Master of Science in Mechanical Engineering
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An Approach For Cable Drum Structure Optimization

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The authors declare that they are the sole authors of this thesis and that they have not used any sources other than those listed in the bibliography and identified as references. They further declare that they have not submitted this thesis at any other institution to obtain a degree.

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Abstract

Performing optimization of structures is always of great interest. There are several different ways to optimize steel structures. Today, several companies are having difficulties with their cable drums during transport. Cable drums with full cable load become heavy and make it difficult to transport. This paper aims to examine existing published research and approaches, with a focus on steel optimization. This paper has two research objectives, the first one is to examine the possibilities for optimizing cable drums in terms of mass without compromising load capacity or yield stress. The second question is to determine how much of the weight/mass of cable drums may be reduced via optimization. To optimize it, measurements, cable drum modeling, research studies, and connecting suitable software's will be carried out in this paper. Participation Action Research and Reverse Engineering methodologies were implemented in combination. A literature review was performed to get a deeper understanding of the methods. A systematic literature review was done to identify available approaches and techniques for structural steel optimization. In order to optimize the cable drum, Excel and Autodesk Inventor were connected through Visual Basic Applications (VBA). The optimization process workflow acted with a server and two clients, where Excel acted as the server and Autodesk Inventor and MATLAB acted as clients. It was found that this was a suitable method for optimizing the cable drum were to work with an optimization process that included connecting a server with clients. The MATLAB function fmincon was applied with both interior-point algorithm and Sequential Quadratic Programming (SQP). The optimal design variables for the cable drum were established, and the objective minimization was accomplished by reducing the cable drum mass of 2495.20 kg. The cable drums mass was minimized to 101.86 kg. The literature review was systematically conducted to find available approaches and methods for structural steel optimization. The combination of Participatory Action Research (PAR) and Reverse Engineering (RE) was ideal for this project since it enabled both approaches to gather data on cable drum capacity and alternative optimization strategies. The schematic optimization workflow was appropriate to apply throughout the implementation phase. The workflow gave the user complete control over the optimization process, and the automated process saved time and was simple to adapt.

Keywords: Cable drum, Finite Element Analysis, MATLAB, Steel Structure

Sammanfattning

Att genomföra optimering av strukturer är alltid av stort intresse. Det finns flera olika sätt att optimera stålkonstruktioner. Idag har flera företag problem med sina kabeltrummor gällande utmattningsgränsen men också med transporten. Kabeltrummor med full kabelbelastning blir tunga och gör den svår att transportera. Syftet är att utvärdera befintlig publicerad forskning och metoder med betoning på ståloptimering för att utvärdera möjligheterna med att optimera kabeltrummor i termer av dess massa utan att kompromissa med lastkapacitet och sträckgränsen. För att optimera kabeltrumman så utfördes mätningar, kabeltrumsmodellering, forskningsstudier och användning av mjukvara att utföras. Metoden som användes i detta examensarbete var Participatory Action Research (PAR) och Reverse Engineering (RE). De två metoderna användes kombinerat. En litteraturstudie genomfördes för att få en djupare förståelse för metoderna. Litteraturstudien genomfördes systematiskt för att hitta tillgängliga tillvägagångssätt och metoder inom konstruktionsståloptimering. För att optimera kabeltrumman kopplades Excel och Autodesk inventor via Visual Basic Applications (VBA). Optimeringsprocessens arbetsflöde agerade med en server och två klienter, där Excel agerade som server och Autodesk Inventor och MATLAB agerade som klienter. Det visade sig att den lämpliga metoden för att optimera kabeltrumman var att arbeta med en optimeringsprocess som innefattade att koppla en server till klienter. MATLAB-funktionen fmincon applicerades med både interior point algoritm och Sequential Quadratic Programming (SQP). De optimala designvariablerna för kabeltrumman fastställdes och målet uppnåddes genom att minska kabeltrummans massa på 2495,20 kg. Kabeltrummans massa minimerades med 101,86 kg. Kombinationen av PAR och RE var idealisk för detta projekt eftersom det möjliggjorde båda metoderna för att samla in data om kabeltrummans kapacitet och alternativa optimeringsmetoder. Optimeringsarbetsflödet var lämpligt att tillämpa under hela implementeringsfasen. Arbetsflödet gav användaren fullständig kontroll över optimeringsprocessen, och den automatiserade processen sparade tid och var enkel att implementera.

Nyckelord: Kabeltrumma, Finita Element Analys, MATLAB, Optimering

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Nomenclature

CAD Computer Aided Design

DOE Design of experiment

EOP Engineering optimization problems

FEA Finite Element Analysis

FEM Finite Element Method

IP Interior point

LP Linear programming

$MILP$ Mixed-integer linear programming

NKT Nordiske Kabel og Traadfabriker

NLP Nonlinear programming

PAR Participate Action Research

QP Quadratic programming

RE Reverse Engineering

SBO Surrogate Based Optimization

$SOCP$ Second-order cone programming

SQP Sequential Quadratic Programming

VBA Visual basic for applications

Chapter 1

Introduction

1.1 Introduction

Today, several companies ship/deliver high-voltage cables in drums. The high-voltage cable is packed in drums, which may hold cable of varying lengths depending on the drum size. The drums are simple in design, with a drum diameter, a drum width, a traverse width, and a traverse diameter. The dimensions are a key part of optimizing the drum in terms of its weight and material selection [1]. By optimizing the cable drums, it will be possible to easier transport more and put a larger amount of cable on the drums. Optimization will also give a deeper understanding of the load capacity and how it affects the cable drum.

When optimizing a cable drum, several characteristics and criteria must be examined, including material properties, size, load capacity, yield strength, breaking point, stress, static and dynamic forces, torque, and friction. It is critical to verify the optimization results to ensure that the product meets the criteria [2]. Some studies show how to calculate the forces on the cable drum while winding the cable by using FEM simulations. The study focuses on cable drums made of steel and reducing the weight of any structure [3].

Because of decreasing raw material supplies and strict limits on sources of energy, the desire for lightweight, effective, and low-cost structures has become critical in advanced engineering design. This necessitates engineers searching for optimum and sturdy design choices to meet design challenges that are frequently huge in size and extremely nonlinear, making solution discovery difficult [4]. Optimization is a helpful tool to generate innovative complex structures and comes with many benefits such as structural costs, volume, and weight. There are several different optimization methods which include essential steps such as numerical algorithms, simulation tools, etc.

The aim of the study is to evaluate existing published research and methods with an emphasis on steel optimization in order to evaluate the possibilities with optimizing cable drums.

1.2 Organization of NKT HV CABLE AB

H. P. Prior, a shipowner, regarded 1891 as a promising year for producing high-quality wire for power distribution and the newfangled telephone. During the second industrial revolution, when coal and gas were being phased out as sources of home and industrial power, he formed NKT. The firm grew quickly and just seven years after its founding was listed on the Copenhagen Stock Exchange as Nordiske Kabel og Traadfabriker. NKT is a world pioneer in cable technology, contributing to the digital era of the fourth industrial revolution and the worldwide shift to renewable energy with sites in several countries and production facilities in Germany, Sweden, Poland, Czech Republic, Norway, and Denmark. NKT was the first business to produce a superconducting cable in 2001. Interconnections, hydroelectric and nuclear power plants, onshore and offshore wind farms, oil and gas platforms, and solar energy all benefit from NKT's adaptable and dependable solutions. NKT is a company that provides long-term solutions that will benefit future generations [5].

This project is of great interest to NKT, where the importance of the analysis is to get greater knowledge regarding drum construction and to understand the requirements. In the future, even produce their own cable drums in the immediate area. In this project, the cable drum that is used for machines is used as a reference for evaluating existing methods, see Figure 1.1.

Figure 1.1: Cable drum, M45

1.3 Purpose, aim and thesis questions

The aim of the study is to evaluate existing published research and methods with an emphasis on steel optimization in order to evaluate the possibilities of optimizing cable drums in terms of its mass without compromising the load capacity and yield stress. Measurements, modeling of the cable drum, research studies, and MATLAB toolbox functions algorithm will be performed to optimize it. The model will be the same as the one already in use at NKT. Calculations and stress analysis will be performed on the present model to compare it to the optimized cable drum. Those objectives lead to the following research questions:

- What approaches and possibilities are available for a design optimization process for a cable drum without compromising the yield strength capacity?
- How much of the cable drums' mass can be reduced by optimization without compromising the cable drums' stress capacity?

1.4 Delimitation

Because of the manufacturing cost and the time limit of 20 weeks, a prototype will not be made. Therefore, there will be a CAD model created close to the current cable drum. The cable drum is made of steel S235 and S355. Due to time limits, the focus will be on a single current cable drum, and not on examining different types of cable drums. The focus will be on a cable drum used for machines and not for shipping.

1.5 Outline

This thesis consists of six chapters, each with several subsections. The first chapter includes an introduction to the thesis as well as a brief history of the participating company, aim, and scope followed by a section of related work. The theory of the cable drum, FEA, and optimization methods such as design exploration, MATLAB optimization toolbox and meta-models are described in the second chapter. Chapter three covers the method used, which is PAR and RE, as well as a detailed explanation of the research methodology, which consists of the phases in PAR mixed with RE. The fourth chapter contains the results of all the steps in participatory action research, as well as the implementation where the results from FE static simulation and the optimization process are presented. The project workflow is discussed in chapter five, followed by a conclusion and future work in chapter six.

1.6 Related work

A literature study was made during this thesis. This section will present some of the studies.

1.6.1 Finite element analysis of winding sequence for cable drums

In this paper "Finite element analysis of winding sequence for cable drums", the authors are looking at cable drums made of steel. The cable drum in this paper is utilized to convey exceptionally rigid and heavy wires to offshore oil sector facilities. The aim of this paper was to be able to predict the loads' behavior during the winding sequence. The used method was by performing simulations with software called LS-DYNA to acquire results. Several assumptions were made to simplify the drum and the cable to be able to reduce simulation time. Because winding velocities in real life are quite extremely slow, the winding velocity has to be raised while still avoiding dynamic effects to minimize simulation durations. The results of the loads applied on the cable drum were obtained by performing explicit finite element simulation, however, no conclusion regarding the result was made because of the small sample size of the simulation. The only conclusion from the report was that it is possible to use finite element tools to perform simulations of the cable drum during the winding sequence [3]. Research result regarding forces applied to the drum is beneficial to optimizing the cable drum without compromising its capacity. This paper can be used as guidance to simulate and analyze the cable drum

1.6.2 Design Optimization of Pressure Vessel with Particular Design Considerations

In "Design Optimization of Pressure Vessel with Particular Design Considerations", Patel's approach was to minimize the total weight of pressure vessels by implementing FEA software with the MATLAB optimization algorithm. The most essential objective in the design of a pressure vessel is to ensure that it performs safely and satisfactorily. Since the model was symmetric, only the half model was used during FEA. This was done to save plenty of time during the Finite element analysis but also during the optimization process. Before executing the FEA, Meshing was applied. The fine meshes should only be used in the focus region, while larger meshes should be used in the zone with the least amount of activity. The pattern and relative placement of the nodes have an impact on the solution, processing efficiency, and time. As a result, proper meshing is essential for a decent computer simulation to produce superior results. The objective was to decrease the shell and flange thickness while still obtaining optimum stress capacity. The paper's primary goal of design optimization regarding pressure vessels was to decrease costs by lowering weight while maintaining adequate strength to avoid any design errors. The size optimization of an axially symmetric pressure vessel is discussed in this paper using an integrated method, in which the optimization technique is carried out by combining the finite element analysis program ANSYS with the MATLAB optimization algorithm. In this paper, the MATLAB toolbox function fmincon was utilized for optimization [6].

1.6.3 Thickness Optimization of Pressure Vessel for Minimum Weight using Finite Element Method (FEM)

In "Thickness Optimization of Pressure Vessel for Minimum Weight using Finite Element Method (FEM)", Widiharso et al presented a design parameter optimization that was based on only using FEM simulations. The paper's goal was to provide information about the detailed design and analysis of pressure vessel thickness. The wall thickness of the vessel is of special relevance as a design variable for minimizing vessel weight. The optimum thickness was obtained by using FEM software ANSYS. By finding the optimum thickness, the minimum weight of the pressure vessel is also given. The optimization results showed that with a given optimum weight the optimum wall thickness was achieved. The pressure vessel was able to use the same safety factor and carry the internal load but had a decreased weight when it was compared to the initial pressure vessel [7].

1.6.4 Related work summary

In summary, the related work includes a variety of challenges and techniques regarding structures that are linked to this paper in many ways. The articles cover a wide range of topics, including Finite Element Analysis and MATLAB optimization which can be used as guidance to this paper when it comes to optimization. In this paper, the combination of the papers provides greater knowledge and assistance for optimizing a cable drum's mass while still considering the yield stress capacity.

Chapter 2

Theory

2.1 Cable drum

Cable drums are used for carrying different types of electrical wires. The drum is also used for shipping different cables/wires. Cable drums are manufactured in different sizes and materials depending on their usage of it. The material choice depends on the weight and which support it is being used for. It also depends on how the drum is supposed to be stored, if it is indoor or outdoor. The cable drums dimension consists of a drum diameter (D), drum core/ barrel (d), the drum width (B), and inside the width (b) [8], as seen in Figure 2.1 below.

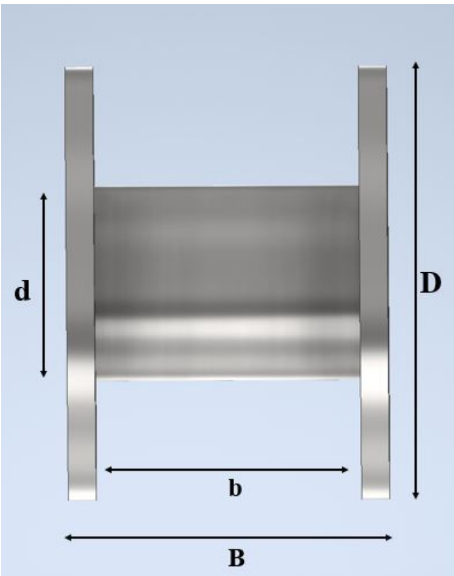

Figure 2.1: Cable drum dimensions

2.1.1 Winding sequence

The winding sequence for cable drums varies depending on the type of drum. In this project, the cable drum is first positioned and connected by its center axis, then a moment is applied. The cable is locked to the drum. The cable goes between caterpillar bands, which keep it in position while applying a pretension load, which is required to offset the moment created by the stiffness of the cable during the winding phase. The cable is guided into the proper position on the drum using a guide. To weave the rows of cables in each layer, this guide goes back and forth.

2.1.2 Material

Cable drums are manufactured of different materials such as plastic, plywood, and metal. Steel is a material that is used in different structures and a variety of areas. Steel comes in different types and even when it comes to the parameter of steel, there are standards and regulations for forms, surface treatments, or connections. Steel is a material that has a construction that is complex and very innovative. When it comes to tensile and compressive strength, steel has high strength [9]. Regarding the manufacturing process for structural steel, the chemical composition and all relevant applications can by used to reference the structural steel grades/products. This project focuses on cable drums that are made out of steel S235 and S355, the S indicates that it is structural steel and the 235 and corresponding 355 represents σ_{yield}. The point of yield is tested when the structure has a thickness of 16 mm [10].

2.2 Finite element analysis

FEA is a numerical method that has the capability to solve different engineering problems. FEA is used for different types of problems such as heat transfer, stresses, vibrations, etc. The underlying principle behind the finite element approach is to solve a complex problem by converting it into a simpler one [11]. The numerical method anticipates the product's behavior when it is subjected to loads. The product parts geometry is divided into elements that are connected at nodes. To perform the FEA, boundary conditions and loads are applied to the part. After dividing the geometry using finite elements and adding boundary conditions to the constructed system, FEA is a numerical method of solving systems of equations [12].

When defining the FEA problem, the equations can be presented as a linear system following as,

$$[A]\{x\} = \{b\} \tag{2.1}$$

where,
[A] is the system matrix

{x} is the response/behaviour
{b} is the input/load

When it comes to conducting stress analysis,
[A] becomes the stiffness matrix
{x} becomes the displacement vector
{b} becomes the force vector

Simulation tools such as Autodesk Inventor Nastran or Solidworks range of software incorporate FEA algorithms. These systems are typically included in CAD software, enabling it considerably simpler for engineers to transit from design to complicated structural analysis.

2.2.1 Static analysis

Static analysis can be used to examine both linear and nonlinear quasi-static systems. The structural response can be determined in a step process in a linear situation with an applied static load. Non-linearity in geometry, contacts, and materials can all be considered. When performing FEA, it is necessary to determine if a static or dynamic analysis is required. There are some significant distinctions between both analyzes. Only if the system being simulated is not time-dependent and the loads that are applied are constant can a static analysis be conducted. The system, the load application, or both may vary over time in a dynamic analysis. The inertial loads created by the system owing to acceleration are taken into consideration in a dynamic analysis, while inertia in static analysis is not considered. The static analysis differs from dynamic analysis in that only the stiffness matrix of the FEA model is solved in a static analysis. When it comes to dynamic analysis, the mass matrix and the damping matrix are both solved in addition to the stiffness matrix. This is one of the causes why, for the same structure, dynamic analyses take longer to compute than static analyses. Because the load or field of conditions does not change over time in the static analysis, it is assumed that the load or field conditions are applied gradually rather than suddenly. The system under consideration in this analysis might be linear or nonlinear [13].

2.2.2 Mesh

In order to mathematically solve the FEA solution, the mesh must be constructed. The mesh is composed of small components known as elements, and at each element's corner is a node. The property definition determines the mesh type. A collection of parameters allows one to control element size, order, and local refinement. Because the validity of the solution is so dependent on mesh fidelity, it is vital to take forth the effort to create a high-quality mesh for your simulations. Mesh control specifies varied element sizes in different sections of the model. A smaller element size enhances the accuracy of the result in the region, i.e. by setting the element size, one can manually improve the result for the stresses in a local or interface area. Mesh control can be specified for verticals, points, edges, surfaces, and components. For solid elements, there are two types of tetrahedron types that are used for 3D solid meshes. There is the linear tetrahedrons type which consists of four nodes and is suitable to use when the result is not important as the relative changes. The parabolic tetrahedrons consist of ten nodes and are suitable elements that can be used in a variety of uses. In certain cases, a mesh control can be needed to use for edges, faces, or points, which allows one to define the number of elements or the sizes of the elements [14].

2.3 Optimization

Optimization is the process of identifying which unit, variables, or quantity best matches a system of specified criteria or conditions. Engineers must make several operational and managerial decisions throughout the design, implementation, and operation of any engineering system. The overall purpose of all such selections is to either reduce the design cycle or enhance the desired output [11]. Because reducing the amount of work needed or enhancing the desired output in every practical scenario is stated as a function of specific criterion variables, optimization is a method of determining the factors that result in the maximum or minimum value of a function. Mathematical optimization is the process of minimizing or maximizing an objective while adhering to a particular set of conditions by controlling a range of variables that affect both the objectives and the constraints [15], [16]. For using mathematical optimization, the objective(s) and constraints should always be stated quantitatively as functions of the design variables or parameters.

The intent of the design optimization problem should be transformed into a mathematical expression that later can be evaluated by an optimization algorithm during the design optimization phase. It is critical to be meticulous in the conceptualization of the optimization problem since the optimizer will identify any errors in the formulation or model [17]. The first phase in formulating design optimization problems is to describe the problem, followed by acquiring data and information, defining design variables, defining the objective, and finally defining the constraints.

Engineering optimization, in general, provides tools for looking for the best possible solution to specific problems, its execution is a process of finding solutions that will assure the maximum or minimum value of the objective function. The mathematical modeling of the problem, the identification of efficient techniques and the application of heuristics are all components of the optimization procedure for EOP [18]. Prior to attempting optimization, the problem in question should be well defined. Mathematical optimization is the method of formulating and solving a fundamental constrained optimization problem. The conceptualization of the optimization problem, often known as "modeling the optimization problem," is especially in the sphere to the selection of optimization methods. The class of optimization techniques available to tackle a known optimization problem is determined with how well the task is framed [15].

The exploration for the minimum (or maximum, depending on the sign) of a process to produce as an optimization problem is the most common mathematical description of an optimization task (optimal criterion or function) [19]. The fundamental generic form of an optimization problem can be expressed as:

$$\begin{aligned} &\text{Minimize f(x)} \\ &\text{Subject to } x \in X \\ &\text{respectively} \min_{x \in R^n} f(x) \end{aligned} \tag{2.2}$$

The feasible region is $X \subseteq \mathbb{R}^n$, the objective function is $f : X \rightarrow \mathbb{R}^n$. The relationship has the validity,

$$\min_{x \in R^n} f(x) = -\max_{x \in R^n} -f(x) \tag{2.3}$$

permits any maximum problem to be converted to a minimum problem.

The initial approach toward an ideal solution is the development of a mathematical model. A comparable model which mathematically characterizes the essential entity, system, or process undergoing examination is required [20]. The aim of a coherent decision-making process should have measurable variables, input variables that affect and output variables that desire to impact.

A mathematical model might include a variety of conditions to become as near to engineering reality as feasible. To obtain the optimum solution, an objective function is needed, which is a variable that indicates whether one design is better than another. This function has to be a scalar that is comparable to a specified vector of design variables. Based on the scenario, the objective function can be minimized or maximized. The formulation of an objective function is a critical stage in successful optimization, and its implementation necessitates extensive technical knowledge in the area of optimization modeling in the particular study field [11]. Throughout an optimization process, the creation of constraints allows for avoiding untenable findings to a particular issue. Following the implementation of the preceding stages, the identification of an appropriate optimization algorithm as well as its execution in a suitable software environment to achieve the optimum to an optimization problem was conducted. Lastly, these findings should be assessed to ensure that this is indeed the ideal outcome to the optimization question. The sequence of the above respective steps can be represented as follows:

Mathematical model → Objective function → Constraint conditions → Selection of optimisation method → Software for processing → Result verification.

The optimization problem statement can be described as optimizing an objective function by modifying the design variables throughout their boundaries while keeping the constraints in mind. To select the most suitable optimization algorithm when addressing a particular optimization problem, the optimization problem should first be identified and the factors that determine the efficiency and suitability of the accessible optimization algorithms must be understood. This is significant since no optimization strategy is efficient or suitable for all sorts of situations. There is no unique optimization algorithm that is effective or even suited for all optimization problems. Hence it is critical to comprehend a problem before setting on an optimization strategy. By "effective" it implies that the algorithm will address the problems and more importantly that it does so consistently and efficiently. Following that, function evaluation is obtained by solving numerical models of the system based on the previously stated optimization problem scenario [21].

2.3.1 MATLAB Optimization Toolbox

MATLAB is a platform for scientific computation and high-level programming that employs an interactive learning interface to do complicated computation operations more effective than the conventional languages like C, C++, and FORTRAN [22]. The complementing tool sets, known as toolboxes (collections of MATLAB functions for various applications that are accessible separately), expand the MATLAB environment, enables to address particular challenges in a wide range of application areas [23]. The Optimization Toolbox includes different functions for determining parameters that minimize or maximize objectives while meeting constraints. Solvers for LP, MILP, QP, SOCP, NLP, constrained linear least squares, nonlinear least squares, and nonlinear equations are included in the MATLAB optimization tool box [23]. The optimization toolbox solvers enable in the finding of optimum solutions by enabling the execution of design optimization operations such as parameter estimation, component selection and parameter modification.

To select the optimal optimization algorithm for a particular optimization problem, it is necessary to classify the problem and understand how its variables influence the effectiveness and applicability of the available optimization algorithms [21]. In the MATLAB optimization toolbox, fmincon is a NLP algorithm. fmincon is a nonlinear constrained optimization program that accepts both linear and nonlinear constraints. To utilize this solution, the solver option must be defined along with the convergence criterion, maximum iterations, and how the gradients will be computed. Utilize Optimize/End Optimize sequence to incorporate an optimizer fmincon in the mission process. In this process, optimization variables must be specified using the vary command and constraints should be established using the minimize and nonlinear constraint commands, correspondingly [24].

2.3.2 Metamodel

Even in the most basic of circumstances, simulation models can take a long time to execute. Long run duration is a concern when optimization projects require a high number of function calls to converge and available resources are restricted in time. Metamodels are one solution to this challenge. A metamodel is a mathematical approximation of the original simulation model's response. Metamodel function calls are typically substantially quicker than the original model. The downside of using metamodels is that the accuracy tends to be lower since higher speed is obtained. The use of metamodels has the advantage of boosting the analyst's comprehension of the system and allowing the integration of domain-specific codes and models [25]. Metamodel optimization uses the surrogate model to conduct optimization. When

employed in optimization, the surrogate may define the entire optimization model (i.e., the inputs are design variables and the outputs are objective and constraint functions), or it may be a part of the overall model. SBO is narrower in scope than surrogate modeling in general. Instead of striving for a globally precise surrogate, SBO just requires that the surrogate model be precise enough to guide the optimizer to the actual optimum. Surrogate models assist to comprehend the design space, or how the objective and constraints (outputs) change when the design factors change (inputs). Functional connections that can be seen more effectively can be obtained by developing a continuous model over discrete data [21].

2.3.3 Design exploration

After defining the optimization problem, the subsequent step is to begin exploring the design space. Design space exploration is an approach of methodically exploring the Design Space for optimum solutions concerning one or more specified optimization objectives. Before optimizing a design, design space exploration can assist engineers and scientists to obtain a convenient, more comprehensive grasp of a structure's capabilities by determining which design parameters will have the most influence on the structure's functionality [6]. Design exploration presupposes that the ideal solution is undefined and unspecified at first. The design exploration method determines design parameters and specifies what an optimum design appears to be through iteration.

Once that has been determined, a linear or convergent design optimization procedure will be used to get the desired outcome. DOE research is the most important quantitative tool for exploring design space. In a DOE research, an analytical model would be automatically assessed many times, with the design parameters modified to various values for every iteration. These findings demonstrate which parameters have the greatest influence on the design and which have the least [6].

A designed experiment is a structured set of tests of a system or process. A designed experiment includes response(s), factor(s) and a model.

- A response is a measurable outcome.
- A factor is any variable that the investigator believes may influence an interest response.
- A model is a mathematical representation of a system or process.
- The experiment entails evaluating the model through a set of values assigned to the defined parameters.

Chapter 3

Method

3.1 Participatory Action Research

The traditional research methodology usually includes a researcher or expert design and formulating a project within an organization. The data is then gathered through monitoring or contacting relevant individuals. After gathering data, the researcher will take a step back from the organization and the subjects in order to examine the data and obtain information. The findings and recommendations for action will be delivered to the organization at the conclusion of the study. As a consequence, organization members will be viewed as passive subjects who will only engage in the research by authorizing the project, serving as its subjects, and receiving the final results. In PAR, some members of the organization or community under investigation interact actively with the researcher throughout the research process, from the initial concept through the concluding presentation of data and discussion of their action implications. PAR, therefore, stands in strong contrast to the traditional paradigm of pure research, in which members of organizations and communities are viewed as passive subjects, with most of these only contributing to the degree of authorizing the project, acting as its subjects, and receiving the findings.

PAR is applied research, but it differs significantly from the most prevalent sort of applied research, in which researchers operate as professional specialists, creating the project, acquiring data, interpreting the results, and advising the client organization on how to proceed. This is an elitist model of research connections, just like the traditional concept of academic research. Some members of the organization we are studying in PAR are actively seeking knowledge and ideas to influence their future activities. PAR can take many different forms, many of which are still being investigated. The scientific needs and opportunities of PAR, on the other hand, are undeniable. Science is not done by isolating oneself from the rest of the world, as generations of scientists have discovered, interaction with the rest of the world poses the greatest conceptual and methodological obstacles. The scientific requirements that must be followed in order to carry out a successful PAR project are difficult to meet. PAR is an effective strategy for advancing science and practice. The strategy includes practitioners in the research process from project conception to data collection and analysis, as well as final conclusions and actions resulting from the research, see Figure 3.1-3.2. [26].

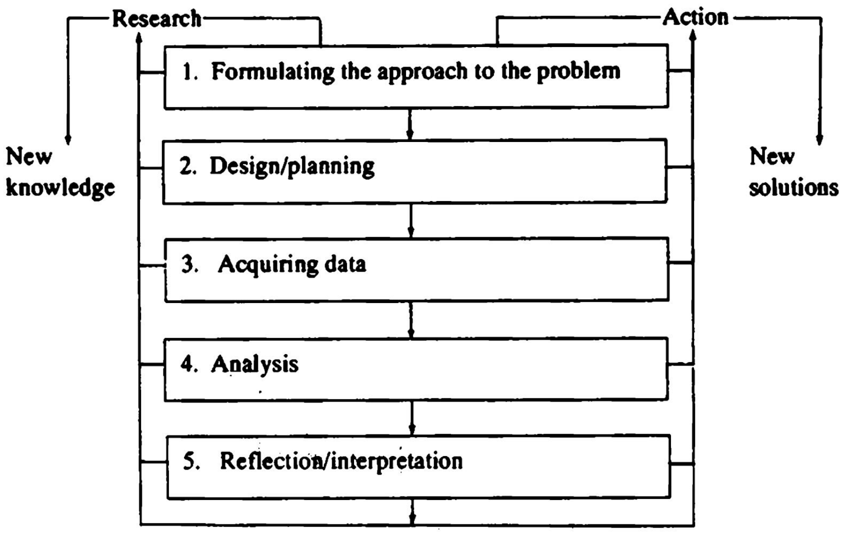

Figure 3.1: Participatory Action Research methodology (adapted from [24])

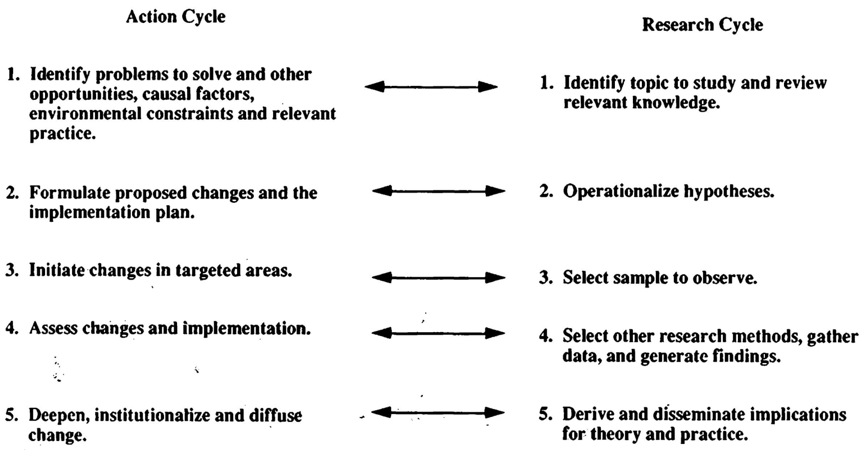

Figure 3.2: Participatory Action Research methodology (adapted from [24])

3.2 Reverse engineering

RE is a methodical process of a product, where the approach is to find the basic principle. This is a method that is used to gain a thorough understanding of the product. The process contains of taking the product and dismantling it component by part, feature by feature, sub-assembly by sub-assembly, this is done until the whole product has been examined and comprehended. RE is done to create a new product that is capable of doing essentially the same thing or fulfilling essentially the same role without relying on or simply duplicating the original product [27].

For products or parts that must be copied or changed, the CAD model is frequently unavailable or useless. This is especially problematic for long-life cycle systems when spare component stocks have been depleted and original suppliers are unable or unwilling to deliver bespoke manufacture runs of replacement parts at reasonable rates and on schedule. For different products, either no CAD systems were utilized in the initial design, or the documentation on the original design is insufficient or missing. Because of different reasons, even if the products CAD model is available, it is uncertain if they are sufficient to allow for alteration or production utilizing modern technology. Reverse engineering can be used to create CAD models of a product or its components. The simplest method for creating a reverse-engineered model structure of a mechanical part is for a developer or researcher to take measurements with basic approaches like calipers and gauges and enter the findings into a typical CAD model [28].

3.3 Research approach

The approach employed in this thesis was a hybrid of RE and PAR. This approach combination was chosen because it was thought to be suitable for the aim of the project. It was suitable since PAR intends to conduct research on optimization methods for steel construction while reverse engineering attempts to comprehend the structure and the capacity of cable drums. This gives a methodology that provides a workflow that meets the needs of both components is of importance.

The first phase, the initiation phase in the process starts with formulating the problem and research questions. The following phase is planning where the importance is to plan, set goals and figure out how to operate together. The third phase is acquiring data, this stage collects data that is both scientific and relevant. Here is RE implemented, to be able to get more understanding of the cable drums' capacity but also to create the same model in CAD and perform simulations. The fourth phase is data analysis where all the acquired data is analyzed to get the answer to the research questions but also to characterize the problem more precisely. The final stage of the process concludes with an evaluation, critique, and interpretation of all of the outcomes in order to identify problems and make recommendations for future work.

3.3.1 Formulate the problem

In the first phase in PAR, The researchers approached NKT HV CABLE AB with project ideas for an existing problem, but NKT HV CABLE AB had a new perspective and came up with another challenge. NKT HV CABLE AB proposed the project, with the goal of analyzing the cable drums' stress and load capacity. The researchers, along with experts from several departments within NKT HV CABLE AB, discussed a shared goal and scope. The team from NKT HV CABLE AB consisted of four members which had different expertise. A brainstorming session was convened within the team, and everyone contributed ideas and proposals to help define the scope. The scope and research topics were developed after obtaining a consensus.

3.3.2 Planning

For the next phase, a thorough project plan was established, with several potential tasks drawn out and evaluated. Potential risks were also recognized and handled, as well as a thorough schedule of prospective actions. Methods of working and project goals were evaluated once the plan was developed.

3.3.3 Acquiring data

This phase contained data collection by using different methods. The data was collected by the researchers that used the method of reverse engineering and with guidance from individuals within different departments at NKT HV CABLE AB. A systematic literature review was also conducted by the researchers.

3.3.3.1 Literature review

The researchers started this section to learn more about optimization methods for cable drums, steel constructions, and pressure vessels. The literature review was systematically conducted. This approach to evaluating literature was chosen based on the thesis's purpose and was unaffected by how others in the survey of relevant material conducted their judgments.

The systematic review is an appropriate choice since this endeavor is addressing a clearly defined research issue that requires as many publications from inside the study area as possible to respond. This was chosen because it gives a methodical approach to discovering and selecting relevant information. The reason for this is that none of the other reviewers mentioned what kind of literature strategy they utilized to gather and review the research. As a result, the method that looked most appropriate for this project was chosen.

The emphasis was strictly narrowed for the various areas by using specific keywords in the databases and only selecting from 2010 to 2022. Papers and research before 2010 were not chosen or reviewed since they did not appear to be relevant given the advancement of technology and optimization approaches. The time constraint was utilized to narrow down the search field and find relevant research. Summon and Scopus were the primary databases used since they provide a wide range of topics and research resources, see Table 3.1-3.3.

Table 3.1: Used Keywords and databases for steel structure optimization

Database	**Used Keywords**	Nr. of studies	Chosen Articles
Scopus	Steel structure AND Metaheuristic algorithms	136	0
Scopus	Steel structure AND Multicriteria objectives	5	0
Scopus	Steel structure AND Design Topology	299	0
Summon	Steel structure AND Metaheuristic algorithms	120	0
Summon	Steel structure AND Multicriteria objectives	69	0
Summon	Steel structure AND Design Topology	62	0

Table 3.2: Used Keywords and databases for cable drum optimization

Database	**Used Keywords**	Nr. of studies	Chosen Articles
Scopus	Cable drum AND Optimization	18	0
Scopus	Cable drum AND simulation process automation	1	0
Scopus	Cable reel AND optimization	19	0
Scopus	Cable reel AND simulation process automation	0	0
Summon	Cable drum AND Optimization	1	0
Summon	Cable drum AND simulation process automation	0	0
Summon	Cable reel AND optimization	2	0
Summon	Cable reel AND simulation process automation	0	0

Table 3.3: Used Keywords and databases for pressure vessel optimization

Database	**Used Keywords**	Nr. of studies	Chosen Articles
Scopus	Pressure vessels AND Metaheuristic algorithms	37	0
Scopus	Pressure vessels AND simulation process automation	41	0
Summon	Pressure vessels AND Metaheuristic algorithms	55	0
Summon	Pressure vessels AND Design optimization	373	2

3.3.3.2 Reverse engineering

On the cable drum, the researchers began gathering measurements. On the drum, certain measures were already known, but not all. There was some existing information regarding the material, the information was that both S235 and S355 were used on the drum but not at which parts. Some measurements were not possible to take for the cable drum for different reasons, thus some assumptions were made. To make the assumptions, the researchers had a discussion with the members of NKT HV CABLE AB, to ensure right assumptions were made. The assumptions were about the thickness of the beams on the drum and also the material that was used. The measurements were taken not just to gain a better understanding of the structure, but also to produce a CAD model that was identical to the actual object. After the model was created, the stress analysis was carried out using Solidworks simulation. This was done to acquire a better knowledge of the capacity of the cable drums.

3.3.4 Data analysis

The data analysis phase consist of attempting to understand the information that was gathered through the acquiring data phase. This phase is carried out to gain a clearer picture and a better grasp of the next phase's objectives. The strategies and tools utilized are described in the sections that follow.

3.3.4.1 Literature review

The researchers went through the databases by writing different keywords. The literature review analysis was divided into three sections, first section consisted of different optimization methods for structural steel, second section was different optimization methods for cable drum and lastly third section was different optimization methods for pressure vessels. The analysis consisted of first going through the results by reading the title and abstract. The analysis was narrowed down by searching for similar geometry/structure as the drum but also searching for similarities regarding forces/stresses that occurs on the drum. For the structural steel optimization literature review, the researchers analysed the papers based on the context, therefor papers that included trusses, steel frames, steel plates and steel skeleton structures were not chosen. All sections were summarised individually, this was done to get a clearer picture of what the sections had in common but also to find advantages of the different methods. The summary of all sections gave a couple of clear statements of what approaches and possibilities exists, it also gave deeper knowledge within the area of optimization methods.

3.4 Implementation

After gathering information and exploring options for improving the cable drum, the researchers chose which procedure to use and proceeded to put it into practice. This was accomplished by combining various software programs such as Autodesk Inventor, Excel, and MATLAB.

3.4.1 Reflection

A reflection of all the outcomes was carried out as the final stage of the approach adopted for this thesis. The technique utilized, the results, and the solutions were all critically analyzed and debated in order to identify its strengths and limitations. It is also analyzed to see if the outcomes are genuine and reliable and whether the task can be done in a different way. This stage of critically assessing the outcomes is essential in any task and is necessary to always be carried out. This is due to the fact that it contributes to the delivery of accurate results, which is critical for scientific activity.

Chapter 4

Results

4.1 Acquiring data

The acquiring data phase consisted of conducting a literature review, RE, and creating a CAD model. From the literature reviews, it can be depicted that there is a lack of existing optimization research papers regarding cable drums. The researchers had a discussion with the members of the organization to extend the search area. From the organization, it was suggested to conduct research for pressure vessels as well. As a result, the researchers had to find other approaches to optimize cable drums. This was accomplished by conducting a literature search on pressure vessels and optimization.

4.1.1 Generating CAD model

Based on the measurements and the material, a CAD model was created. The material choice was steel S235. This was chosen because it has a lower yield strength than S355. There were three sections to the model. The frame skeleton, which contained the beams and rolled sheets was the initial component, see Figure 4.1. The drum's core was the second section, as seen in Figure 4.2. Finally, the skeleton frame's component of the rolled metal sheets, see in Figure 4.3. Following that, all of the parts were assembled, as shown in Figure 4.4.

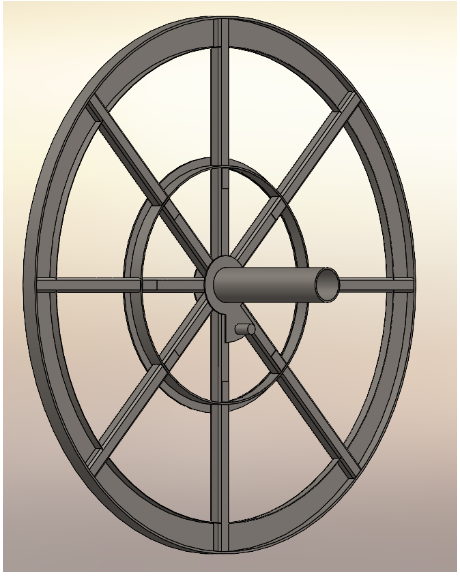

Figure 4.1: Skeleton Frame

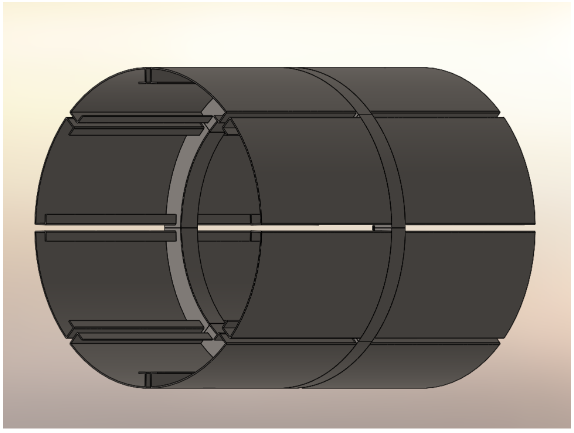

Figure 4.2: Cable core

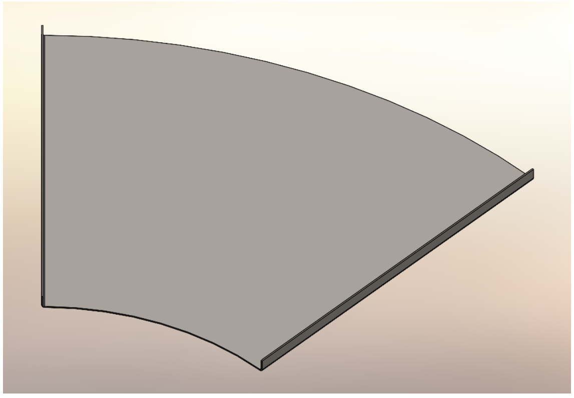

Figure 4.3: Rolled sheet metal

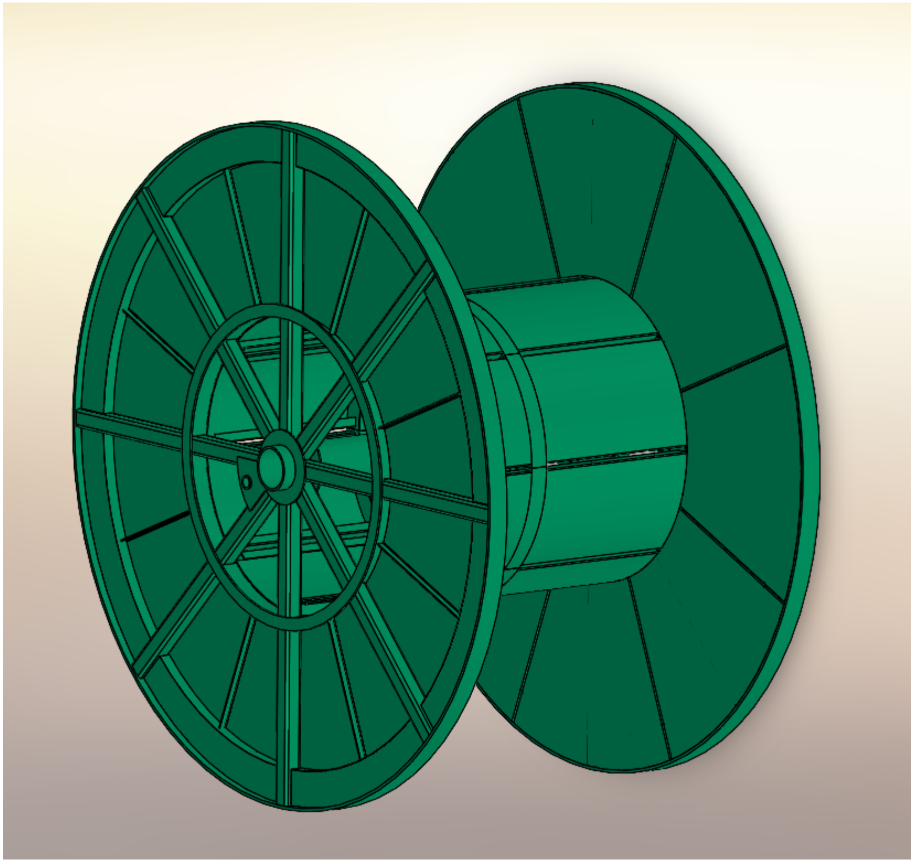

Figure 4.4: Assembled cable drum

4.1.1.1 Symmetry

If a part or unit has symmetry and the loads are symmetrical, half of the model, or even a quarter, can be employed in the analysis. When symmetry is enabled, the number of elements required can be greatly decreased, resulting in a large reduction in computation time. During repeated assembly, an analytical model of a component may be created, and the same basic model can be used to execute many analyses on the part. The function symmetry was used in Solidworks and only a quarter of the model was used in this project to save time, see Figures 4.5, 4.6, and 4.7 below.

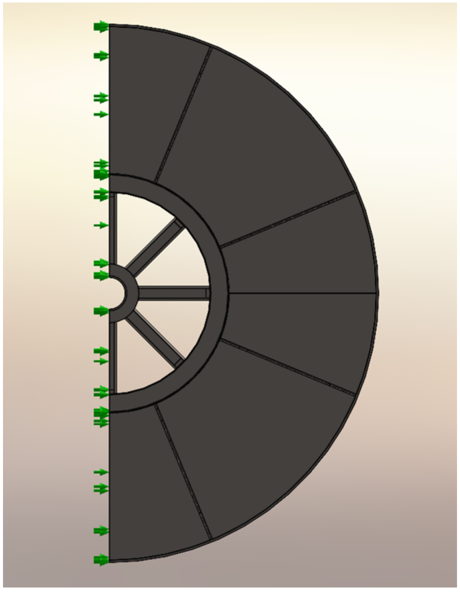

Figure 4.5: Symmetry condition

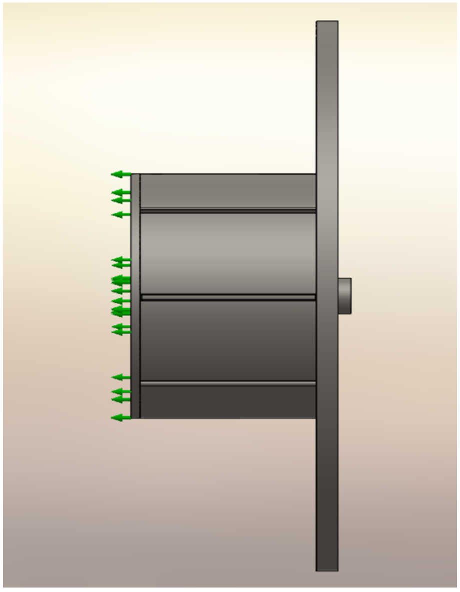

Figure 4.6: Symmetry condition

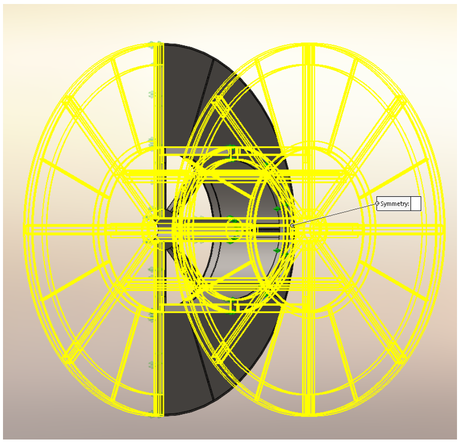

Figure 4.7: Symmetry preview

4.2 Data analysis

4.2.1 Literature review

The review of the literature was analyzed. This was done to determine the optimal technique not only for optimization but also for implementation. The literature review included the best methodologies for optimizing the cable drum, such as various metaheuristic algorithms and optimization methods. Some of the studies that the researcher considered suitable were analyzed and were used in the implementation phase.

4.2.2 FE static simulation

The cable drum's FEA was examined in three separate scenarios. The cable drum was hung from the pipe by two pinols in the first scenario, which was done by setting fixed constraints along the pipe in all directions. In the second scenario, the cable drum was placed on the ground by creating a virtual wall on the lower edge of the cable drum.

In both cases, gravity was applied in the direction of the y-axis, as shown in Figure 4.8. Following that, a bearing load was applied around the cylindrical face in the direction of the negative y-axis, as shown in Figure 4.9. At the contact interface, the bearing forces produce a non-uniform pressure. The applied bearing load was selected as a sinusoidal variation, as can be seen in equation 4.1. The force equilibrium determines the value of F_0, and n represents the number of nodes around the circumference.

$$F = \sum_{i=1}^{n} (F_0)_i sin^2\theta \tag{4.1}$$

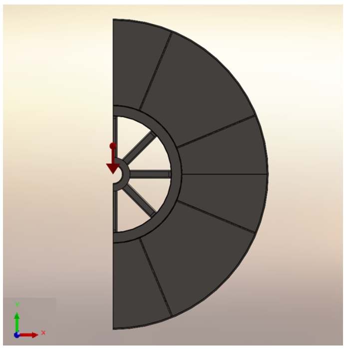

Figure 4.8: Gravity

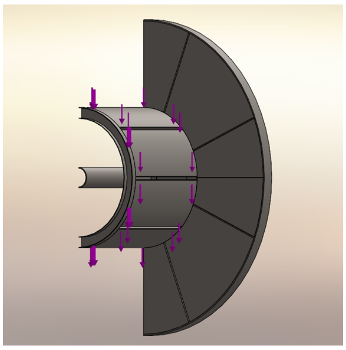

Figure 4.9: Bearing load

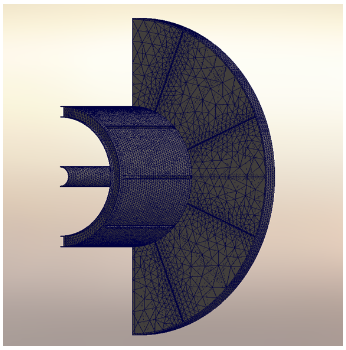

Figure 4.10: Mesh

The third scenario refers to when the cable drum is shipped at sea. The cable drum is restrained with a cable drum cradle during transit. Because forces are applied in various directions at sea, the assumptions for this case is that the cable drum is tilted at a 45-degree angle and the forces are applied along the x and y axes. The forces for case three, are computed by dividing the total load into individual forces using the resultant. This is done to apply forces in the correct direction as well as to the correct surface on the cable drum. All input parameters can be seen in Table 4.1.

´

Table 4.1: Input Loads

Parameters	**Gravity [m/s^2]**	**Bearing Load [kN]**	**Load [kN]**
Values	9.81	125	125

A mesh was generated and a mesh control with a finer mesh was applied to the cable drum's middle, as shown in Figure 4.10. All mesh settings can be seen in Table 4.2

Table 4.2: Mesh settings

Mesh settings	**Case 1**	**Case 2**	**Case 3**
Number of elements	100332	100332	214023
Number of nodes	202061	202061	429879
Mesh type	Solid mesh	Solid mesh	Solid mesh
Mesher used	Curvature meshed base	Curvature meshed base	Curvature meshed base
Mesh max size	252.32 mm	252.32 mm	134.15 mm
Mesh min size	50.46 mm	50.46 mm	26.82 mm
Mesh control size	36.73 mm	36.73 mm	25.00 mm
Jacobian points	16	16	16

The cable drum analysis consider the entire model as the material properties of S235, which has a yield strength of 215 MPa. In the first scenario, with the cable drum supported by two pinols shows that the most tension is concentrated in the center of the cable drum as shown in Figure 4.11. In the second scenario, when the cable drum was put on the ground, the maximum stress value was located at the center of the drum, as shown in Figure 4.12. The maximum stress value in the second scenario results in a 3,34 percent increase. The third and final scenario gave a maximum stress at the bottom of the flange, as shown in Figure 4.13. All stress results can be seen in Table 4.3.

Table 4.3: Stress results

Parameter	**Case 1**	**Case 2**	**Case 3**
Yield strength [MPa]	215.00	215.00	215.00
von Mises stress [MPa]	193.41	200.10	289.29

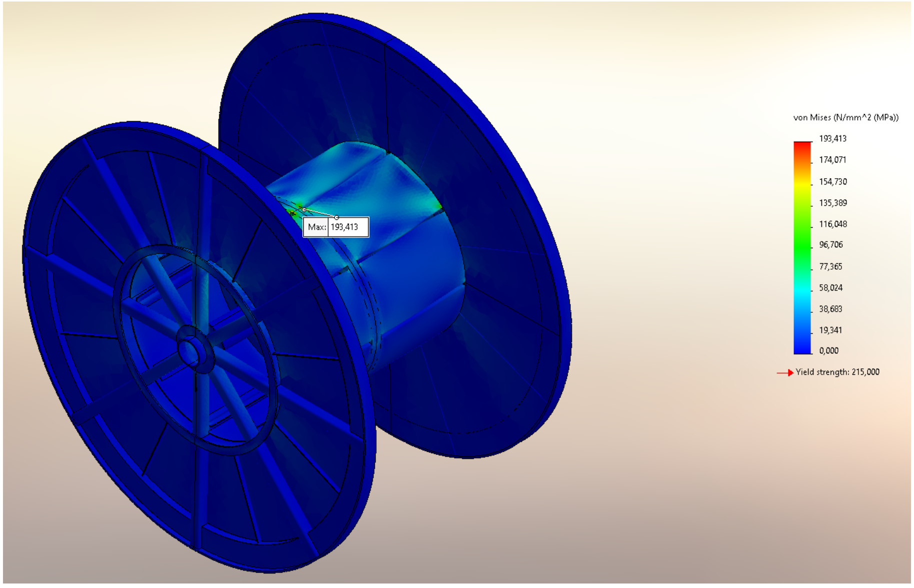

Figure 4.11: Case 1

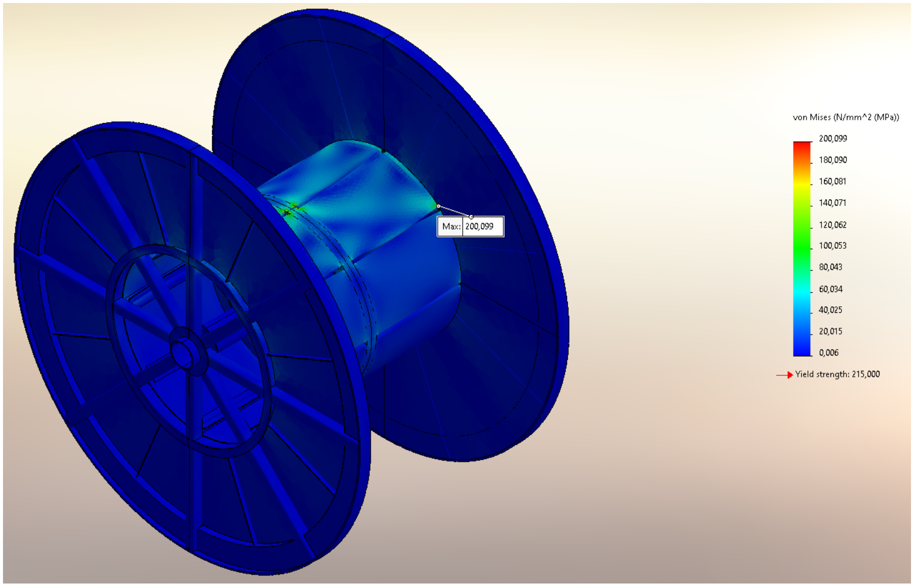

Figure 4.12: Case 2

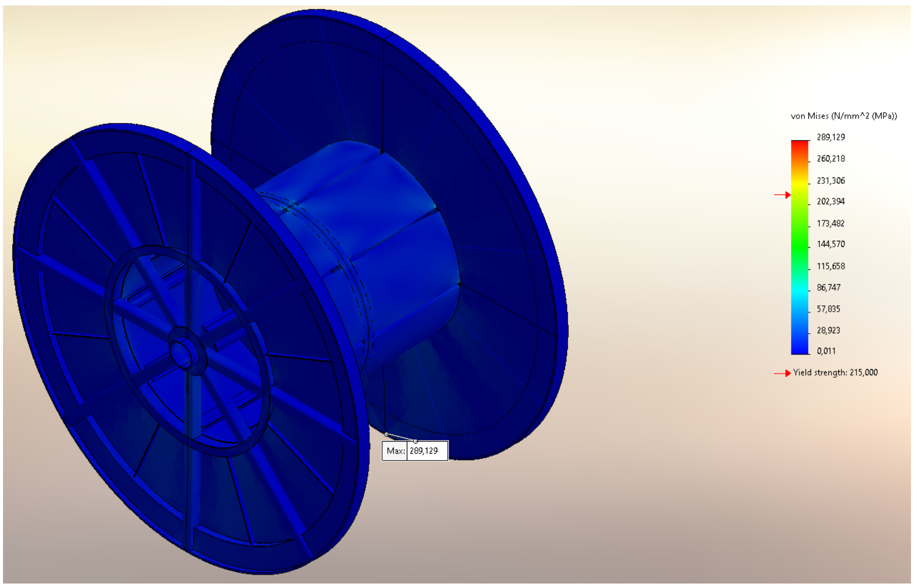

Figure 4.13: Case 3

4.3 Implementation

4.3.1 Setting and running optimization

The optimization process started with the creation of a 3D model of the cable drum in Autodesk Inventor that was similar to the current cable drum on NKT HV CABLE AB, see Appendix A.2 in Figure A.1. To reduce the computational time it takes for the FEA, symmetry was adopted, and the entire model was divided into half. The next step was to connect Autodesk Inventor to Excel. This was accomplished by building a VBA script capable of obtaining and changing the parameters of the cable drum model through Excel, see Figure 4.14. The VBA script can be seen in Appendix A.1.

	A	B	C	D	E	F
1	Path_1	C:\Users\shra16\OneDrive - BTH Student\Desktop\Thesis\Cable drum autodesk inventor\Mid_section.ipt				
2	Path_2	C:\Users\shra16\OneDrive - BTH Student\Desktop\Thesis\Cable drum autodesk inventor\Cable_drum.iam				
3		Inputs			Outputs	
4	Parameter	Value	Unit	Parameter	Value	Unit
5	Thickness	9	mm	Mass	2495.198573	kg
6	Thickness_beam	10	mm	Stress	194.879	N/mm^2
7			mm			
8			mm			

Run Simulation

Update Stress value

Figure 4.14: VBA Setup

Furthermore, the VBA script enabled the automatic execution of a simulation in Autodesk Inventor. The CAD model was automated by incorporating API into the VBA script. The outputs, which included the von Mises maximum stress value and mass, were then transmitted back to Excel. The process was based on a server and clients. In this case, Excel acted as the server that provided with a set of variables. The clients in this case was Autodesk inventor and MATLAB, which modified the models variables to the logic that was applied. The simulation process by using text files is done by the server that contains a text file which consist of the inputs and changes of the model. The steps through the optimization process can be seen in Figure 4.15. To solve the optimization problem, fmincon was applied and the optimization algorithms IP and SQP.

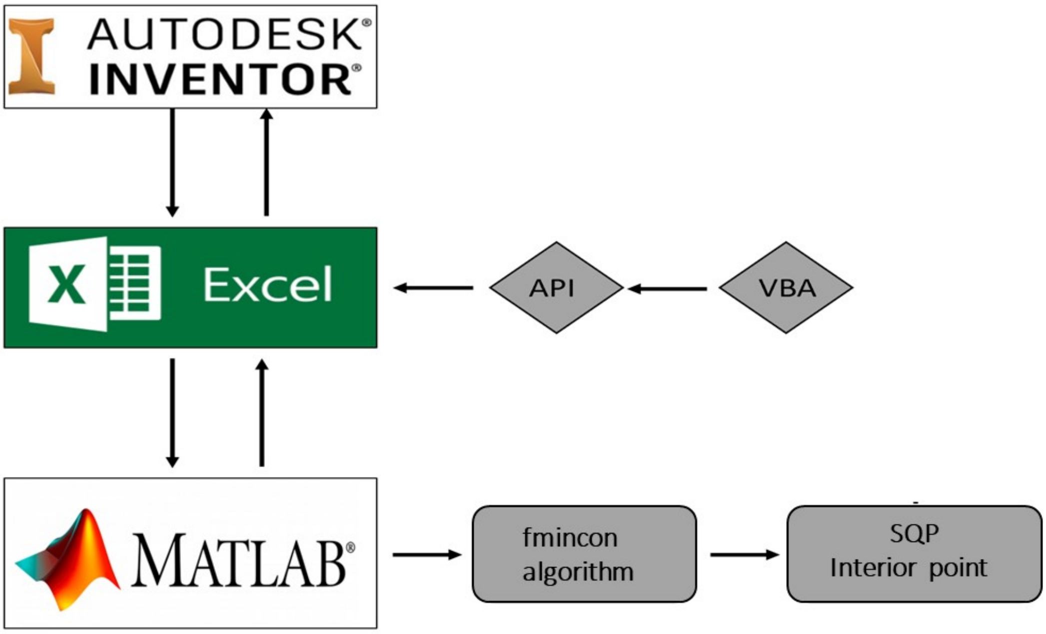

Figure 4.15: A schematic representation of the optimization process

In MATLAB, design variables were defined that could vary within a certain range. The cable drum's design variables were established as thickness at certain regions where stress values were highest, as shown in Figures 4.16, 4.17, and 4.18. The range can be described as follows:

$$\underline{x_i} \leq x_i \leq \overline{x_i}, \quad i = 1, 2 \tag{4.2}$$

where the lower bound is $\underline{x_i}$ and the upper bound is $\overline{x_i}$. A starting point for the design variables was established prior to the use of optimization.
The design variables range is set as following,

$$\begin{aligned} 4 \leq \text{Thickness } x_1 \leq 16 \\ 5 \leq \text{Thickness } x_2 \leq 20 \end{aligned} \tag{4.3}$$

The next step in the formulation of the optimization problem was to specify the objective and define the constraints, which was to minimize the mass of the cable drum. The cable drum optimization problem can be formulated as,

$$\begin{aligned} f(x) &\rightarrow \text{Minimize weight} \\ \text{Subject to} & \\ g(x) &= \text{von Mises stress} \leq \text{Yield stress} \end{aligned} \tag{4.4}$$

The initial values for the cable drum can be seen in Table 4.4,

Table 4.4: Initial values

Drum parameters	**Initial values**
Thickness x_1 [mm]	9.00
Thickness x_2 [mm]	10.00
Mass [kg]	2495.20
von Mises stress [MPa]	194.87

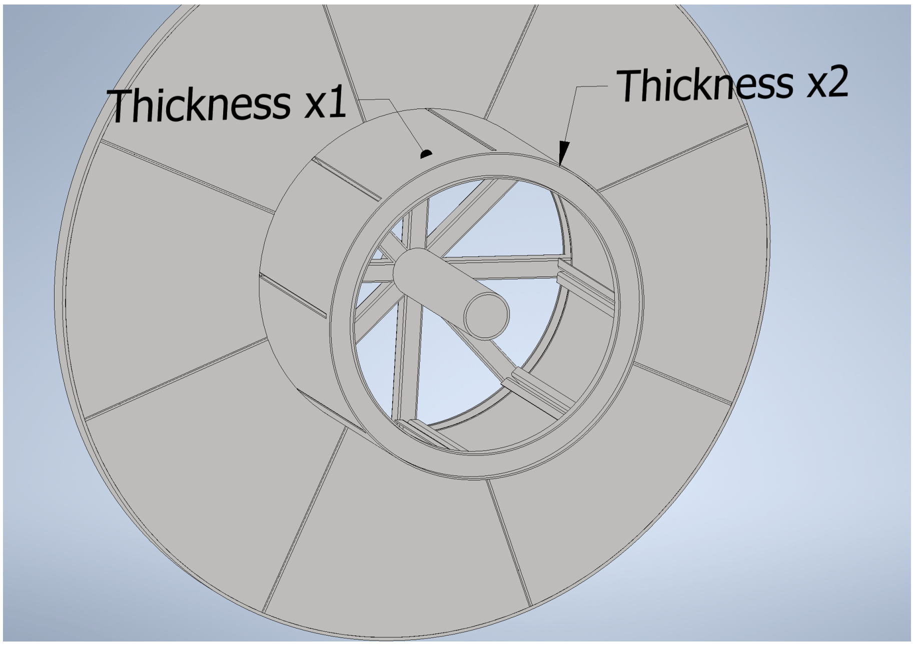

Figure 4.16: The design variables in Autodesk Inventor

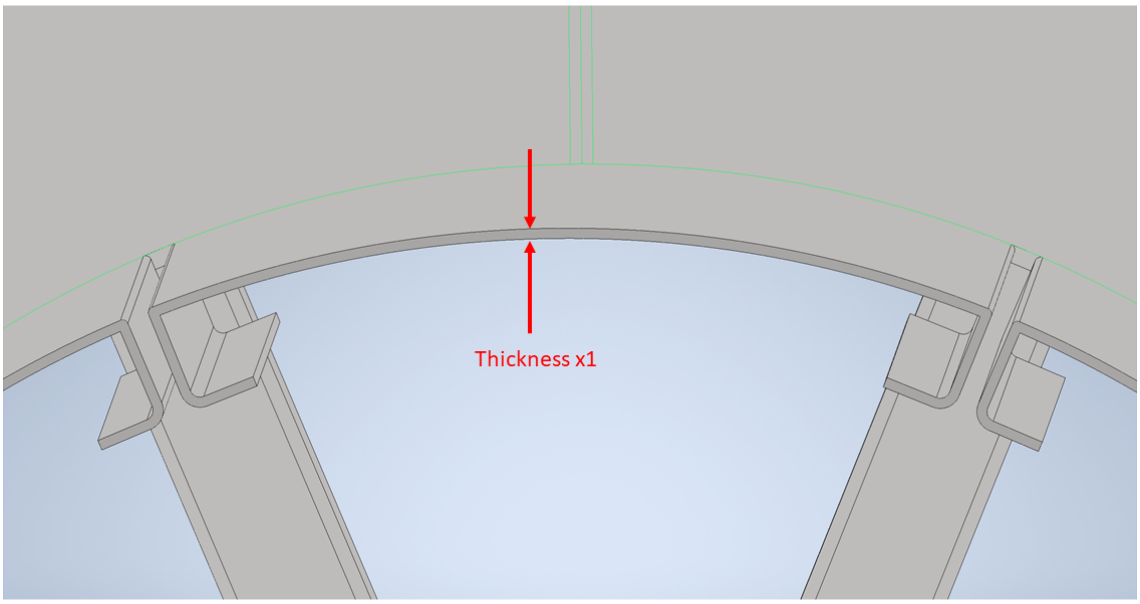

Figure 4.17: Cross section for Thickness x_1

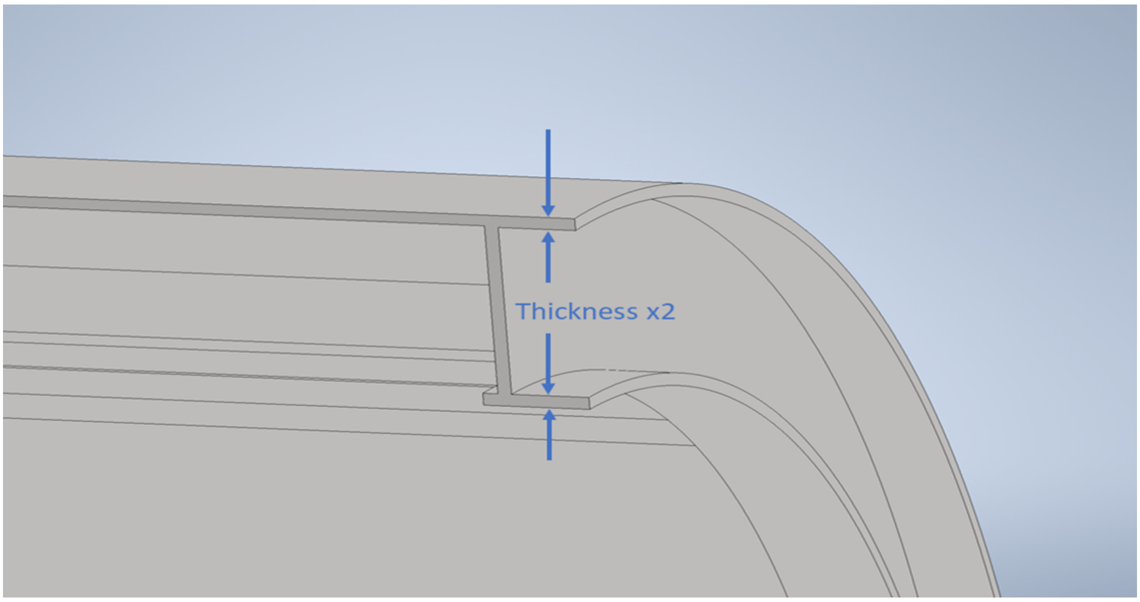

Figure 4.18: Cross section for Thickness x_2

In the software Isight, the boundary was set for each design variable. This was applied to generate a function that is suitable for the values. The number of points was 20 and the Latin hypercube was set as a DOE technique, as shown in Figure 4.19.

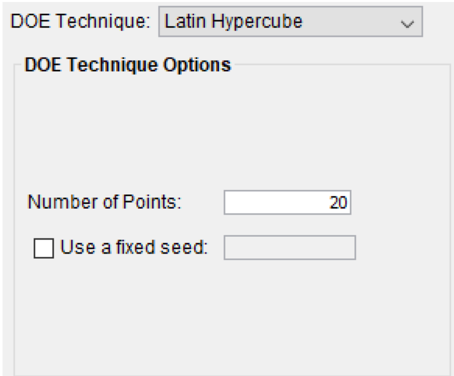

Figure 4.19: DOE technique options

By using the Latin hypercube with 20 points, the design matrix was obtained with a spread of values.
By conducting several simulations in Autodesk inventor with the design matrix, the various stress and mass values were then obtained. The regression was able to generate the function of the objective and constraints.
A linear regression was conducted to generate a function in order to optimize the mass. The linear regression was generated in the software Weka, which was a relationship between the thickness parameters and the mass, see equation 4.5 below.

$$Mass = 72.0237 \cdot x_1 + 5.4589 \cdot x_2 + 1788.9567 \tag{4.5}$$

A linear regression with a correlation between the thickness parameters and the von Mises maximum stress values was also performed to generate a function for the constraints, see equation 4.6 below.

$$\sigma_{Von-Mises} = -22.8287 \cdot x_1 - 3.6917 \cdot x_2 + 445.7954 \tag{4.6}$$

After obtaining the functions of the objective and constraints, an optimization algorithm was selected. The MATLAB program fmincon was used to implement SQP and IP algorithm. MATLAB's fmincon was used with IP algorithm with a total of five iterations, see Figure 4.20. The total number of iterations using the SQP algorithm was three, as shown in Figure 4.21. See Appendix A.1.1 for MATLAB code.

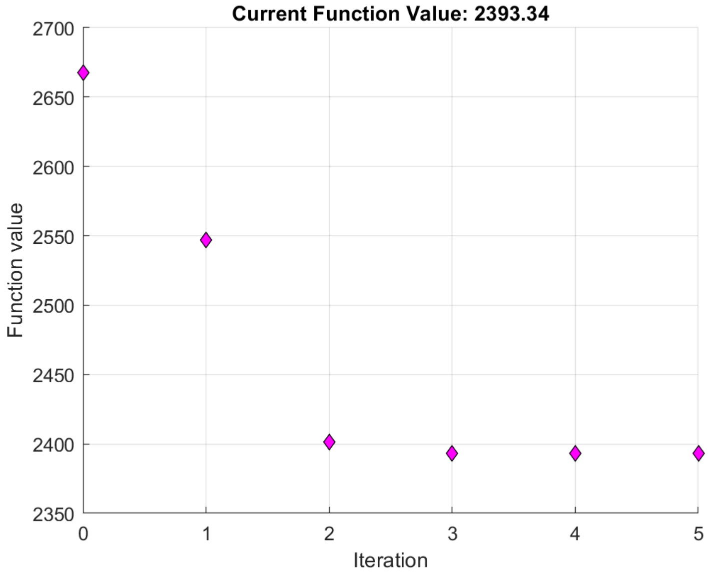

Figure 4.20: Iterative optimization process - Interior point algorithm

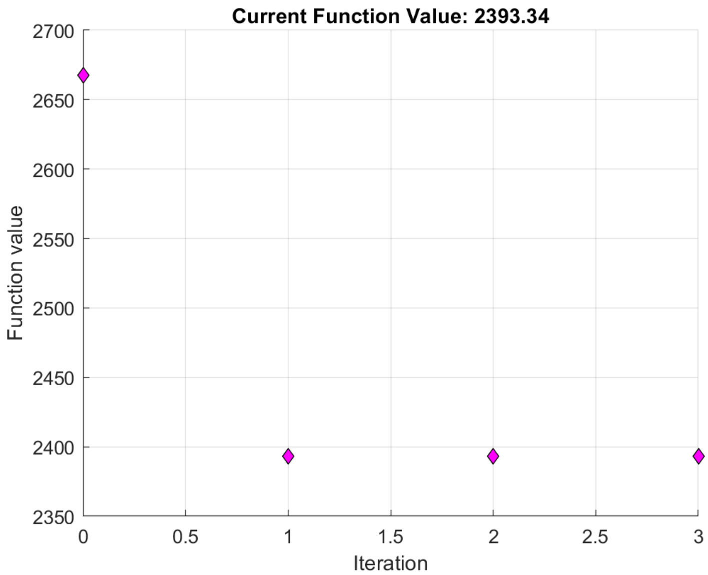

Figure 4.21: Iterative optimization process - SQP algorithm

The new obtained values can be seen in Table 4.5, where it can be seen that the mass and the first thickness parameter were decreased while the second thickness parameter was increased. The cable drum´s mass was reduced by 101.86 kg using IP and SQP algorithm. The regression model was verified by entering the new thickness values into Excel and running a new simulation. The values from the simulation were compared with the values that were obtained from IP and SQP algorithm, the deviation between the stress and mass values can be seen in the equations (4.7)-(4.8).

$$Deviation: \quad \sigma_{Von-Mises} = \frac{221.56 - 215.00}{221.56} \cdot 100 = 2.9608\% \tag{4.7}$$

$$Deviation: \quad Mass = \frac{2393.44 - 2393.34}{2393.44} \cdot 100 = 0.0041\% \tag{4.8}$$

Table 4.5: Optimization results

Parameters	**Initial**	**Interior point**	**SQP**	**Verification**	**Deviation [%]**
Thickness x_1 [mm]	9.00	6.87	6.87	6.87	–
Thickness x_2 [mm]	10.00	20.00	20.00	20.00	–
von Mises stress [MPa]	194.87	215.00	215.00	221.56	2.9608
Mass [kg]	2495.20	2393.34	2393.34	2393.44	0.0041

A FEA simulation of the design variables with 7 mm and 20 mm steps was performed, and the maximum von Mises stress was 209.9 MPa, as shown in Figure 4.22. This was performed whilst also keeping manufacturing requirements in mind, since the optimized design variables obtained were 6.87 mm and 20 mm, respectively.

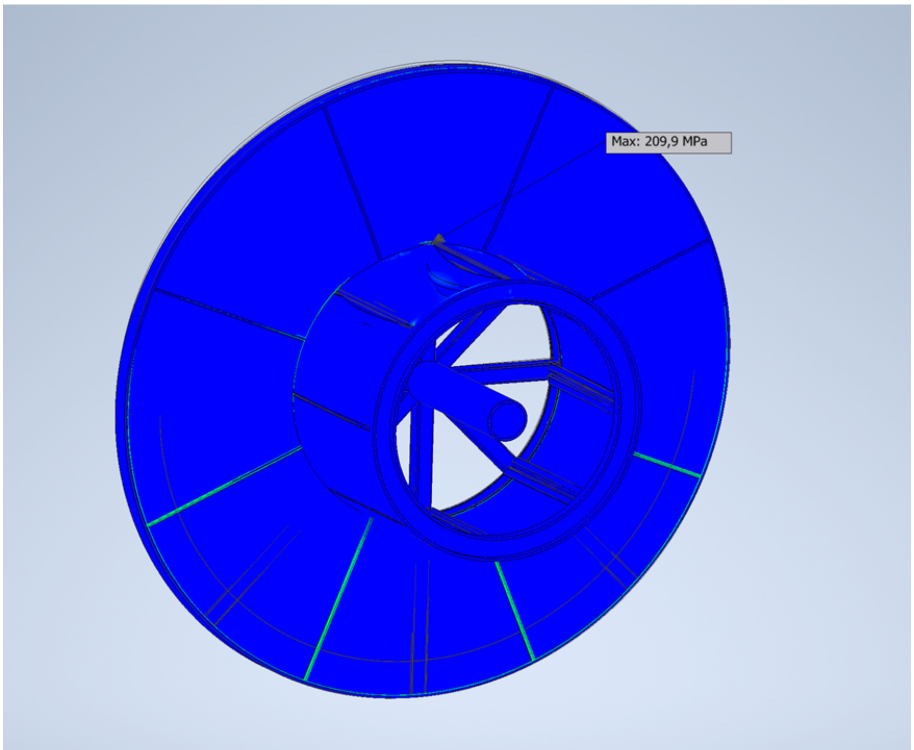

Figure 4.22: FEA verification considering the manufacturing requirements

Chapter 5

Discussion

5.1 Research methodology

The methodologies for this study were PAR and RE. This was a suitable match because NKT HV CABLE AB already knew what kind of information they required from this project, which was knowledge of the cable drum they use. NKT HV CABLE AB has received minimal information about the cable drums from its supplier. NKT HV CABLE AB could participate and obtain the desired information through this combination and the researchers shared the obtained knowledge. RE is the process of disassembling individual components of larger items. The RE process starts with extracting information, then modeling and this was particularly used during the acquiring data and the data analysis phase. The last phase of RE is to review the model which was executed during the analysis phase with FE simulations. The researchers made sure that the model that was created was almost exactly the same as the original product even with the assumptions that were made during the extract information process. To carry out a successive PAR

approach, the method should guarantee that those who will be affected have the opportunity to participate in selecting which parts of the problem will be managed. The organization should be allowed to engage in decisions on which measures to pursue. As a result, the researchers attempted to satisfy these requirements while working, and the findings indicated that they were satisfied to some extent. NKT HV CABLE AB, for example, was mostly involved in developing the project scope and, to a large degree, affected the project's route. NKT HV CABLE AB was mostly interested in the cable drums capacity since they do not receive that information from their drum suppliers.

The project was proposed by NKT HV CABLE AB, however, it was up to the researchers to define the investigation and what research questions were suitable for this project. The researchers came up with different suggestions for the team of NKT HV CABLE AB. After a few teams meeting, the scope and aim were defined. There have been a few updates on the results of the different research questions during the research. The systematic literature review was used to conduct the research about what approaches and possibilities exist when it comes to optimizing cable drums. The review showed that there is a lack of methods for optimizing specific cable drums but there are a lot of different methods and strategies regarding optimization. In this project, the only objective was to minimize the mass and the constraint was that von Mises should be less or equal to yield stress, this led to narrowing down the search area. To find more information, it was assumed that the cable drum had similar qualities to a pressure vessel, and this led to finding more articles and papers regarding optimization. There were a lot of papers regarding pressure vessel optimization by using different metaheuristic algorithms which could have been applied here if there were several variables involved. One paper regarding pressure vessels utilized the MATLAB fmincon function to optimize the design variables. In this project, the consideration was with the design variables within the midsection of the cable drum, which led to the use of MATLAB fmincon.

During the work process, the researchers often had meetings with the team from NKT HV CABLE AB, this was done so the team was updated on the project but also so they could have some inputs. If anything was going in the wrong direction or not suitable for the project, meetings were held to discuss and find a solution together.

RE is a method that is used often to duplicate or enhance the product. The method works by deconstructing products and learning everything about the product. In this case, the researchers were examining a cable drums capacity by conducting RE. Reverse engineering starts with the extracting information phase, and in this project, it was the measurement of the cable drum.

During the measurements, the researchers could not measure some parts and it was impossible to see what material was placed where on the drum, which led to making assumptions. Before making assumptions, the researchers discussed with the members of NKT HV CABLE AB to make sure that the right assumptions were made. It is important when it comes to assuming dimensions to consider the capacity, the drum should not be over-or under dimensioned and it should be close to the reference drum. The risks with assumptions are that the thickness might be over-dimensioned which may lead to some results that are not accurate or that the dimensions are too small which will lead to poor load capacity and this means that the drum will not meet the criteria for still managing the same capacity. There were some assumptions regarding the angles of the beams on the drum too, but there was a similar drum examined to make sure that the angles were accurate to the cable drum. After getting measurements and combining them with some assumptions, the extraction phase was ended and it was time for the modeling phase, and a CAD model was created. The CAD model was created with different parts such as the frame of the drum skeleton, the drum core, and rolled sheet metals. Then the parts were assembled to generate a complete CAD model for the cable drum. The main goal is to gain information from the original and create a general model that is used for extracting information and later can be used as guidance for designing new drums.

When it came to creating the model, some sections were not considered such as welding sections. The last phase was to review to built model, and this was done by running simulations that could verify the load and stress capacity. The values differed a small bit, and the reason is because of the assumptions of thickness on the drum but also since the material of the drum was set as steel S235. This showed that they were acceptable assumptions. RE is a suitable method to work within when it comes to problems where information about the product is needed or wanted. It allows one to get knowledge but also how the product can be improved.

5.2 Implementation

5.2.1 Optimization

The use of API was a useful technique to automate the CAD model, such as adjusting the desired thickness parameters while performing a simulation. There are major benefits to using API. For example, it is possible to develop several applications that can be used to analyze engineering and related situations. Using API during the project improved the optimization process by running multiple simulations and allowing the software that was needed to be linked. Figure 4.15 shows a well-explained illustration of how simulation process automation can occur. Excel is used as a server to control and as a link between the clients Autodesk Inventor and MATLAB. Hence, working directly from Autodesk to MATLAB and vice versa presents multiple difficulties. This is a preferable workflow in this project since it allows one to control the optimization process in a straightforward way.

The design parameters were chosen based on the locations with the highest stress values. The design variables required to have reasonable boundaries in order to minimize the cable drum's mass. The lower bound for the thickness design variable, for example, could not have been zero. The first design variable's thickness was reduced, while the thickness of the second design variable was increased. Hence, the maximum stress value with the initial value is already close to the yield stress limit, compromising the thickness based on which design variable has the least impact on the objective. Having additional design variables to minimize the objective would almost certainly result in a significant reduction of mass. The main focus was to implement the design variables where the stress values were at their highest, but different components where the stress values did not have a large impact could also be added to reduce the mass even further.

Linear regression metamodel is a useful method for determining the relationship between a dependent variable and one or more linearly behaved independent variables. In this project, using linear regression was a useful method to obtain the relationship between the input thickness variables and the output values in order to generate functions for the application of fmincon. The regression model verification showed a minimal divergence, indicating a good prediction. Furthermore, using a large number of independent variables does not always mean that the regression model is good. A preferable option would be to generate many regression models with different variable combinations, which can then be merged into a single regression model.

Optimizing the cable drum using the IP and SQP algorithm gave identical results. Although the fact that the results of different algorithms were the same, the IP uses a combination of a direct search utilizing the Karush-Kuhn-Tucker condition and a conjugate gradient utilizing a trust region for each iteration. The SQP algorithm, on the other hand, uses a quasi-Newton updating method to get the Hessian of the Lagrangian function, which then generates a Quadratic Programming subproblem to create a search direction for each iteration. The reason that the different algorithms obtained the same result might be related to the mathematical model being simple. The SQP method, on the other hand, converged to the optimal solution faster than the IP algorithm. The SQP required three iterations while the IP algorithm required five, showing that the SQP is more efficient with less computation time than the IP algorithm.

Chapter 6

Final remarks

6.1 Conclusion

The approaches and possibilities for a design optimization procedure for a cable drum while not compromising the yield strength capacity were examined in this research. It began with the formulation of two research questions, which was followed by the application of several research approaches, procedures, and software to answer the questions.

The combination of PAR and RE was suitable for this project since both approaches enabled together to extract information about cable drums capacity and different optimization methods. The systematic literature review gave information on what approaches and methods exist for other optimization problems such as pressure vessel optimization. However, it showed that there is a lack of papers when it comes to cable drums and suitable optimizing methods.

When it comes to extracting information in RE, taking measurement was used in this situation as a method. Since some parts were assumed, it is important to be cautious when assuming some parts. Some parts of the drum can not be too small since this would lead to a fragile drum, and some parts can not be too thick either because that would increase the weight and give false results during the simulations. It was essential for the researchers to consult with the drum specialist from the team to make sure that the right assumptions were made. Another point to consider when one is making assumptions is that it will influence the outcome of the results. The goal was to recreate the identical cable drum in order to extract information about its load and stress capacity, if the assumptions were incorrect, the results would be incorrect as well.

When it comes to the implementation phase, the schematic optimization workflow was appropriate to use. The workflow allowed full power to control the optimization process, the automation process is time-saving and the process is simple to adjust. The total mass of the cable was reduced by 101.86 kg without exceeding the yield stress limit of 215 MPa. Optimal design variables for the cable drum and the objective minimization by reducing the mass were accomplished.

6.2 Future work

For cable drums, future research could contain an investigation of different materials. In this project, steel S235 was used but several different steel materials could be a better fit regarding stress and load capacity. Also to conduct dynamic simulations of the winding sequence to gain information on the fatigue life of the drum. Other events impact the drum's fatigue life too such as the handle of the drum in the industries, example of events could be trucks that lift the drums incorrectly or collusion between trucks and drums. Conducting dynamic simulations with these aspects could gain some useful information when considering fatigue life.

When it comes to optimization, there are several methods and approaches to performing. Topology Optimization could be used to remove unnecessary material from specific cable drum components. The next step could include involving several variables for the drum, such as more design variables and considering welding. More objective functions could be applied, not just minimizing the weight of the midsection instead minimizing the whole drum and material cost. More constraints could be added such as fatigue life, static stress, etc. The Optimization process could include a fatigue analysis. By using a VBA script in Excel, the fatigue failure could be calculated automatically by simulating Autodesk Inventor. The API should be included in the VBA script to obtain access to the CAD model's material parameters, which will subsequently generate plotted fatigue curves. The results of the fatigue analysis will subsequently be transmitted to MATLAB for optimization. As constraints, the fatigue life and static stress could be applied.

If more objectives and constraints are added, the optimization problem could be solved by using global optimization algorithms based on metaheuristics, such as the genetic algorithm. In this case, there are several different types of metaheuristic algorithms that could be applied to this problem.

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Appendix A
Supplemental Information

A.1 Code: VBA script

```
Sub Main()

'%%%%%%%%%%%%%%%%%%%%%%%%%% Pre-requisite %%%%%%%%%%%%%%%%%%%%%%%%%%
' Make sure that you have added the Invertor Library in your reference available at:
' Tools -> References -> Autodesk Invertor Object Library -> Tick mark

'%%%%%%%%%%%%%%%%%%%%%%%%%% Get the application %%%%%%%%%%%%%%%%%%%%%%%%%%
Dim invApp As Inventor.Application
Dim InvParam As Inventor.Parameter
Dim OPartDoc As PartDocument
Dim oAssmemblyDoc As AssemblyDocument


Set invApp = GetObject(, "Inventor.Application")

'%%%%%%%%%%%%%%%%%%%%%%%%%% Set part file %%%%%%%%%%%%%%%%%%%%%%%%%%
Dim FilePath As String
FilePath = ThisWorkbook.Worksheets("Sheet1").Cells(1, 2).Value
Set oDoc = invApp.Documents.Open(FilePath)

If oDoc.DocumentType <> DocumentTypeEnum.kPartDocumentObject Then
    MsgBox ("A part file must be open")
    Exit Sub
End If
Set OPartDoc = invApp.ActiveDocument


'%%%%%%%%%%%%%%%%%%%%%%%%%% Set assembly file %%%%%%%%%%%%%%%%%%%%%%%%%%
Dim FilePath1 As String
FilePath1 = ThisWorkbook.Worksheets("Sheet1").Cells(2, 2).Value
Set oDoc1 = invApp.Documents.Open(FilePath1)

If oDoc1.DocumentType <> DocumentTypeEnum.kAssemblyDocumentObject Then
    MsgBox ("A assembly file must be open")
    Exit Sub
End If
```

```
Set oAssmemblyDoc = invApp.ActiveDocument
'%%%%%%%%%%%%%%%%%%%%%%%%%%% Input parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%
Dim DesVarNr As Integer
Dim ParamName As Variant
Dim ParamValue As Variant


DesVarStartNr = 5 ' User defined
DesVarEndNr = ThisWorkbook.Worksheets("Sheet1").Cells(Rows.Count, 2).End(xlUp).Row 'Last filled row
ReDim ParamNameRange(DesVarEndNr - DesVarStartNr) ' To make a list

For i = 0 To (DesVarEndNr - DesVarStartNr)
    ParamName = ThisWorkbook.Worksheets("Sheet1").Cells(DesVarStartNr + i, 1).Value
    ParamValue = ThisWorkbook.Worksheets("Sheet1").Cells(DesVarStartNr + i, 2).Value

    Set InvParam = OPartDoc.ComponentDefinition.Parameters.Item(ParamName) 'Select parameter by name
    InvParam.Expression = ParamValue

'    If InvParam.Units <> "Text" Then
'        InvParam.Expression = ParamValue
'    Else
'        InvParam.Value = Mid(InvParam.ExpressionList.Item(ParamValue), 2, Len(InvParam.ExpressionList.Item(ParamValue) - 2)
'    End If
Next


'%%%%%%%%%%%%%%%%%%%%%%%%%%% Output parameters %%%%%%%%%%%%%%%%%%%%%%%%%%%

OPartDoc.Update
oAssmemblyDoc.Update

Dim oMassProps As MassProperties
Dim dMass As Double

dMass = oAssmemblyDoc.ComponentDefinition.MassProperties.Mass
ThisWorkbook.Worksheets("Sheet1").Cells(5, 5).Value = dMass




'Dim StressValue As Variant
'
'StressValue = oAssmemblyDoc.ComponentDefinition.Parameters.ReferenceParameters.Item("sa_eq_max").Expression
'
'
'ThisWorkbook.Worksheets("Sheet1").Cells(6, 5).Value = StressValue
'sa_eq_max
'Dim dArea As Double
'
'
'
'    dArea = oAssmemblyDoc.ComponentDefinition.MassProperties.Area
'     ThisWorkbook.Worksheets("Sheet1").Cells(7, 5).Value = dArea
'
'
'
'Dim dVolume As Double
'
'
'
'    dVolume = oAssmemblyDoc.ComponentDefinition.MassProperties.Volume
'     ThisWorkbook.Worksheets("Sheet1").Cells(8, 5).Value = dVolume
'%%%%%%%%%%%%%%%%%%%%%%%%%%% Run Static Simulation %%%%%%%%%%%%%%%%%%%%%%%%%%%

OPartDoc.Update
oAssmemblyDoc.Update


'      'if stress simulation is activated
     Dim UIManager As UserInterfaceManager


 Set UIManager = invApp.UserInterfaceManager

'    Set UIManager = ThisApplication.UserInterfaceManager
```

```
If UIManager.ActiveEnvironment.InternalName <> "FEA Environment Internal Name" Then
'         'if it Is Not Activated

        Dim environmentMgr As EnvironmentManager

        Set environmentMgr = oDoc.EnvironmentManager

        Dim dsEnv As Environment

        Set dsEnv = UIManager.Environments.Item("FEA Environment Internal Name")

        Call environmentMgr.SetCurrentEnvironment(dsEnv)
    End If

'    'get [simulation] command

    Dim oCol As ControlDefinition

    Set oCol = invApp.CommandManager.ControlDefinitions("FeaSimulateCmd")

'     'send [enter] key to the dialog to mimic the clicking [Run]
Application.Wait (Now + TimeValue("0:00:10"))
SendKeys "{ENTER}", True
'Application.Run
''execute the command. The dialog will pop out and execute run automatically.
    oCol.Execute
'%%%%%%%%%%%%%%%%%%%%%%%%%%%% Static Simulation Results %%%%%%%%%%%%%%%%%%%%%%%%%%%%
OPartDoc.Update
oAssmemblyDoc.Update
'Dim StressValue As Variant
'StressValue = oAssmemblyDoc.ComponentDefinition.Parameters.ReferenceParameters.Item("sa_eq_max").Expression
'ThisWorkbook.Worksheets("Sheet1").Cells(8, 5).Value = StressValue
'%%%%%%%%%%%%%%%%%%%%%%%%%%%% Part update %%%%%%%%%%%%%%%%%%%%%%%%%%%%
UpdatePart:
OPartDoc.Update
```

A.1.1 Code: MATLAB

```
function mass = objectiveCable(x,UB,LB)
 x=(LB+x.*(UB-LB));

 mass =   72.0237 * x(1) +5.4589 * x(2) + 1788.9567

end

function [c,ceq] = constraintCable(x,ub,lb)
x=(lb+x.*(ub-lb));

c(1) = (-22.8287 * x(1) + -3.6917 * x(2) + 445.7954)-215

ceq=[]; % No equality constraints
end

clear all; close all; clc;


t1_initial = 9;
t2_initial = 10;

t1_min = 0.5*t1_initial
t1_max = 2*t1_initial
t2_min = 0.5*t2_initial
t2_max = 2*t2_initial

UB = [t1_max t2_max];
LB = [t1_min t2_min];

x0 = [mean([t1_min t1_max]) mean([t2_min t2_max])];
x1=((x0-LB)./(UB-LB));
lb=zeros(2);
ub=ones(2);


options = optimoptions(@fmincon,'Algorithm','sqp','display','iter','TolX'
'FiniteDifferenceStepSize',1E-12,'PlotFcn','optimplotfval');

[x,fval,exitflag,output] = fmincon('objectiveCable',x1,[],[],[],[],lb,ub,
grid on
```

```
x_new = (LB+x.*(UB-LB))


t1_opti = x_new(1);
t2_opti = x_new(2);

stress = -22.8287 * t1_opti + -3.6917 * t2_opti + 445.7954

ExcelName= 'CableDrum_vba_opti.xlsm';
run = actxGetRunningServer('Excel.Application');
myBook= run.Workbooks.get('Item',ExcelName);
mySheet= myBook.Worksheets.get('Item', 'Sheet1');
mySheet.Range('B5').Value= t1_opti;
mySheet.Range('B6').Value= t2_opti;
delete(run);
```

A.2 List of figures

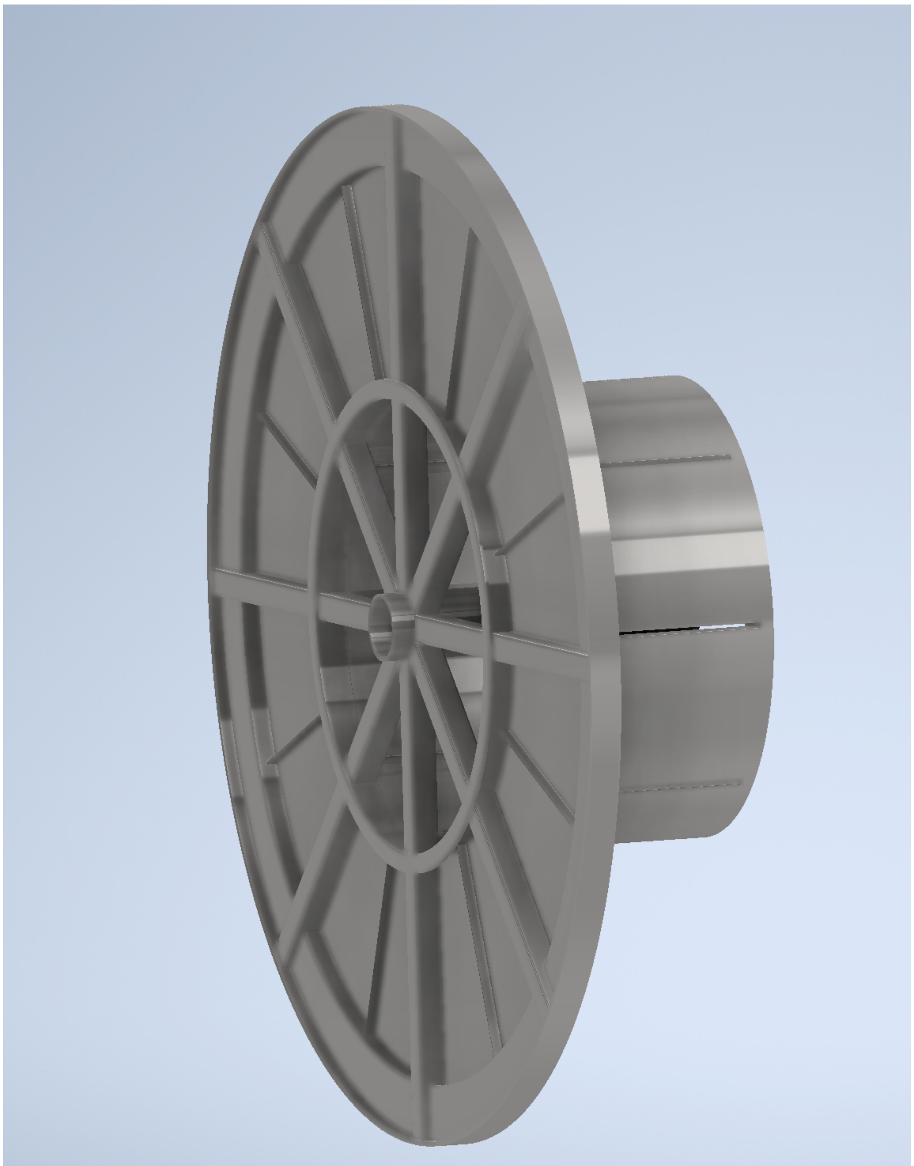

Figure A.1: The CAD model in Autodesk Inventor

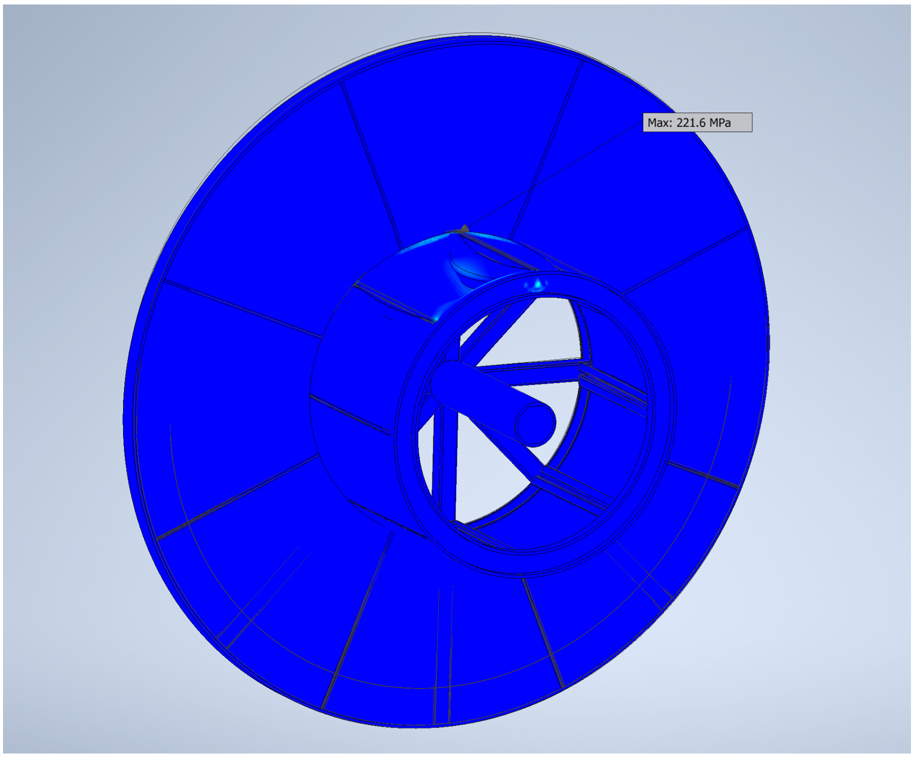

Figure A.2: Verification of the regression model

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