilled**
Expansion dowel having a Zinc alloy coating	An expansion dowel is provided, which includes at least one dowel body and a bolt, the bolt including an expansion body, which forces the dowel body radially to the outside when the expansion body is displaced in an extraction direction relative to the dowel body.	The expansion dowel utilizes a tapered shank and an outer sleeve to expand and firmly tighten the setup. But, the setup is difficult to disassemble when needed. The patent was similar to the other benchmarked products in the market employing the same principle of operation.

Patent PL1767794(T3)	**Sections of relevance in prior art**	**Subject features fulfilled**
Expansion dowel for fastening insulating panels	The anchor (1) has an expansion area (5), spreader unit (8), which is made up of plastics, and a retaining plate (7). The spreader unit is an expanding screw with a pull linkage at its header (11). The pull linkage is formed by a circulating groove in the header of the expanding screw. The expanding screw has a conical and cylindrical core section in an area of its screw thread.	The principle of operation also uses a tapered screw with a tapered sleeve and on tightening, expands to firmly hold the setup onto the panels. The material used is plastic and hence the application is limited to low shear force applications.

Table 4.1: Patent search analysis

4.5 Interviews

The lead users for the product were identified to be a Design Engineer for the existing product, a Product Service Engineer, who deals with the relevant customer complaints regularly and a Manufacturing Technician, who manufactures the product for test conditions. The interview was carried out to understand the problem better and map the expectations for the concept. The interview guide is attached in the appendix A.1. The audio from the interviews was recorded and the key customer statements were listed. Some of the key customer statements and the preliminary interpreted needs are shown in table 4.2.

No.	Customer Statements	Converted needs
1	Bolt should transmit power with a certain level of security.	The shear strength of the bolt should be more than the torque transmitted
2	Some classification societies demand gap-free assemblies.	Interference fit type of bolt to be used.
3	Onsite manufacturing of components, not favourable	Components to be designed for manufacturability
4	Expansion bolts eliminate the need for reaming	Surface finish on the surfaces should NOT be a critical criterion
5	Principle of shrink fit coupling used for expansion bolts	Surface pressure on the surface of flange needed to withstand shear forces on the pin.
6	If the bolt has ceased and not getting loose during disassembly, use oil with higher viscosity	Alternate choices for assembly/disassembly should be available
7	Hydraulics gives better control over the assembly/disassembly process	Assembly/Disassembly process should be controlled
8	Hydraulics provide the additional force necessary to assemble the bolts	Assembly should be easy
9	Using liquid nitrogen is difficult to work with compared to hydraulic dowels	The assembly process should be in a controlled manner.
10	Having an assembly process on one side aids assembly of both open and closed connections	The assembly process should be only on one side of the component
11	Cylindrical dowel pins easy to manufacture in-house rather than purchasing expansion dowels from third party suppliers	Simple mechanisms to be used for easier manufacturing
12	Expansion dowels easier to disassemble than cylindrical pins	Disassembly should not be complex
13	If expansion dowel is damaged, it is hard to replace	Simple mechanisms to be used for easier manufacturing
14	If surfaces on cone not good enough, has a possibility to cease	De-skilling to be done in manufacturing
15	If the torque is applied, we do not know for sure if the expansion dowel expanded	Clear feedback on assembly/disassembly
16	Don't manufacture bolts in big varieties of size as maintaining tools are hard	Standard tooling to be used for manufacturing
17	Super cooled bolts expand in diameter and length. This leads to oil leakage.	Simple mechanisms to be used for easier manufacturing
18	Manufacturing requires more skill for expansion dowels	De-skilling to be done in manufacturing

Table 4.2: List of customer statements and their corresponding needs

The clear theme from the interviews was revolving around how the product was designed. The general expectations from the interviewees were to arrive at a concept that improved the ease of manufacturing and assembly, while, at the same time, retaining the cost.

4.6 Establishing customer needs

All the information collected from previous data collection methods such as Voice of Customers(VOC), Voice of Regulations(VOR) and Voice of Business(VOB) were interpreted into customer needs. The needs were categorized so as to define a consistent theme for the need and a specific importance was attached to it depending on how well the customers value it.

No.	Need	Wish/Demand	Imp.	Category
1	The system should adhere to regulations	Demand	D	Design
2	The system to be designed for manufacturability	Wish	5	Design for Manufacturing
3	The system should be cylindrical	Wish	4	Design for Manufacturing
4	Surface finish on the surfaces should NOT be a critical criteria	Wish	1	Design for Manufacturing
5	The system should withstand shear forces on the pin.	Wish	3	Design for Manufacturing
6	The system should have a surface contact with flange holes	Wish	3	Design for Manufacturing
7	The system should have a clearance fit with the flange hole before assembly	Wish	3	Design for Manufacturing
8	The system should have a controlled assembly/disassembly	Wish	2	Design for Assembly
9	The cost of the system should be less than the existing solution	Wish	5	Design for cost
10	The system should have minimum number of components 2	Wish	2	Design for Assembly
11	Assembly of the system should be deskilled	Wish	1	Design for Assembly
12	Assembly of the system should be simple and easy	Wish	2	Design for Assembly
13	The bolt circle diameter of the flange can be reduced. 1	Wish	1	Design for Assembly
14	The manufacturing of the system should be de-skilled	Wish	4	Design for Manufacturing
15	Standard manufacturing techniques to be used.	Wish	3	Design for Manufacturing
16	The system should work on multiple modes of expansion	Wish	1	Design for Manufacturing
17	Alternate choices for assembly/disassembly of the system should be available	Wish	3	Design for Assembly
18	The mechanism for expansion of the system to be simple	Wish	1	Design for Manufacturing
19	The system should be accessible from either end of the system for the purpose of assembly 3	Wish	3	Design for Assembly
20	The assembly process should be carried out from one side	Wish	1	Design for Assembly
21	Simple mechanisms to be used for easier manufacturing of the system	Wish	3	Design for Manufacturing
22	Inspection of the system should be minimal 3	Wish	3	Design for Assembly
23	Standard tooling to be used for manufacturing of the system	Wish	3	Design for Manufacturing
24	Disassembly of the system should not be complex 1	Wish	1	Design for Assembly
25	The system needs clear feedback on assembly/disassembly 2	Wish	2	Design for Assembly

Table 4.3: Customer needs list

4.7 Establishing target specifications

Base on the derived customer needs, the first phase of Quality Function Deployment(QFD) model was used to drive down all the customer needs into the corresponding design requirements on how the ideal product should behave. The entire structure of the Phase 1 QFD chart developed for the new concept is attached in the appendix B.1 and B.2. A sample of the relationship matrix is shown in figure 4.4.

	<--Customer Importance	Requirements: Expanded Diameter of the bolt	Angle of Taper of the sleeve	Surface Roughness of the sleeve	Surface pressure between surfaces	Clearance diameter of bolt before assembly	Total cost of manufacturing	Part count	Time to assembly
Customer Needs (VOB, VOC, VOR)									
Interference fit type of bolt to be used	5	9							
The system to be designed for manufacturability	5		3						
The system should be cylindrical	4		9						
The system should have low surface finish	1			9					
Surface of coupling should withstand shear forces on the pin.	3				9				
The system should have a surface contact with flange holes	3		3		3				
The system should have a clearance fit with the flange hole before assembly	3					9			
The system should have a controlled assembly/disassembly	2								
The cost of the system should be less than the existing solution	5						9		1
The system should have minimum number of components	2							9	
Assembly of the system should be deskilled	1								9
Assembly of the system should be simple and easy	2								3
Requirement Importance		45	60	9	36	27	45	18	20
Target		66.06 mm	15°	6.3	28 Mpa	66 mm	≤ 2000 sek	≤ 5 nos.	≤ 10 mins

Figure 4.4: Quality Function Deployment Phase 1 - A sample of needs to design relationship Matrix

The correlation between individual design requirements was also taken into account to mitigate the design conflicts in the future. The correlation matrix is also shown in the appendix B.3

The list of design requirements, derived from Phase 1 QFD, were then discussed with stakeholders to arrive at individual target values. Some of the target values were also based on bench-marked values with the existing product and some values were based on wishes for the product. The full list of target specifications and their corresponding target values are shown in table 4.4. These values were just preliminary metrics and were refined throughout the project.

Metric no.	Metric	Unit	Target value
1	Expanded Diameter of the bolt	mm	66.06
2	Angle of Taper of the sleeve	deg	15
3	Surface Roughness of the sleeve	Ra	6.3
4	Surface pressure between surfaces	MPa	28
5	Clearance diameter of bolt before assembly	mm	66
6	Total cost of manufacturing	sek	$\leq$2000
7	Part count	Nr	≤ 5
8	Time to assembly	mins	≤ 10
9	Bolt circle diameter	mm	970 mm
10	Number of special operations	Nr	0
11	Mode of expansion	subj.	Mechanical
12	Number of sides involved in assembly	Nr	1
13	Number of special charecteristics	Nr	0
14	Time taken for disassembly	mins	≤ 5
15	Number of Special tools for assembly	Nr	0
16	Clear feedback on assembly/disassembly	subj.	NA

Table 4.4: List of design requirements and their target values

5

Concept Generation and Selection

5.1 Concept Generation

Concept generation is an innovative part of Product Development. To generate effective concepts that match the design requirements, two methodologies were used in this thesis for concept generation: Morphological method and Rapid Ideation techniques. To enable easier concept generation, the functional requirements of the concept was broken down into different sub-functions using two methods: Process Flow Model and Function-means tree.

The flowchart for identifying the sub-functions based on the process flow is detailed in figure 5.1 and figure 5.2.

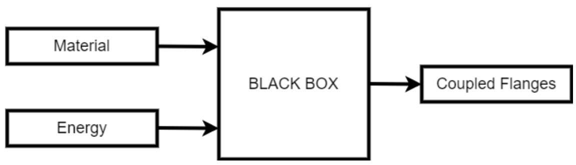

Figure 5.1: Simplified Process Flow model

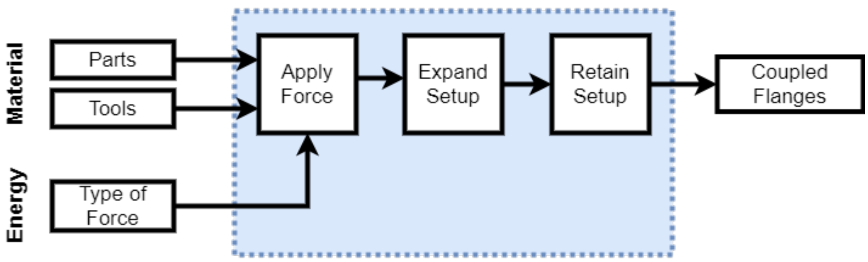

Figure 5.2: Detailed Process Flow model

The functions can also be identified, based on the identified requirements, using the Function means tree and it is illustrated in figure 5.3

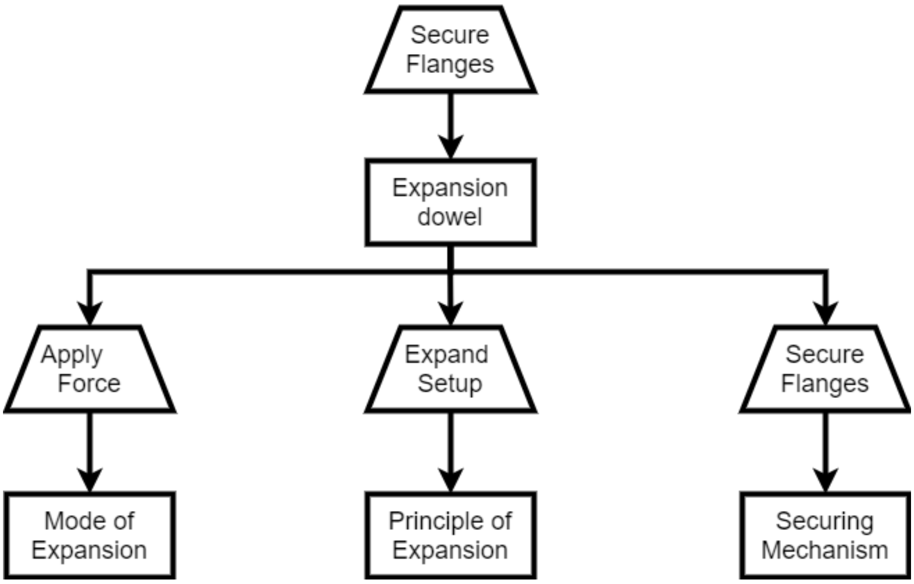

Figure 5.3: Function means tree

The generated sub-functions were then translated to the morphological matrix for the actual concept generation.

Morphological matrix

Morphological matrix was used to generate concepts for each of the sub-functions identified and all the individual concepts were later combined to arrive at a feasible solution. The idea behind every generated concept is sketched in the figure 5.4 and explanation for each generated concept is detailed in the figure 5.5

Functions	**Concept 1**	**Concept 2**	**Concept 3**	**Concept 4**	**Concept 5**	**Concept 6**	**Concept 7**	**Concept 8**
Apply Force	A.1 Mechanical	A.2 Electrical	A.3 Thermal	A.4 Hydraulic	AIR A.5 Pneumatic	A.6 Magnetic		
Expand setup	B.1 Screw Jack	B.2 Chuck	B.3 Electro magnet	B.4 Rack and pinion	B.5 Spring loaded	B.6 Liquid Pressure	B.7 Tapered expansion	B.8 Temperature variation
Retain setup	C.1 Nut	C.2 Sleeve	C.3 No retainer					

Figure 5.4: Morphological matrix

A. Apply force	B. Expand Setup	C. Retain expansion
A.1 Mechanical : Physical forces utilized to achieve the required torque. Example: Manual torque wrench for tightening a bolt.	**B.1 Screw Jack** : The rotational force at the center is translated into linear expansion pushing the sleeves outward.	**C.1 Nut** : Standard retaining mechanism to ensure that the applied force is maintained.
A.2 Electrical : Tool operated by a DC Motor to achieve the required force. Example: DC Tool tightening of a bolt.	**B.2 Reverse Chuck** : The rotation at the center shaft makes the jaws to expand. Example: Mechanical chuck in the lathe	**C.2 Sleeve :** Hollow shaft that ensures that the achieved outer diameter after expansion is maintained. Example: Go/No-Go gauge.
A.3 Thermal : Utilizing the thermal properties of materials to apply the required force. Example: Mounting of bearings in holes after cooling	**B.3 Electro magnet** : Polarise the two ends of the sleeves to achieve expansion Example: Large electromagnets used to lift objects	**C.3 No retainer**
A.4 Hydraulic : Using hydraulic properties of fluids to apply force. Example: Applying brakes in cars.	**B.4 Rack and pinion** : Rotational action to achieve linear movement. Example: Manual steering of cars	
A.5 Pneumatic : Using Pnematics energy to apply force to joints. Example: Pneumatic tools to tighten joints.	**B.5 Spring loaded** : Poténtial energy of springs used for expansion between sleeves. Example: Valves in engine are closed using the potential energy of springs	
A.6 Magnetic : Utilizing the magnetic effect of iron particles between the materials Example: Magnetic levitation of trains.	**B.6 Liquid Pressure** : Using liquids to actuate pistons for expansion. Example: Hydraulic jacks for lifting cars.	
	B.7 Tapered expansion : The tapered shaft pushes the tapered sleeve outward to cause expansion. Example: Anchor bolts and rivets	
	B.8 Temperature variation : The shrinkage/expansion effect of metals are used to cause expansion Example: Super cooled expansion pins for assembly	

Figure 5.5: Explanations of solutions to the sub-functions in morphological matrix

Out of the 144 possible outcomes from the morphological matrix, only a few feasible outcomes exist. 9 working concepts were identified and synthesized. The sketch of synthesized concepts are shown in the figure 5.6.

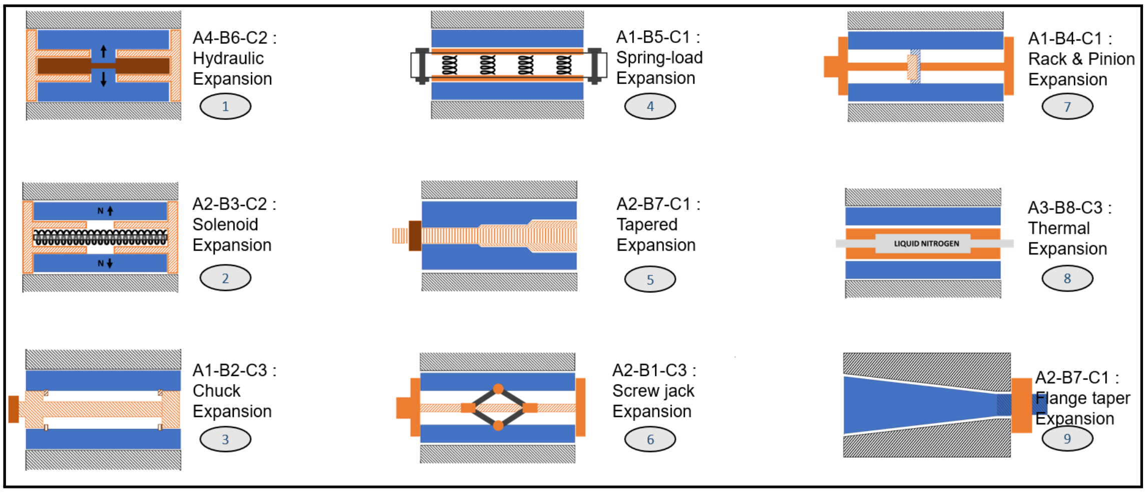

Figure 5.6: Concepts generated from morphological matrix

Rapid Ideation method

Rapid ideation method as a brainstorming technique proved to be an effective tool in realizing some concepts. 5 concepts were generated from this method. The concepts are shown in fig 5.7

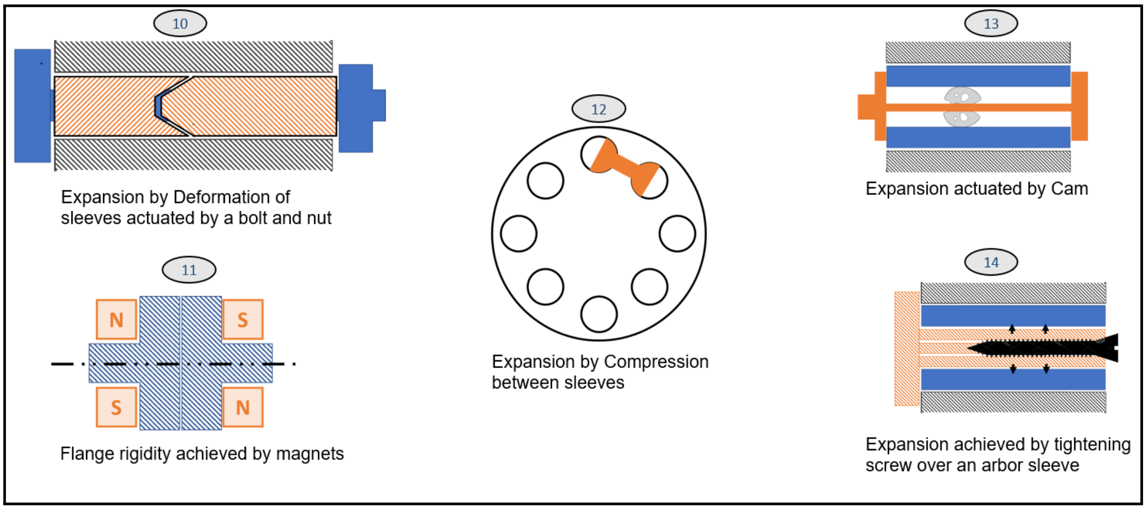

Figure 5.7: Concepts generated from rapid ideation techniques

So, a total of 14 concepts were generated. A preliminary description for all the 14 generated concepts are detailed in the table 5.1 and 5.2.

Concept number	**Concept Name**	**Concept Description**
1	HYDREX	Hydraulic oil is injected using a cylindrical hydraulic injector. Two split sleeves expands to exert surface pressure and retained using two end sleeves.
2	SOLEX	Two split sleeves, polarized and expanded using solenoid at the center. The repulsive force between the solenoid and the split sleeves is leveraged.
3	CHEX	Similar to a chuck mechanism, rotation at the center would cause the lugs to expands outwards causing surface pressure on the sleeve, and in turn, on the flange holes.
4	SPEX	Two split sleeves, expanded using a spring setup at the center. The spring setup would be compressed before sliding inside the flange hole and then made to expand inside the hole.
5	TAPEX	Similar to the expansion dowel, the taper on the bolt shank and on the sleeve would be over a short length alternated by flat surfaces, to improve manufacturability
6	SCEX	Two split sleeves, connected to a screw jack arrangement, would expand outward causing the required surface pressure. The screw jack is self-locking and torqued by electrical input.
7	RACKEX	Two split sleeves, attached to a rack arrangement, which would be in contact with a pinion at the center shaft, driven by an external force. The shaft is retained using a nut
8	THEREX	Nitrogen gas is pumped inside the pin to shrink the pin before inserting it between the split sleeves. The thermal expansion caused the sleeves to expand. Disassembly also made possible.
9	FLATAPEX	The Flange hole can be machined to correspond with the tapered shank on-site. The setup reduces the parts but increases the amount of tools and work for the service technician onsite.

Table 5.1: Explanation of the concepts generated from morphological method

Concept number	Concept Name	Concept Description
10	DEFEX	The assembly process should be only on one side of the component.Bolt and nut is used to compress the sleeves at the center and cause deformation of the inner sleeve, in turn causing an expansion.
11	MAGNA	A powerful magnet is used to keep the flanges together in place. The disassembly might be difficult.
12	COMPREX	Instead of expanding inside the hole, the compressive force can be used between two holes by using a connected couplers that can be inserted into two holes and tightened, causing expansion inside holes.
13	CAMEX	A Cam connected to a center shaft, is used to expand the outer sleeves.
14	ARBEX	Expanding arbor principle is used. A center screw is used to expand the arbor and, in turn, would expand the sleeves to exert surface pressure on the flange holes.

Table 5.2: Explanation of concepts generated from rapid ideation method

5.2 Concept Evaluation

Having generated a total of 14 concepts, the concepts were then evaluated using multiple evaluation techniques, before the best concept can be chosen. This evaluation process was divided into two stages; Concept screening and concept scoring. For concept screening, Elimination matrix and Pugh matrix were used and for concept scoring, Kesselring matrix was used.

Concept Screening

Elimination matrix was used for the first level of concept screening. The purpose of the Elimination matrix was to filter out the concepts that had little technical or functional feasibility. Based on that, a decision was taken on whether to pursue the concept or not. Six concepts were eliminated in this stage. The concepts were primarily eliminated due to its inability to solve some critical criteria which were discussed in the elimination matrix chart shown in figure 5.8.

The Pugh matrix was used for the next level of concept screening. The selection criteria were based on the list of customer needs collected earlier. In the first iteration of Pugh matrix, as shown in figure 5.9, out of the 8 concepts evaluated, 2 concepts, namely 'CHEX' and 'CAMEX', were eliminated because of too many '-' scores.

In the second iteration, as shown in figure 5.10, the concept 'HYDREX' was used as a reference, as it was the best-ranked product in the first iteration. During this iteration, 'ARBEX' was eliminated due to a low score of '+'. The remaining 5 concepts were taken forward for Concept scoring.

Elimination matrix

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Elimination criteria

(+) Pass
(-) Fail
(?) More information needed
(!) Check with specifications

Decision

(+) Continue
(-) Remove
(?) More information needed
(!) Check with specifications

A: Solves the main problem
B: Fulfills all requirements
C: Is compatible/realizable
D: Has a reasonable cost
E: Is safe to use
F: Easy to manufacture
G: Enough information acquiried

Solution	A	B	C	D	E	F	G	Comment	Decision
HYDEX	(?)	(+)	(+)	(+)	(+)	(+)	(!)	The effect of expansion at the center may act as a cantilever at the ends, but the concept as a whole, is feasible.	(+) Continue
SOLEX	(+)	(+)	(-)	(-)	(+)	(+)	(!)	The power required to cause repulsion is huge and may not be cost competitive	(-) Remove
CHEX	(+)	(+)	(+)	(-)	(+)	(+)	(+)	The number of moving parts are high and that may have an increased cost. But it satisfies all the other requirements.	(+) Continue
SPEX	(+)	(+)	(?)	(-)	(+)	(+)	(?)	Instead of springs, Material can be compressed and then made to expand inside the flange holes	(+) Continue
TAPEX	(+)	(+)	(+)	(+)	(+)	(+)	(!)	The tapered expansion is an established concept that is also part of benchmarked data.	(+) Continue
SCEX	(+)	(+)	(+)	(-)	(+)	(-)	(?)	The screw jack has lot of moving parts. Also, the cost of manufacturing complex mechanisms would lead to failure of the project.	(-) Remove
RACKEX	(+)	(+)	(-)	(-)	(+)	(-)	(?)	The rack and pinion needs an internal setup, that might increase the diameter of the hole of the flange.	(-) Remove
THEREX	(+)	(+)	(+)	(+)	(+)	(+)	(+)	Liquid nitrogen is available in most of the sites, where assembly is carried out.	(+) Continue
ARBEX	(+)	(+)	(+)	(+)	(+)	(+)	(+)	Opportunities exist for the manufacturing of a simple yet effective expansion.	(+) Continue
DEFEX	(+)	(+)	(+)	(+)	(+)	(+)	(+)	This method of expansion utilizes existing fasteners, which in turn can lead to effective cost reduction.	(+) Continue
FLATAPEX	(+)	(-)	(+)	(-)	(-)	(-)	(-)	This concept will require the service engineer to carry out manufacturing activities at site.	(-) Remove
MAGNA	(+)	(+)	(-)	(-)	(+)	(+)	(?)	The investment of high power magnet is high and the effects of it on the adjacent material are unknown.	(-) Remove
CAMEX	(+)	(+)	(+)	(+)	(+)	(+)	(+)	The cost of making a cam is high but opportunities exist.	(+) Continue
COMPREX	(+)	(+)	(-)	(+)	(+)	(-)	(?)	The concept is not realizable as it constraints the rest of the assembly	(-) Remove

Figure 5.8: Elimination Matrix

Chalmers University of Technology	Pugh matrix								
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Criteria	**REF**	**HYDEX**	**CHEX**	**SPEX**	**TAPEX**	**THEREX**	**ARBEX**	**DEFEX**	**CAMEX**
The system should have a controlled assembly/disassembly	0	+	-	-	+	-	+	+	-
Assembly of the system should be deskilled	0	+	-	-	+	+	+	+	-
Assembly of the system should be simple and easy	0	+	+	+	0	+	+	+	-
Alternate choices for assembly/ disassembly should be available	0	+	-	-	-	-	-	-	-
The system should be accessible from either end for assembly	0	+	+	+	+	+	+	+	+
The assembly process should be carried out from one side	0	+	+	+	+	-	+	-	-
Disassembly of the system should not be complex	0	0	+	+	+	+	+	0	-
The system needs clear feedback on assembly/disassembly	0	-	-	-	+	-	-	-	-
The cost of the system should be less than the existing solution	0	+	-	+	0	+	-	+	-
The system should have minimum number of components	0	+	-	-	+	+	+	0	-
Inspection of the system should be minimal	0	+	+	-	+	+	+	+	-
The system to be designed for manufacturability	0	+	+	+	+	+	-	+	-
The system should be cylindrical	0	+	+	+	-	+	+	+	-
The system should have low surface finish	0	+	+	+	-	+	+	+	-
The system should withstand shear forces on the pin.	0	+	+	-	+	+	-	+	-
The system should have a surface contact with flange holes	0	+	+	+	0	+	+	0	-
The system should have clearance fit with flange hole before assembly	0	0	0	0	0	0	0	0	0
The manufacturing of the system should be de-skilled	0	+	-	-	-	+	-	+	-
Standard manufacturing techniques to be used.	0	+	+	-	+	+	-	+	-
The system should work on multiple modes of expansion	0	0	-	-	-	-	-	-	-
The mechanism for expansion of the system to be simple	0	0	-	+	0	+	-	+	-
Simple mechanisms to be used for easier manufacturing of the system	0	+	-	+	+	+	-	+	-
Standard tooling to be used for manufacturing of the system	0	0	-	+	+	+	+	+	-
Number of +	0	17	11	12	13	17	12	15	1
Number of 0	23	5	1	1	5	1	1	4	1
Number of -	0	1	11	10	5	5	10	4	21
Net value	0	16	0	2	8	12	2	11	-20
Rank		1	6	5	4	2	5	3	7
Further development		YES	NO	YES	YES	YES	NO	YES	NO
Decision		Continue	Remove	Continue	Continue	Continue	Continue	Continue	Remove

Figure 5.9: Pugh Matrix - First Iteration

Chalmers University of Technology	**Pugh matrix**							
Issued by: Shiyam Subburaman								Page 2
Criteria	**HYDREX**	[redacted]	**SPEX**	**TAPEX**	**THEREX**	**ARBEX**	**DEFEX**	[redacted]
The system should have a controlled assembly/disassembly	0		+	+	-	+	+	
Assembly of the system should be deskilled	0		-	-	+	0	0	
Assembly of the system should be simple and easy	0		+	-	+	+	+	
Alternate choices for assembly/ disassembly should be available	0		-	-	-	-	-	
The system should be accessible from either end for assembly	0		-	-	+	-	-	
The assembly process should be carried out from one side	0		0	0	+	-	-	
Disassembly of the system should not be complex	0		-	+	+	-	0	
The system needs clear feedback on assembly/disassembly	0		-	+	-	-	-	
The cost of the system should be less than the existing solution	0		+	-	+	-	-	
The system should have minimum number of components	0		-	+	+	+	-	
Inspection of the system should be minimal	0		+	0	+	-	0	
The system to be designed for manufacturability	0		+	0	+	-	0	
The system should be cylindrical	0		+	-	+	-	-	
The system should have low surface finish	0		+	-	+	+	+	
The system should withstand shear forces on the pin.	0		-	0	+	-	0	
The system should have a surface contact with flange holes	0		+	-	+	-	-	
The system should have clearance fit with flange hole before assembly	0		0	0	0	0	0	
The manufacturing of the system should be de-skilled	0		+	-	+	-	-	
Standard manufacturing techniques to be used.	0		+	-	+	-	-	
The system should work on multiple modes of expansion	0		-	-	-	-	-	
The mechanism for expansion of the system to be simple	0		+	-	+	-	-	
Simple mechanisms to be used for easier manufacturing of the system	0		+	-	+	-	-	
Standard tooling to be used for manufacturing of the system	0		+	+	+	-	+	
Number of +	0		13	5	18	4	4	
Number of 0	23		2	5	1	2	6	
Number of -	0		8	13	4	17	13	
Net value	0		5	-8	14	-13	-9	
Rank	0		2	3	1	5	4	
Further development	YES		YES	YES	YES	NO	YES	
Decision	Continue		Continue	Continue	Continue	Remove	Continue	

Figure 5.10: Pugh Matrix - Second Iteration

Concept Scoring

Kesselring matrix was used for concept scoring. In the first iteration, the 5 concepts were evaluated. The least scored concepts in first iteration of Kesselring matrix, as shown in figure 5.11, were 'SPEX' and 'TAPEX'.

Chalmers University of Technology		Kesselring matrix											
Issued by: Shiyam Subburaman		Created: 2020-04-14						Modified: 2020-04-15				Page 1	
Criteria		**IDEAL**		**HYDREX**		**SPEX**		**TAPEX**		**THEREX**		**DEFEX**	
Name	**w**	**v**	**t**	**v**	**t**	**v**	**t**	**v**	**t**	**v**	**t**	**v**	**t**
The system should have a controlled assembly/disassembly	2	5	10	4	8	2	4	4	8	1	2	4	8
Assembly of the system should be deskilled	1	5	5	2	2	3	3	2	2	4	4	3	3
Assembly of the system should be simple and easy	2	5	10	3	6	3	6	2	4	4	8	2	8
Alternate choices for assembly/ disassembly should be available	3	5	15	4	12	1	3	1	3	1	3	1	3
The system should be accessible from either end for assembly	3	5	15	4	12	1	3	4	12	5	15	4	12
The assembly process should be carried out from one side	1	5	5	4	4	1	1	4	4	5	5	3	3
Disassembly of the system should not be complex	1	5	5	4	4	2	2	3	3	5	5	3	3
The system needs clear feedback on assembly/disassembly	2	5	10	3	6	1	2	4	8	2	4	3	6
The cost of the system should be less than the existing solution	5	5	25	3	15	4	20	2	10	4	20	2	20
The system should have minimum number of components	2	5	10	3	6	2	4	4	8	3	6	2	6
Inspection of the system should be minimal	3	5	15	3	9	4	12	2	6	5	15	2	6
The system to be designed for manufacturability	5	5	25	3	15	4	20	2	10	5	25	2	15
The system should be cylindrical	4	5	20	4	16	4	16	3	12	4	16	3	12
The system should have low surface finish	1	5	5	3	3	5	5	3	3	5	5	3	3
The system should withstand shear forces on the pin.	3	5	15	5	15	3	9	4	12	5	15	4	12
The system should have a surface contact with flange holes	3	5	15	5	15	4	12	3	9	5	15	3	12
The system should have clearance fit with flange hole before assembly	3	5	15	5	15	5	15	5	15	5	15	5	15
The manufacturing of the system should be de-skilled	4	5	20	2	8	3	12	2	8	5	20	2	12
Standard manufacturing techniques to be used.	3	5	15	4	12	3	9	4	12	5	15	4	12
The system should work on multiple modes of expansion	1	5	5	4	4	1	1	1	1	1	1	1	1
The mechanism for expansion of the system to be simple	1	5	5	4	4	1	1	2	2	1	1	1	5
Simple mechanisms to be used for easier manufacturing of the system	3	5	15	3	9	1	3	4	12	5	15	4	12
Standard tooling to be used for manufacturing of the system	3	5	15	3	9	3	9	4	12	5	15	4	12
Total		115	295	82	209	61	172	69	176	90	245	65	201
Rel total		1,0	1,0	0,7	0,7	0,5	0,6	0,6	0,6	0,8	0,8	0,6	0,7
Mean		5,0	12,9	3,6	8,7	2,4	7,1	3,1	8,9	3,9	11,7	3,0	9,9
Deviation		0,0	4,5	0,8	2,9	1,2	4,7	1,3	4,4	1,6	6,1	1,4	3,9
Median		5,0	15,0	4,0	9,0	3,0	9,0	4,0	12,0	5,0	15,0	4,0	12,0
Number of weak points		0,0		0,0		3,0		1,0		2,0		2,0	
Rank					II		V		IV		I		III
Decision					Pass		Fail		Fail		Pass		Pass

Figure 5.11: Kesselring Matrix - First Iteration

Chalmers University of Technology		Kesselring matrix											
Issued by: Shiyam Subburaman		Created: 2020-04-15						Modified: 2020-04-27				Page 2	
Criteria		IDEAL		HYDREX		SPEX		TAPEX		THEREX		DEFEX	
Name	w	v	t	v	t	v	t	v	t	v	t	v	t
The system should have a controlled assembly/disassembly	2	5	10	4	8	2	4	4	8	1	2	4	8
Assembly of the system should be deskilled	1	5	5	2	2	3	3	2	2	4	4	3	3
Assembly of the system should be simple and easy	2	5	10	3	6	3	6	2	4	4	8	4	8
Alternate choices for assembly/ disassembly should be available	3	5	15	4	12	1	3	1	3	1	3	1	3
The system should be accessible from either end for assembly	3	5	15	4	12	1	3	4	12	5	15	4	12
The assembly process should be carried out from one side	1	5	5	4	4	1	1	4	4	5	5	3	3
Disassembly of the system should not be complex	1	5	5	4	4	2	2	3	3	5	5	3	3
The system needs clear feedback on assembly/disassembly	2	5	10	3	6	1	2	4	8	2	4	3	6
The cost of the system should be less than the existing solution	5	5	25	3	15	4	20	2	10	5	25	4	20
The system should have minimum number of components	2	5	10	3	6	2	4	4	8	4	8	3	6
Inspection of the system should be minimal	3	5	15	3	9	4	12	2	6	5	15	2	6
The system to be designed for manufacturability	5	5	25	3	15	4	20	2	10	5	25	3	15
The system should be cylindrical	4	5	20	4	16	4	16	3	12	4	16	3	12
The system should have low surface finish	1	5	5	3	3	5	5	3	3	5	5	3	3
The system should withstand shear forces on the pin.	3	5	15	5	15	3	9	4	12	5	15	4	12
The system should have a surface contact with flange holes	3	5	15	5	15	4	12	3	9	5	15	4	12
The system should have clearance fit with flange hole before assembly	3	5	15	5	15	5	15	5	15	5	15	5	15
The manufacturing of the system should be de-skilled	4	5	20	2	8	3	12	2	8	5	20	3	12
Standard manufacturing techniques to be used.	3	5	15	4	12	3	9	4	12	5	15	4	12
The system should work on multiple modes of expansion	1	5	5	4	4	1	1	1	1	1	1	1	1
The mechanism for expansion of the system to be simple	1	5	5	4	4	1	1	2	2	1	1	5	5
Simple mechanisms to be used for easier manufacturing of the system	3	5	15	3	9	3	9	4	12	5	15	4	12
Standard tooling to be used for manufacturing of the system	3	5	15	3	9	3	9	4	12	5	15	4	12
The setup should be robust during operation	5	5	25	2	10	1	5	1	5	5	25	3	15
The system should be operational with less number of parts	5	5	25	1	5	1	5	3	15	5	25	3	15
Total		115	295	82	224	63	188	69	196	92	302	77	231
Rel total		1,0	1,0	0,7	0,8	0,5	0,6	0,6	0,7	0,8	1,0	0,7	0,8
Mean		5,0	12,9	3,6	8,7	2,7	8,0	3,1	8,9	3,9	11,7	3,7	9,9
Deviation		0,0	4,5	0,8	2,9	1,0	4,0	1,3	4,4	1,6	6,1	1,0	3,9
Median		5,0	15,0	4,0	9,0	3,0	9,0	4,0	12,0	5,0	15,0	4,0	12,0
Number of weak points		0		0		2		1		2		1	
Rank					III		V		IV		I		II
Decision					Pass		Fail		Fail		Pass		Pass

Figure 5.12: Kesselring Matrix - Second Iteration

The three highest scored concepts from the first Kesselring matrix were 'THEREX', 'HYDREX' and 'DEFEX'. These concepts were analysed further and discussed with stakeholders on the robustness of the solution. Based on the discussion and feedback, a few additional criteria like 'The setup should be robust during operation' and 'The system should be operational with less number of parts' were added and a second iteration of the Kesselring matrix was done. This is shown in figure 5.12.

With the added criteria, the highest scored concepts were 'THEREX', 'DEFEX' and 'HYDREX'. So, all the selected concepts were moved over to the concept selection phase, where the final selection was made.

Combining concepts

Improvements were made on the conceptual design of the selected parts. Though opportunities were explored to combine concepts throughout the concept evaluation process, only the concepts 'DEFEX' and 'TAPEX' were combined, by incorporating the tapered surfaces over a short length from 'TAPEX' into the 'DEFEX' concept.

5.3 Concept Selection

Some preliminary CAD Models for the shortlisted concepts, as shown in figures 5.13 to 5.15, were drafted and presented in the 'Concept gate' at Caterpillar propulsions. After carefully evaluating each concept, 'DEFEX' was selected. The main reason for the selection of 'DEFEX' was due to the simplicity of the mode of operation. 'THEREX' used nitrogen to achieve expansion/shrinkage of the pin, 'HYDREX' used hydraulic oil to achieve expansion, while 'DEFEX' just needed mechanical force to achieve expansion.

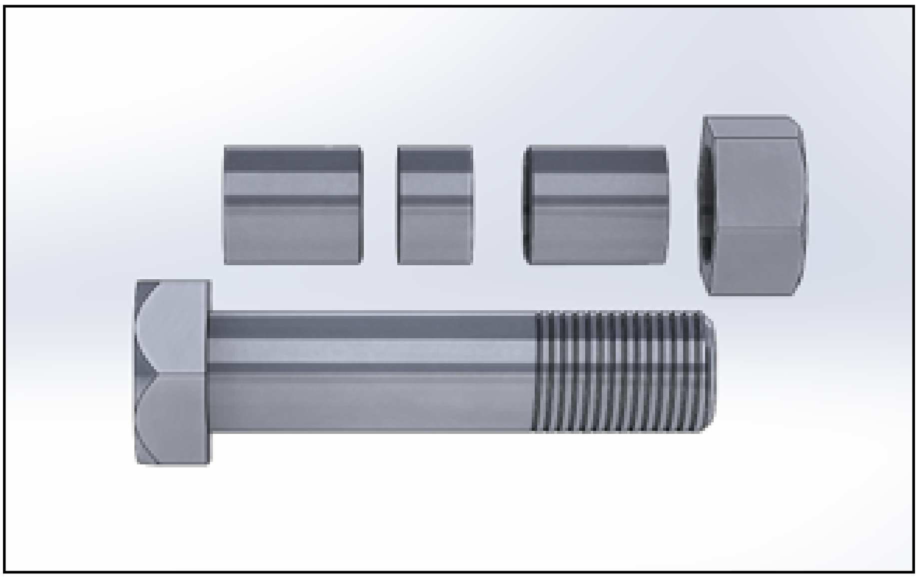

Figure 5.13: A preliminary CAD Model of 'DEFEX'

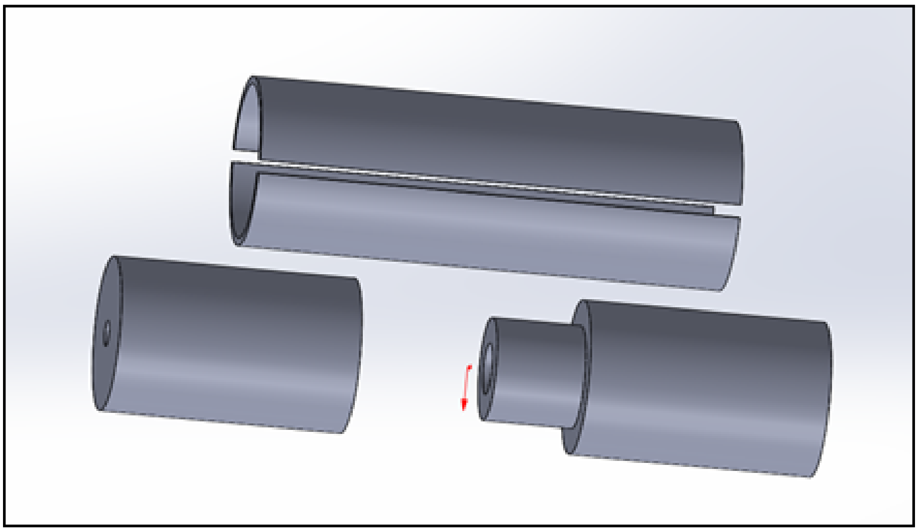

Figure 5.14: A preliminary CAD Model of 'THEREX'

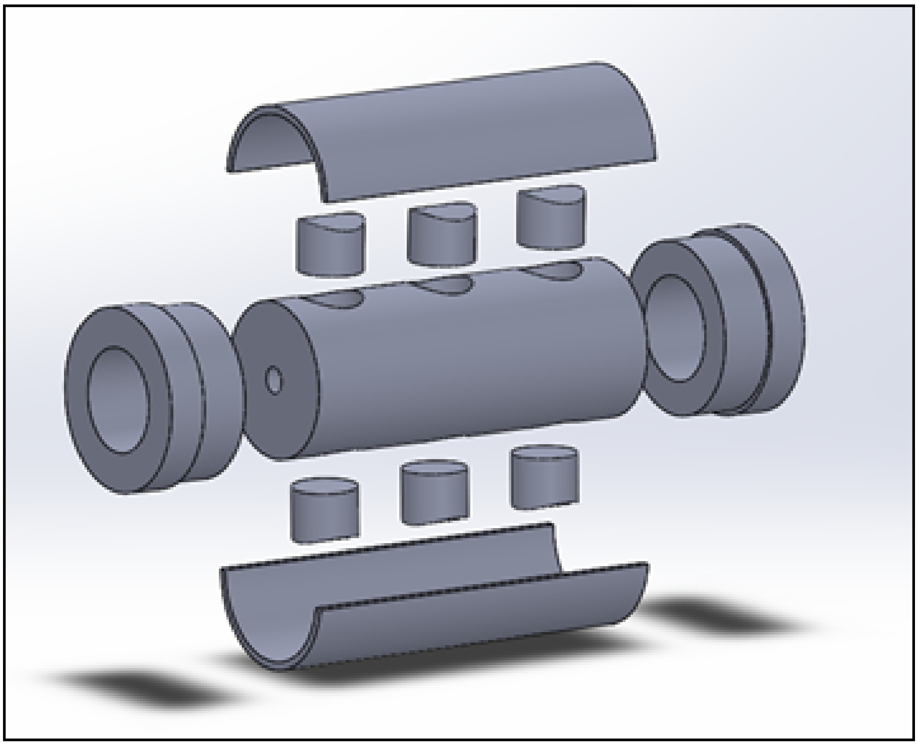

Figure 5.15: A preliminary CAD Model of 'HYDREX'

The economical factors like number of parts and complexity of manufacturing were also taken into account during the selection process.

6

Detailed Design and Prototyping

In this section, results from the modelling and analysis of the final concept were detailed. The individual systems and the judgements made for the design were also explained.

6.1 Detailed Design

The final concept was detailed with a brief description of the functions and dimensions of the individual components involved. The reasons behind the material selection of the components were also detailed.

6.1.1 Material Selection

Caterpillar Propulsions develops most of the components with material properties that comply with the European Standards. Material Selection for the developed concept was done keeping in mind the material properties of different materials as per the European classifications(for Standardization, 2006).
CES EduPack Material Selector software was primarily used for Material selection. The boundary conditions for the material properties were applied based on the regulatory requirements for the interference type of bolts. The limits for different material properties of the material were listed and accordingly a material chart was generated. Some of the material properties taken into consideration are:

- The tensile strength of the material can be a maximum of 1000 N/mm2(ABS, 2019).
- The material elongation or the percentage of engineering strain should be a minimum of 15%(de Mello, 2018).
- The cost of the material can be limited to a maximum of 10 SEK/kg.

A trade-off curve is plotted to find out the best material within the given constraints is given in 6.1. The final material selection was done based on the CES Material selector cross-referenced with European material standards for practical reasons of standardization(for Standardization, 2006).

The material selected was AISI 4140 Low Alloy steel. (EN Name: 42CrMo4).The selected material would be applicable for all the parts involved in the system since the design is made in such a way that all the parts withstand the forces acting on it as a single system.

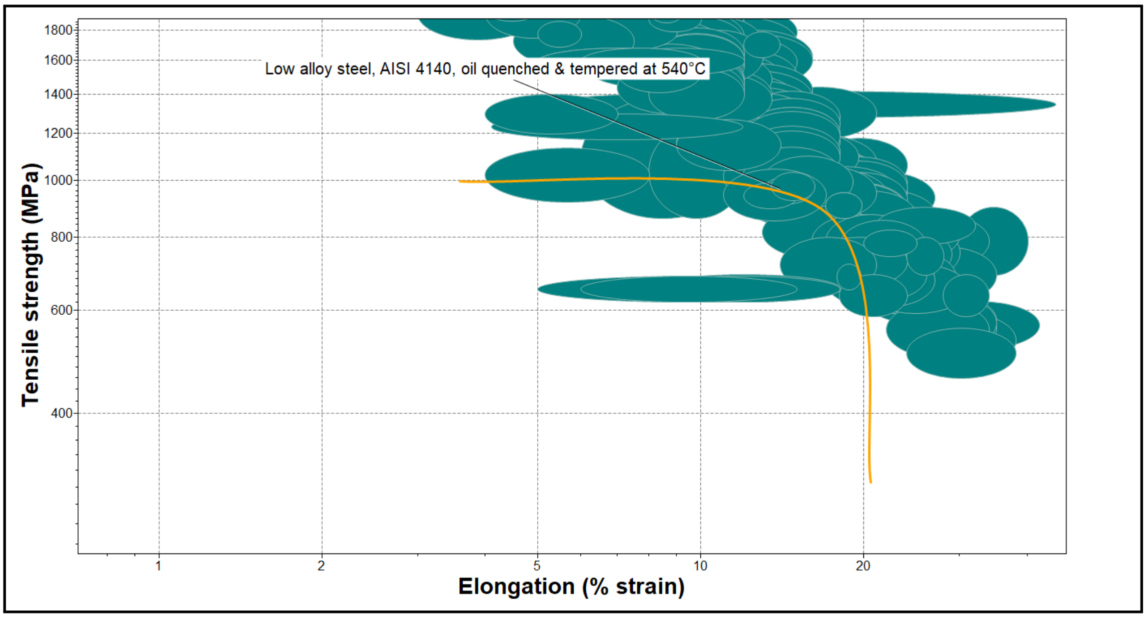

Figure 6.1: A trade-Off curve in the plot between the tesnsile strength and Elongation %

6.1.2 Product Assembly

The system consists of a bolt, a mid-sleeve, an end-sleeve and a nut. The design of the cross-sectional view of the assembly is shown in figure 6.2. The design from the preliminary CAD model to the final design had undergone a lot of changes. Most of the changes were primarily made to increase the robustness of the design and improve the manufacturability of the part inline with Caterpillar standards.

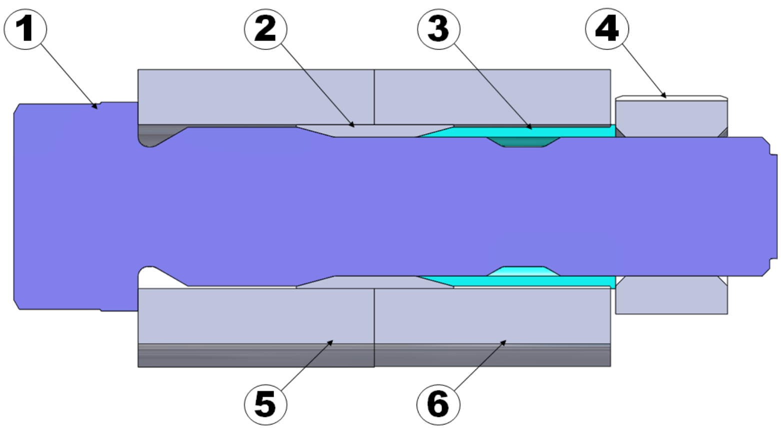

Figure 6.2: A 3D model of the DEFEX Assembly cut section

The system is set up in such a way that the bolt(1), mid sleeve(2) and end sleeve(3) can be assembled and then inserted into the flange hole(5). The nut(4) is the final component that will be assembled from the other side of the flange hole(6) over the bolt thread after the sleeves are placed. The centre of the mid sleeve is supposed to be in line with the contact surface of the two flange holes. The tapers in the mid sleeve are in contact with the bolt taper on one side and the end sleeve taper on the other side.

The 'DEFEX' concept acts on the principle of 'wedge', the end sleeve being the wedge that brings forth the expansion of the mid sleeve. When the nut is tightened, the compressive force gets transmitted through the end sleeve in an axial direction. Due to the angle of the contact between the end sleeve and mid sleeve, the end sleeve surface slips and moves into the mid sleeve in the axial direction, thereby expanding the mid sleeve in the radial direction. The dimensions of the components are changed accordingly to enable the wedge effect such that the system satisfies the regulatory requirements.

6.1.3 Design Setup

The design of 'interference bolts' should comply with the criteria on the minimum diameter of the system in contact with the flange holes. This criterion is governed by the classification societies to ensure the cross-sectional area of the system is sufficient enough to transmit the stresses experienced at the flange connections, thereby, ensuring the safe operation of ships.

$$diameter, d_b \geq 66\sqrt{\frac{(2T_{peak} - T_f)}{nD\sigma_y}}$$

$$\geq 66\sqrt{\tfrac{(2(1350000)-(728000)}{10*970*650}}$$

$$\geq 36.9mm$$

The diameter holds good for a solid pin. In our case, the diameter of the 'soli pin' can be correlated with the thickness of the mid sleeve, by comparing the cross-sectional area between the two, which should be equivalent.

$$\text{Area of the solid pin,} A_s = \text{Area of the midsleeve,} A_m$$

$$\text{Area of the solid pin,} A_s = \tfrac{\pi*(36.9)^2}{4} = 1068.8mm^2$$

Area of the midsleeve,A_m = Area of outer diameter,$Area_{OD}$ - Area of inner diameter,$Area_{ID}$

$$1068.8 = \frac{\pi * (66)^2}{4} - Area_{ID}$$

$$Area_{ID} = 2350.6mm^2$$

ie. Inner diameter = 54.7 mm

Therefore, the mid-sleeve should have a minimum thickness of 6mm at the centre. The mid-sleeve thickness for the final design of the developed concept was 7 mm, thus, satisfying the requirements.

Bolt

The design of a standard M48 bolt, manufactured at Caterpillar was used as a benchmark to not increase the in-house tooling requirements. The 3D model of the bolt is shown in figure 6.3. To ensure the right placement of the mid sleeve, the bolt taper dimensions are optimized to enable the mid sleeve to expand and provide an interference fit to the flange hole. The maximum diameter of the bolt for the 66 mm flange hole is 64 mm, to enable the mid sleeve to overlap over the bolt taper during expansion.

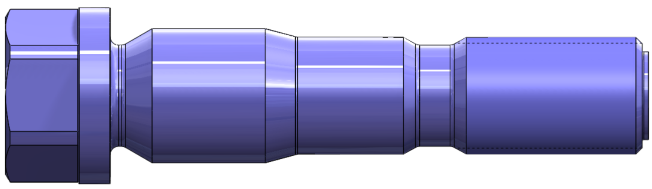

Figure 6.3: A 3D model of the bolt

Midsleeve

The mid sleeve is the actual expanding part, the outer surface of which would come in contact with the flange holes and transmit the varying stresses due to the torque acting on the shaft line to the bolt setup. The 3D model of mid-sleeve is shown in figure 6.4. The length of the mid sleeve is 55 mm. The part is tapered inwards on both ends of the mid sleeve so that the only contact the mid-sleeve has with the system after tightening would be on the tapers. To avoid stick-slip motion and enable sliding between the surfaces, the surface finish at the taper is manufactured with a surface roughness of 1.2 Ra.

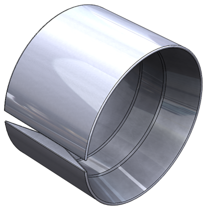

Figure 6.4: A 3D Model of the midsleeve

The mid sleeve has a slit in the longitudinal direction to enable the expansion of mid sleeve within the elastic range of the material and also to ensure the mid sleeve expands first before the bolt starts to yield.

Endsleeve

The 3D model of the end sleeve is shown in figure 6.5. The end sleeve is flat on one end and tapered on the other end. The flat end is in contact with the nut, which transfers force from the nut.

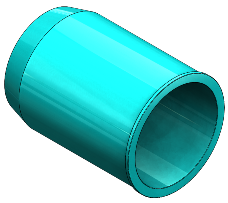

Figure 6.5: A 3D Model of the endsleeve

The axial force that acts on the tapered end of the end sleeve slides inwards towards the mid sleeve, making the mid sleeve to expand. To enable sliding of the surfaces, the surface finish at the taper is manufactured with a surface roughness of 1.2 Ra.

Nut

The nut is a standard M48 nut from the repository that already adheres to Caterpillar standards. The 3D model of the bolt is shown in figure 6.6. The nut face would primarily be in contact with the end-sleeve and not the flange surface.

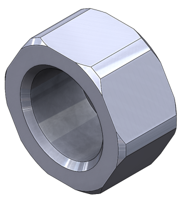

Figure 6.6: A 3D Model of the nut

6.2 Virtual Simulation

The simulations were done using ANSYS analysis workbench software to achieve the test condition. The dimensions and features of the components were constantly finetuned to get the best results on Static Analysis and virtual prototyping conditions.

6.2.1 Static Analysis

The setup works on the principle of 'wedge effect' between the sleeves and to realise this, a force has to be applied longitudinally. The force has to be applied by a torque wrench over the nut, which is run over the bolt thread. In an ideal case, The mid sleeve expansion has to happen first and the bolt deformation should happen next. To ensure this phenomenon happens, the system was checked in ANSYS analysis software for:

- The total deformation acting on the system.
- The surface pressure acting on the outer surface of the mid sleeve.

The total deformation acting on the system

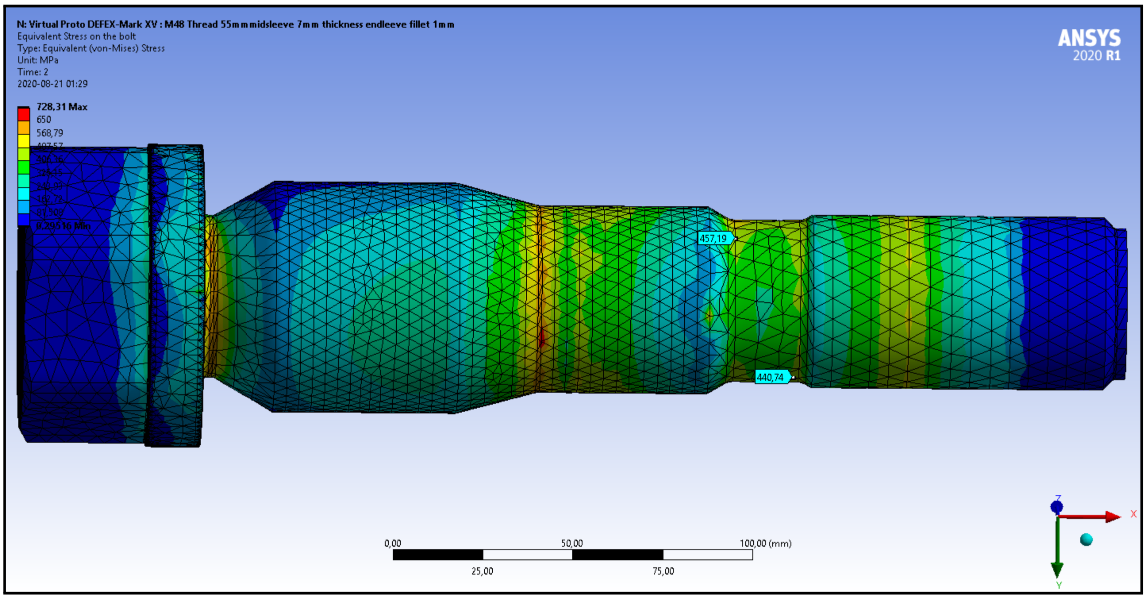

Figure 6.7: The result of the equivalent stress experienced by the bolt under bolt-pretension

The deformation of the system should correspond to 70% of the yield strength at the minimum cross-section of the bolt when tightened by the nut, to retain the material properties of the bolt. A bolt pretension load of 723.3kN was applied at the minimum cross-section of the bolt, that corresponded to the diameter of 45 mm.

The results of equivalent stresses, as shown in figure 6.7, were probed at the minimum cross-section of the bolt, to ensure the bolt experienced around 70% yield at that area.

The surface pressure acting on the outer surface of the mid sleeve

The surface pressure on the outer surface of the mid sleeve was checked to ensure if the system had provided an interference fit to the flange holes. The result of the analysis is shown in figure 6.8. The surface pressure acting on the centre of mid sleeve indicates that the mid sleeve has expanded and there is an interference fit between the setup and the flange hole.

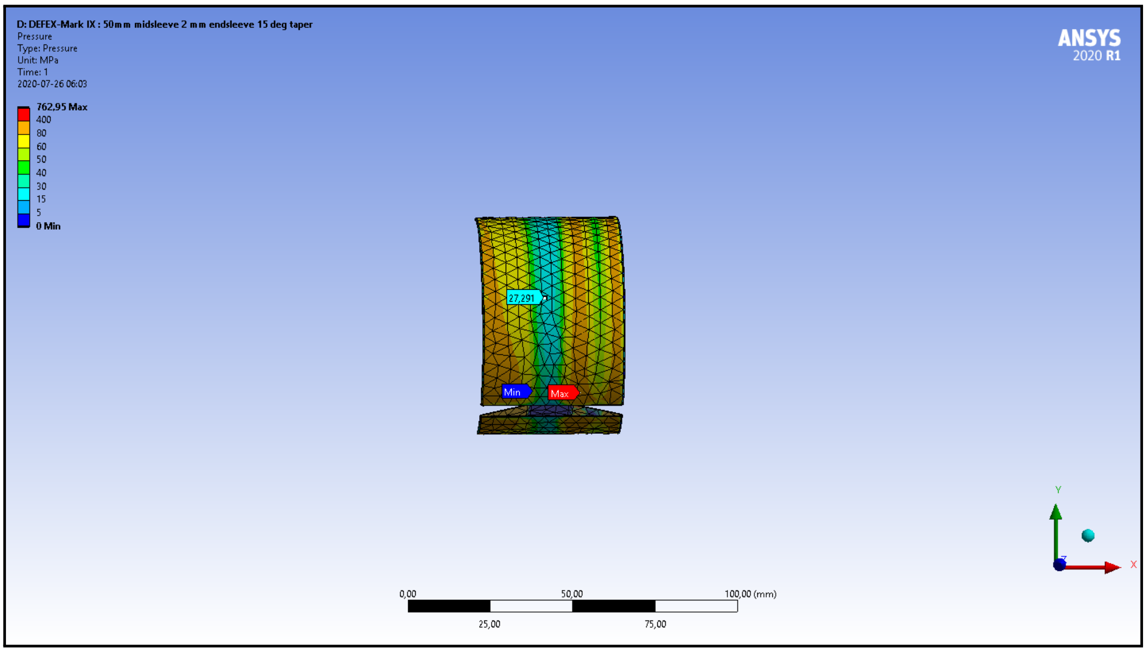

Figure 6.8: The result of the Surface pressure acting on the outer surface of the mid sleeve

After conducting several iterations by varying the dimension of the bolt, the mid sleeve, the end sleeve and the nut, as shown in the figure 6.10, the minimum surface pressure of 28 MPa was achieved for ensuring the interference fit.

6.2.2 Virtual Prototyping

The ability of the system to retain its properties even after the application of loads that simulate worst operating conditions, determines the success of the project as a whole. The Virtual prototyping was done to simulate the varying loads that would act on the system and check for the robustness of the system.

Virtual prototyping was done by applying a load of 528.6kN in tangential direction on either end of the flange surfaces. The maximum stresses acting on the system was analysed at loaded and unloaded conditions for various dimensions.

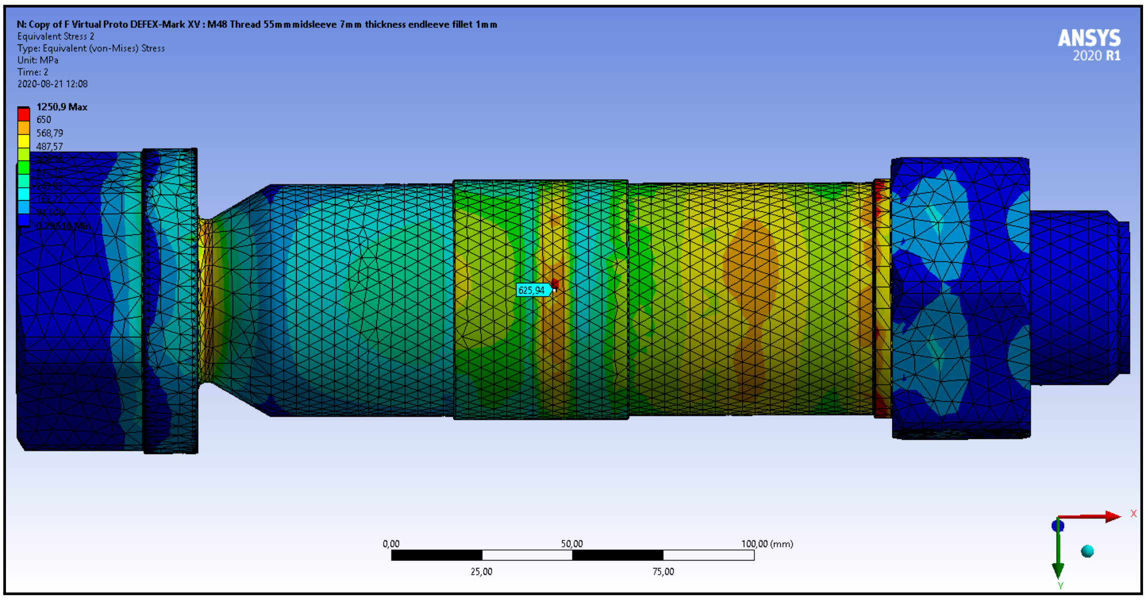

Figure 6.9: The result on the equivalent stress acting on the system under load

The dimensions of the components were refined until the system achieved all the deliverables of Static analysis and virtual prototyping conditions. The setup and feedback from the various analysis are presented in 6.10. The various iterations for the dimensions were tabulated and presented as shown in appendix C.1 and C.2. The final dimensions of the developed concept achieved 70% yield during bolt pretension, a minimum surface pressure of 28 MPa and the shear stresses under load was well within the limit of 390MPa. The equivalent stresses acting on the system under load is shown in figure 6.9.

6.3 Refining Technical Specifications

Phase 2 QFD, as shown in figure 6.11, lists out all the design requirements and the significance of their relationship with every dimension of the components involved. The struction of the Phase 2 QFD is detailed in appendix C.3

The highly ranked dimensions were surface roughness at the tapers and the taper angle of the taper involved. During the design iterations, the taper angle played a major factor in the success of the project. Phase 2 QFD ensured that all the design requirements were successfully converted at the design level.

S. no	Model	Static Analysis	Virtual Prototyping	Simulation setup	Feedback from simulation
1	DEFEX - MARK 1	NA	NA	Design study was only done	NA
2	DEFEX - MARK 2	NA	NA	Design study was only done	NA
3	DEFEX - MARK 3	NA	NA	Design study was only done	NA
4	DEFEX - MARK 4	NA	NA	Design study was only done	NA
5	DEFEX - MARK 5	Fail	NA	42CrMo4 Material was used for the system. A bolt pretension by pre-adjustment was used	Localised stresses were experienced at the sides of the midsleeve but not at the center.
6	DEFEX - MARK 6	Fail	NA	Remote displacement was added at one of the edges to prevent rotation of the flange model when tightening.	The bolt pretension was not propagated to the outer surface of the sleeve.
7	DEFEX - MARK 7	Fail	NA	Frictional contacts with a friction co-efficient of 0,15. Weak springs were also added to provide damping to the system.	The 70% yield achieved. Surface pressure values were maximum, but at the center of the midsleeve.
8	DEFEX - MARK 8	Fail	NA	Same setup was replicated with a bolt pretension by load of 723kN	Surface pressure at the middle of the midsleeve still remained 0.
9	DEFEX - MARK 9	Pass	Fail	A tangent force of 528 kN was applied on the surface of the flanges to simulate peak torque conditions.	The virtual prototyping condition were not satisfied with the stresses exceeding the yield.
10	DEFEX - MARK 10	Fail	Fail	Setup conditions are freezed as in the previous iterations.	The required surface pressure at the center of the midsleeve was not satisfied.
11	DEFEX - MARK 11	Pass	Fail	A step-by-step loading of the system for static analysis and prototyping were sequenced in the same analysis	The prototyping results were approaching requirements, except some extraordinary values at unrealistic areas of sleeve.
12	DEFEX - MARK 12	Fail	Pass	The material selection was changed from linear to bi-linear material for realistic results.	The required surface pressure at the center of the midsleeve was not satisfied.
13	DEFEX - MARK 13	Fail	Pass	Tangent forces was replaced by tangential displacement of 5mm and force reaction that matches 528kN was identified	The required surface pressure at the center of the midsleeve was not satisfied.
14	DEFEX - MARK 14	Pass	Fail	The tangential displacement was reduced to 4.5mm to achieve the force reaction of 528kN for the bi-linear materials.	The prototyping results were satisfactory, except for some singularity at the ends of the endsleeve
15	DEFEX - MARK 15	Pass	Pass	Same conditions were retained as in the previous iteration.	All the static analysis and virtual prototyping conditions were satisfied.

Figure 6.10: Results and feedback from the Static Analysis and Virtual Prototyping

System -->		Midsleeve						Bolt						Endsleeve						Nut		
Product Requirements	<--Requirement Importance	Outer Diameter of the midsleeve	Thickness of the midsleeve	Taper angle at the ends of the midsleeve	Length of the midsleeve	Surface roughness at the outer surface of the midsleeve	Surface roughness at the taper of the midsleeve	Minimum diameter of the bolt	Metric thread of the bolt	Taper angle of the bolt in contact with the midsleeve	Surface roughness at the taper of the bolt	Maximum diameter of the bolt	Length of the bolt	Outer Diameter of the endsleeve	Thickness of the endsleeve	Taper angle at one end of the endsleeve	Length of the endsleeve	Surface roughness at the outer surface of the endsleeve	Surface roughness at the taper of the endsleeve	Minimum diameter of the nut	Metric thread of the nut	Length of the nut
Expanded Diameter of the setup	5	9		3		3				3		3		3		3					3	
Angle of Taper of the expander	5			9						9						9						
Surface Roughness of the sleeve	4					3	9				9							3	9		1	
Surface pressure between surfaces	5			9	9	3	3	3		9	3		3			9	9		3		3	
Clearance diameter of setup	4	9				3						9		9						1		
Surface pressure to be maintained	1	3	3	3	9	3						3					3		3		3	3
Total cost of manufacturing	5	9		9	9		9	9		9	9	9	9	9		9	9		9		1	3
Part count	2				3								3				3					1
Time to assembly	1	9	3				9				9				3				9		1	
Bolt circle diameter	1	1																				
Number of special operations	1						3														9	
Mode of expansion	3			9						9						9					1	
Number of sides involved in assembly	1	3										3		3						3		
Number of special charecteristics	1						3				3								3		3	
Time taken for disassembly	1	9	3				9				9				3				9			1
Number of Special tools for assembly	1						1			1	1					1			1		3	1
Clear feedback on assembly/disassembly	1								3												3	
Requirement Importance		151	9	180	105	57	121	60	3	178	118	102	66	99	6	178	99	12	121	7	64	22
Target		66 mm	7 mm	15 deg	55 mm	6.3 Ra	1.2 Ra	45 mm	M48	15 deg	1.2 Ra	64 mm	307 mm	66 mm	6 mm	15 deg	75.5 mm	6.3 Ra	1.2 Ra	48 mm	M48	45 mm

Figure 6.11: Phase 2 Quality Function Deployment(QFD2)

7 Results

The thesis set out to design and develop a flange coupling connection that transmit primarily the shear forces acting on the flange joint. Though the existing design is operational, the ease of manufacturability of the existing design was a case of concern. From the interviews, it was clear that the root cause of the issue was the difficulty in manufacturing long 'tapered surfaces' of the tapered shank bolt and a matching tapered sleeve that maintains a surface contact. In other words, maintaining a consistent taper on the inner surface of the sleeve that is 180 mm long increases the complexity of the manufacturing process. The regulations on expansion dowels also did not specify the need for such a taper, although the 'taper' was an industry-standard in marine propulsions for expansion devices. Many concepts were ideated and evaluated based on several customer needs criteria and three concepts were presented. Based on expert feedback and combining concepts, one final concept was finalized.

The main principle of the developed product also utilises tapered surfaces, but it is only for a short length. This increases the ease of manufacturing by reducing the need for special cutting tools and improves the quality even when manufactured in a simple lathe machine. The developed product also does not need an external source, like hydraulic oil to enable expansion. The need for the quality gate can be eliminated since the developed product does not need complex gauges to check for quality. Design for Manufacturing and Assembly principles were followed for designing the product, like, Instead of using two end sleeves, one of the end sleeves was integrated into the design of the bolt, reducing the number of parts in the assembly. The existing Caterpillar designs were also referenced to ensure no additional tooling would be necessary for the developed product.

Attempts were made to answer the research questions that were earlier considered at the start of the thesis

- Lot of opportunities does exist for designing a bolt that would improve the power train resilience and at the same time, keeping the manufacturing cost low. Towards the end of the project, three possible solutions existed for realising the intent for which the project set out for, indicating the variety of solutions available. The manufacturing cost of the developed product was not above the manufacturing cost of the existing solution, since all the components use standard tooling and manufacturing techniques. There is also an additional scope for cost reduction by reducing the bolt head diameter of the developed solution as the stresses experienced by the threads are lesser than intended.

- Alternate type of interference fit that does not use lubricant for mounting and dismounting does exist. The final concept was developed keeping that in mind. Standard lubricant like grease can be used at the tapered surfaces for assembly. Although, this can only be confirmed after physical prototyping results.
- After conducting many design iterations and system validations, the final product does withstand the stresses from peak transient torque experienced by the system and also fulfils all the criteria from a regulatory standpoint.

Commercial Assessment

The commercial assessment was performed to study the feasibility and sustainability of the final product to its competition based on manufacturing and number of applications, etc. This allows the company to forecast demand and plan for downstream logistics. It also helps to estimate cash flows which enable the overall cost roll-up. The product consists of 4 parts: a bolt, a midsleeve, an endsleeve and a nut. The estimated price for all parts are presented in Table 7.1. The price was arrived based on referencing similar parts within Caterpillar and hence the price includes the certification cost, manufacturing cost,material cost and designing cost as well.

Sr no	Component	Sourcing	Manufacturing Cost (SEK)
1	M56 Bolt	In-house	1261
2	Midsleeve	In-house	450
3	Endsleeve	In-house	350
4	M56 Nut	Outsource	111
Total			2172

Table 7.1: Estimated Product manufacturing cost

The manufacturing cost of 2172 SEK was slightly more than the target value of the design requirement ie. 2000 SEK, but still less than the existing manufacturing cost for the expansion dowel, which was 2236 SEK. The estimated price can still be reduced if Caterpillar propulsion changes the sourcing strategy and make business to business deals with different suppliers. Another way of reducing cost is if the demand for the product increases.

Fulfilment of target deliverables

A quick review of the target deliverables and their fulfilment can be effective in determining the success of the project. The table 7.2 present an outline of the metrics that the product has been able to fulfil,✓, could not fulfil,✗. For some metrics, there wasn't sufficient time or resources to be able to evaluate the product's performance. These metrics have been marked with a (?) symbol.

Metric no.	Metric	Unit	Target value	Fulfilment(✓/✗/?)
1	Expanded Diameter of the bolt	mm	66.06	✓
2	Angle of Taper of the sleeve	deg	15	✓
3	Surface Roughness of the sleeve	Ra	6.3	✓
4	Surface pressure between surfaces	MPa	28	✓
5	Clearance diameter of bolt before assembly	mm	66	✓
6	Total cost of manufacturing	SEK	$\leq$2000	✗
7	Part count	Nr	≤ 5	✓
8	Time to assembly	mins	≤ 10	?
9	Bolt circle diameter	mm	970 mm	✓
10	Number of special operations	Nr	0	?
11	Mode of expansion	subj.	Mechanical	✓
12	Number of sides involved in assembly	Nr	1	✓
13	Number of special charecteristics	Nr	0	?
14	Time taken for disassembly	mins	≤ 5	?
15	Number of Special tools for assembly	Nr	0	✓
16	Clear feedback on assembly/disassembly	subj.	NA	?

Table 7.2: Fulfilment of the metrics and the target values

All the expected target deliverables are met except for one. The cost of manufacturing of the developed concept was slightly above the target value but still managed to be less than the cost of the existing solution. The cost can be controlled within the target value by optimizing the bolt head diameter. All the other critical target values were fulfilled, indicating the success of the project. However, some metrics like Time to assembly/disassembly, feedback on assembly/disassembly and Number of special characteristics/operations could not be tested, as physical prototyping and further development, based on the feedback, was not possible.

From the design study and virtual prototyping, it is clear that the developed product has the potential to effectively replace the expansion dowels. The final concept has an advantage over the existing product when it boils down to assembly, manufacturability and cost. However, further development is needed, in terms of physical prototyping, to strengthen the business case and to fully realise the solution as a strong alternative to the existing product.

8

Discussion

Though the developed final product seems to have an advantage over the existing product, the new concept does not have a benchmark, even in other industries, in terms of 'robustness of solution'. The resilience of the developed solution was also not checked. Since the physical prototyping was not carried out, the results from the virtual prototyping should only be taken with a pinch of salt.

Compared to the final concept, another concept that scored higher in concept scoring phase was 'THEREX'. The 'THEREX' concept used the properties of the material to expand/shrink based on temperature variations. This is an established form of interference fit that is extensively used in a lot of interference fit applications. Caterpillar also tried this form of interference pins in the earlier designs, but this concept was discarded due to their expansion in the longitudinal direction and their inability to be disassembled without damage. Factoring all these failure modes, 'THEREX' was conceptualised. The expansion in the longitudinal direction was avoided by introducing a set of split sleeves outside the cylindrical pin. The disassembly was enabled by introducing a hollow chamber inside the cylindrical pin, where Nitrogen gas can be pumped inside the chamber to shrink the pins at the time of disassembly. The pin was split in half to enable easier manufacturing and assembly. The only downside to using this concept was that an external source, like nitrogen gas, would be needed for expansion/shrinkage of the setup. This means that the availability of nitrogen had to be ensured onsite for assembling the part. The DEFEX concept does not have any such dependence on external sources and that was a reason for it being chosen as the final concept.

The costs of the competitor's products were much higher than the cost of the developed solution. The competition has a lot of highly complex systems in place to achieve interference fit, which is also achieved by the developed solution with a simpler framework. One of the reasons for the high cost of the competition may be because the competitor's products may have been used for multiple applications, whereas the developed product is solely used for the propulsion flange joints. From the interviews, it was also understood that the competitors use special tools for manufacturing or might spend more time on ensuring the quality of the component. Caterpillar propulsion can also follow the same methods for the existing design as the competition, but it would then increase the part cost eventually.

Also, during the thesis, it was found that the number of patents for expansion devices in the propulsion industry were very few. Most of the patents were relating to the construction industry, where disassembly was not a concern. So, patenting the product can give Caterpillar propulsion an edge over competitors to improve on this concept for other applications as well in the future.

Business Case

The material and parts involved were similar to parts that are manufactured in-house. So, the new tooling cost would be greatly reduced. Since all the parts are symmetrical and the number of special operations is only at the taper over a short length, the ease of manufacturability is improved and the manufacturing time is greatly reduced compared to the existing product. The assembly/disassembly time would also be expected to improve, since, a mechanical force is used for expansion, unlike using external devices like a hydraulic pump for assembly/disassembly for the existing design.

An example calculation was performed using assumed values. Assuming that it would cost 15,000 SEK, considering the level of complexity, to get the product ready for production. Of this 15,000 SEK, 6000 SEK can be assumed to be the salaries for the project group, which can consist of 2 senior employees working for one month to finish the product. The remaining budget will be allocated to building a final prototype, getting the production ready after completion of necessary certifications. Secondary costs such as CAD, Analysis, Programming, Project planning software license costs would also be included in this. Also, there is zero additional investment in tooling and the average time savings per day due to improved manufacturing and assembly is 300 man minutes. Considering a base salary of 170 SEK per hour, the cost savings would be 850 SEK per part and 8500 SEK per order(considering 10 parts are used per order) for the company. Considering the product cost to be 2172 SEK, the theoretical break-even for the product would be 2 customer orders. This does not take into account the cost savings from the field failures that could be avoided when the developed solution becomes operational.

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A

Appendix 1

A.1 Interview Guide

The interviews should be face-to-face and it is preferable to take place at the interviewee's location. The questionnaire is divided into two parts: generic and specific questions. The generic questions would be repeated for all the interviewees and specific questions are framed in such a way that they have a common theme.

A.1.1 Generic questions

1. **Introduce the project**
2. **Introduce what the interview will be about.**
   - **Interview will be centered around the flange connection i.e more specifically the expansion dowel used for 'Ice class' ships that have diesel engine driven marine propulsion systems.**
   - **Semi-Structured interview. So, feel free to share all data that comes to your mind**
3. **Tell me a bit about yourself?**
   (We need to find out the following)
   (a) **What is your overall experience?For how long have you been working at this company?**
   (b) **For how long have they worked in this role?**
4. **Nature of your job at Caterpillar? How often you interact with these type of flange connections in a month?**
5. **How involved are you in the development process?** (if not answered in the previous question)

A.1.2 Specific questions for Design

1. **Tell me the circumstances that led to the development of expansion bolts**
   (a) **What type of bolts were used earlier ?**
   (b) **What inspired you to conceptualize this type of an hydraulic mechanism ?**
2. **In your opinion, how different is the expansion dowels compared to other bolt types that are used in Cat marine couplings?**

   (a) **What were the other concepts that you considered?**
3. **Why not choose a third party shear bolt/expansion dowel?**
4. **Were there enough possibilities for choice of material for the bolt ?**
5. **What are the similar type of customizations that were done in Caterpillar**
6. **What do you think can be improved in the design of expansion dowels**
   (a) **Is the design limited by the size of the flange/pretensioned bolts**
7. **In your opinion, How hard do you think is it to assemble the expansion dowel?**
8. **How important is the contamination level of the hydraulic oil used for lubrication ?**
   (a) **What is good?**
   (b) **What is bad?**
   (c) **If possible, what would you have changed/added?**
9. **What are your thoughts on other shrink fit applications that involve other methods like super-cooled bolts, interference pins, etc.?**

A.1.3 Production specific questions

1. **Can you describe the process of flange assembly in detail. Which stage of the process is it done in ?**
   (a) **Do you follow any torquing procedure/sequence while tightening bolts in the flange**
   (b) **DO you use any special procedures for assembling the bolts, during special circumstances, other than what is mentioned in the drawing?**
2. **In your opinion, how different is the expansion dowels compared to other bolt types that are used in Cat marine couplings?**
   (a) **What are the advantages of expansion dowels?**
   (b) **What are the downside to using expansion dowels?**
   (c) **What are most common trivial issues you faced with regards to expansion dowels?**
3. **What do you think can be improved in the design of expansion dowels**
4. **In your opinion, How hard do you think is it to assemble the expansion dowel ?**
   (a) **Does it depend on size of dowels used ?**
5. **What do think about competitor's product like SKF Supergrip, Nord-lock HyFit couplings etc**
6. **In your opinion, How hard do you think is it to assemble the expansion dowel?**
7. **What are your thoughts on other shrink fit applications that involve other methods like super-cooled bolts, interference pins, etc.?**

A.1.4 Product Service Specific questions

1. **How long does it take to service the expansion dowels?)**
   (a) **Does the level of servicability vary between different ships**
   (b) **At times of service, how hard is it to get the necessary tools for servicing? For eg. Getting hydraulic oil source for removing the expansion dowel connection**
2. **In your opinion, how different is the expansion dowels compared to other bolt types that are used in Cat marine couplings?**
   (a) **What are the advantages of expansion dowels?**
   (b) **What are the downside to using expansion dowels?**
   (c) **What are most common trivial issues faced by customers with regards to expansion dowels?**
3. **How likely is a flange connection prone to failure?**
4. **What do think about competitor's product like SKF Supergrip, Nord-lock HyFit couplings etc**
   (a) **How do you convince customers to choose CAT expansion dowels over third party flange connections.**
5. **In your opinion, How hard do you think is it to assemble the expansion dowel?**
6. **What are your thoughts on other shrink fit applications that involve other methods like super-cooled bolts, interference pins, etc.?**
7. **How important is the contamination level of the hydraulic oil used for lubrication?**
8. **What do you think can be improved with respect to design of expansion dowels?**

B

Appendix 2

B.1 Phase 1 Quality Function Deployment

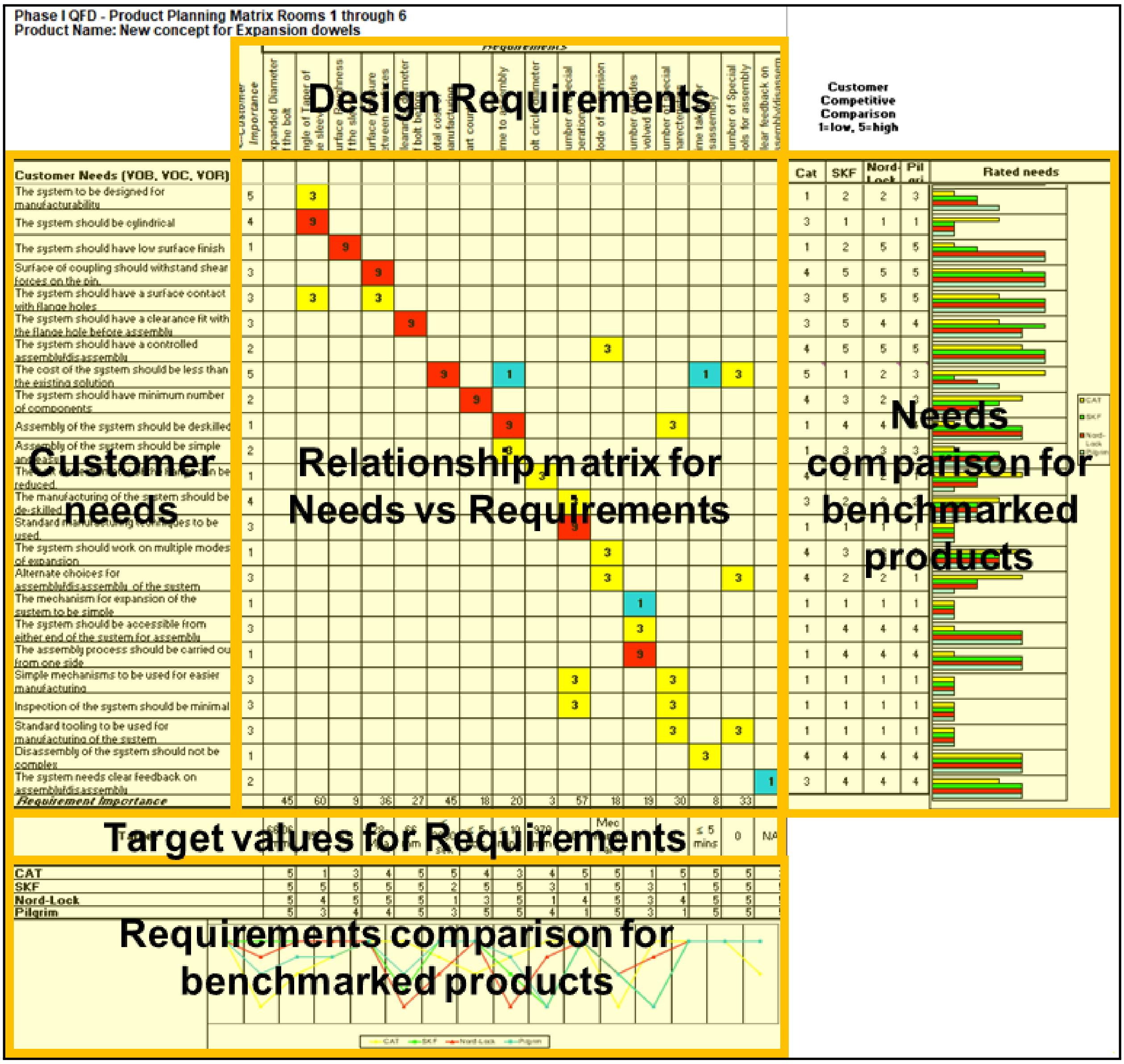

Figure B.1: Structure of the Phase 1 Quality Function Deployment(QFD1)

B.1.1 Relationship matrix for customer needs Vs design requirements

		Requirements															
	<--Customer Importar.	Expanded Diameter of the bolt	Angle of Taper of the sleeve	Surface Roughness of the sleeve	Surface pressure between surfaces	Clearance diameter of bolt before assembly	Total cost of manufacturing	Part count	Time to assembly	Bolt circle diameter	Number of special operations	Mode of expansion	Number of sides involved in assembly	Number of special charecteristics	Time taken for disassembly	Number of Special tools for assembly	Clear feedback on assembly/disassembly
Customer Needs (VOB, VOC, VOR)																	
Interference fit type of bolt to be used	5	9															
The system to be designed for manufacturability	5		3														
The system should be cylindrical	4		9														
The system should have low surface finish	1			9													
Surface of coupling should withstand shear forces on the pin.	3				9												
The system should have a surface contact with flange holes	3		3		3												
The system should have a clearance fit with the flange hole before assembly	3					9											
The system should have a controlled assembly/disassembly	2											3					
The cost of the system should be less than the existing solution	5						9		1						1	3	
The system should have minimum number of components	2							9									
Assembly of the system should be deskilled	1								9					3			
Assembly of the system should be simple and easy	2								3								
The bolt circle diameter of the flange can be reduced.	1									3							
The manufacturing of the system should be de-skilled	4										3						
Standard manufacturing techniques to be used.	3										9						
The system should work on multiple modes of expansion	1											3					
Alternate choices for assembly/disassembly of the system	3											3				3	
The mechanism for expansion of the system to be simple	1												1				
The system should be accessible from either end of the system for assembly	3												3				
The assembly process should be carried out from one side	1												9				
Simple mechanisms to be used for easier manufacturing	3										3			3			
Inspection of the system should be minimal	3										3			3			
Standard tooling to be used for manufacturing of the system	3													3		3	
Disassembly of the system should not be complex	1														3		
The system needs clear feedback on assembly/disassembly	2																1
Requirement Importance		45	60	9	36	27	45	18	20	3	57	18	19	30	8	33	2

Figure B.2: Relationship matrix of QFD1

B.1.2 Correlation matrix between design requirements

Requirement Correlation Matrix (Room 7)
Product Name: New concept for expansion dowels

Requirements	***<---Direction of Improvement***	Expanded Diameter of the bolt	Angle of Taper of the sleeve	Surface Roughness of the sleeve	Surface pressure between surfaces	Clearance diameter of bolt before assembly	Total cost of manufacturing	Part count	Time to assembly	Bolt circle diameter	Number of special operations	Mode of expansion	Number of sides involved in assembly	Number of special charecteristics	Time taken for disassembly	Number of Special tools for assembly	Clear feedback on assembly/disassembly
Direction of Improvement--->		▲	▼	▲	o	o	▼	▼	▼	o	▼	▲	▼	▼	▼	▼	▲
Expanded Diameter of the bolt	▲		+	−	++	++	−	++	−	+	+	+	−	+	−	+	++
Angle of Taper of the sleeve	▼			++	+	+	++	++	++	−	++	++	++	++	++	++	++
Surface Roughness of the sleeve	▲				−	−	++	++	+	−	++	++	−	++	+	−	+
Surface pressure between surfaces	o					+	−	+	+	+		++	−		+	−	+
Clearance diameter of bolt before assembly	o						+	+	++	+	+	+	+	+	+	++	+
Total cost of manufacturing	o							++	++	+	−	++	−	−	++	−	−
Part count	▼								++	+	−	+	+	+	+	−	−
Time to assembly	▼									+	−	++	+	−	+	−	−
Bolt circle diameter	o										+	+	+	+	−	+	+
Number of special operations	▼											++	++	++	−	++	+
Mode of expansion	▲												+	+	++	++	+
Number of sides involved in assembly	▼													−	+	+	+
Number of special charecteristics	▼														−	++	+
Time taken for disassembly	▼															++	+
Number of Special tools for assembly	▼																+
Clear feedback on assembly/disassembly	▲																

Legend:
- ▲ Direction of Improvement Large the Better
- ▼ Direction of Improvement Smaller the Better
- o Direction of Improvement Nominal the Best
- ++ Strong positive Correlation
- + Positive Correlation
- − Negative Correlation
- ≡ Strong Negative Correlation

Figure B.3: Correlation between design requirements

B.1.3 Needs comparison for benchmarked products

Customer Needs (VOB, VOC, VOR)	Imp.	Cat	SKF	Nord-Lock	Pilgrim	Rated needs
Interference fit type of bolt to be used	5	5	5	5	5	
The system to be designed for manufacturability	5	1	2	2	3	
The system should be cylindrical	4	3	1	1	1	
The system should have low surface finish	1	1	2	5	5	
Surface of coupling should withstand shear forces on the pin.	3	4	5	5	5	
The system should have a surface contact with flange holes	3	3	5	5	5	
The system should have a clearance fit with the flange hole	3	3	5	4	4	
The system should have a controlled assembly/disassembly	2	4	5	5	5	
The cost of the system should be less than the existing solution	5	5	1	2	3	
The system should have minimum number of components	2	4	3	2	3	
Assembly of the system should be deskilled	1	1	4	4	4	
Assembly of the system should be simple and easy	2	1	3	3	3	
The bolt circle diameter of the flange can be reduced.	1	4	2	2	1	
The manufacturing of the system should be de-skilled	4	3	2	2	2	
Standard manufacturing techniques to be used.	3	1	1	1	1	
The system should work on multiple modes of expansion	1	4	3	3	3	
Alternate choices for assembly/disassembly of the	3	4	2	2	1	
The mechanism for expansion of the system to be simple	1	1	1	1	1	
The system should be accessible from either end of the system for	3	1	4	4	4	
The assembly process should be carried out from one side	1	1	4	4	4	
Simple mechanisms to be used for easier manufacturing	3	1	1	1	1	
Inspection of the system should be minimal	3	1	1	1	1	
Standard tooling to be used for manufacturing of the system	3	1	1	1	1	
Disassembly of the system should not be complex	1	4	4	4	4	
The system needs clear feedback on assembly/disassembly	2	3	4	4	4	

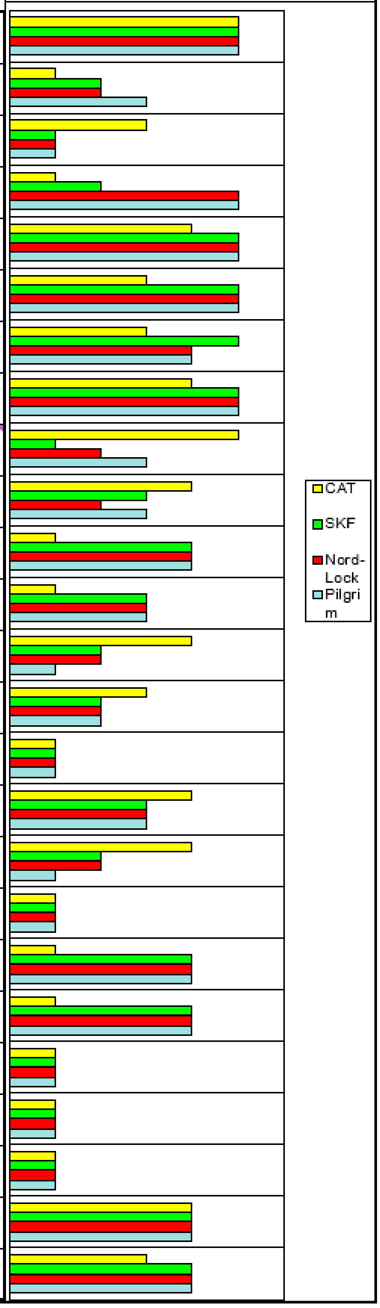

Figure B.4: Full list of needs comparison for individual benchmarked products

C

Appendix 3

C.1 Design detailing for the developed concept

S.no	Model	Reason for the dimension change
1	DEFEX - MARK 1	Midsleeve provides an interference fit of 50 mm on either side of the flanges, the same working length as an expansion dowel.
2	DEFEX - MARK 2	The thickness of the flanges are also factored in the overall length of the design.
3	DEFEX - MARK 3	Additional 5mm length on the endsleeve to enable the forces from the nut gets transferred to the midsleeve.
4	DEFEX - MARK 4	The midsleeve length is reduced from 100 to 70 mm, as the working length of the system is approximated to the diameter of the hole.
5	DEFEX - MARK 5	To avoid bending of the sleeve, the diameter of the bolt was matched with the inner diameter of the midsleeve a slide fit.
6	DEFEX - MARK 6	The excess length of the endsleeve was not needed since the expansion would have no effect on the system.
7	DEFEX - MARK 7	The midsleeve length was reduced to a minimum to check the effect of surface pressure
8	DEFEX - MARK 8	The lowest possible working area cannot be less than 25 mm on each side for the 95 mm thick flange.
9	DEFEX - MARK 9	The taper angle was reduced to enable better torque transmission and enable the required expansion.
10	DEFEX - MARK 10	With the reduced taper angle all the previous midsleeve length were checked
11	DEFEX - MARK 11	The metric thread was reduced to accomodate the increased thickness of the midsleeve. The thickness of midsleeve was increased to 7 mm as the minimum required thickness at the center of the midsleeve is 6 mm
12	DEFEX - MARK 12	The thickness was increased to 8 mm for additional factor of safety and design stability.
13	DEFEX - MARK 13	The thickness was increased to 9 mm for additional factor of safety and design stability.
14	DEFEX - MARK 14	The dimensions of DEFEX-Mark XI were retained with an increase in the fillet at the taper of the endsleeve.
15	DEFEX - MARK 15	The fillets were increased from 0,2 to 1mm to avoid sharp edges

Figure C.1: Log of all the dimensional changes from the initial to the final concept

S.no	Model	Bolt					Midsleeve				Endsleeve				
		Max diameter	Mid Diameter	Min diameter	Taper angle	Metric	Length	Max diameter	Min diameter	Taper angle	Length	Max diameter	Mid diameter	Min diameter	Taper angle
		mm	mm	mm	deg	mm	mm	mm	mm	deg	mm	mm	mm	mm	deg
1	DEFEX - MARK 1	64	48.3	48.3	30	M56	100	66	58	30	25	60	60	56	30
2	DEFEX - MARK 2	64	48.3	48.3	30	M56	100	66	58	30	48	66	64	56	30
3	DEFEX - MARK 3	64	48.3	48.3	30	M56	100	66	58	30	53	66	64	56	30
4	DEFEX - MARK 4	64	48.3	48.3	30	M56	70	66	56	30	68	66	64	56	30
5	DEFEX - MARK 5	64	56	48.3	30	M56	70	66	56	30	68	66	64	56	30
6	DEFEX - MARK 6	64	56	48.3	30	M56	70	66	56	30	65	66	64	56	30
7	DEFEX - MARK 7	64	56	48.3	30	M56	30	66	56	30	85	66	64	56	30
8	DEFEX - MARK 8	64	56	48.3	30	M56	50	66	56	30	95	66	64	56	30
9	DEFEX - MARK 9	64	56	48.3	15	M56	50	66	56	15	95	66	64	56	15
10	DEFEX - MARK 10	64	56	48.3	15	M56	70	66	56	15	65	66	64	56	15
11	DEFEX - MARK 11	64	52	45	15	M48	55	66	52	15	73.50	66	64	52	15
12	DEFEX - MARK 12	64	50	45	15	M48	65	66	50	15	68.50	66	64	50	15
13	DEFEX - MARK 13	64	48	45	15	M48	70	66	48	15	65.50	66	64	48	15
14	DEFEX - MARK 14	64	52	45	15	M48	55	66	52	15	73.50	66	64	52	15
15	DEFEX - MARK 15	64	52	45	15	M48	55	66	52	15	73.50	66	64	52	15

Figure C.2: The feedback for dimension change for all the concept improvements

C.2 Phase 2 Quality Function Deployment

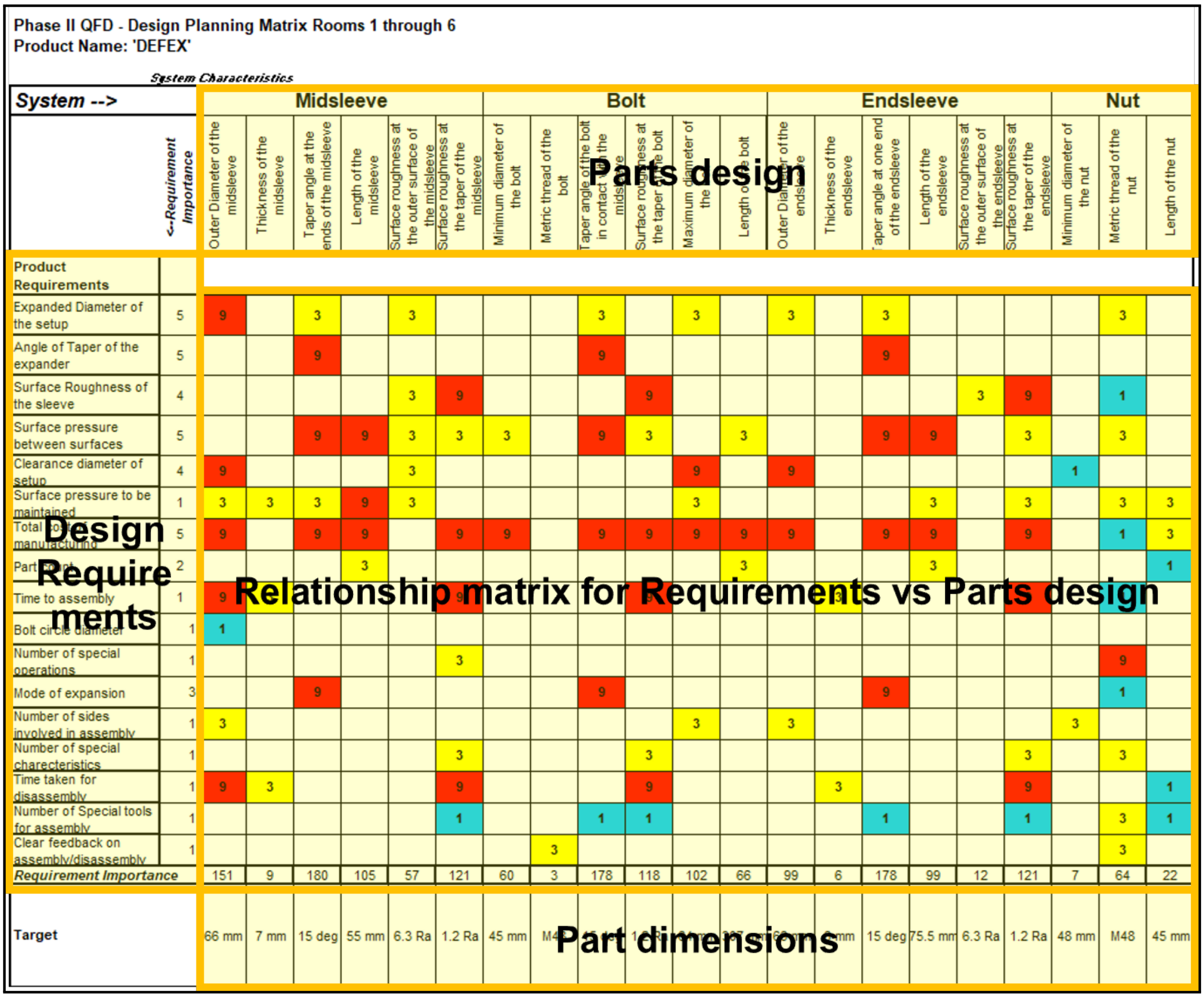

Figure C.3: Structure of the Phase 2 Quality Function Deployment(QFD2)