Detailed Design Report Group 1

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Contents

1 Introduction

A four-bar linkage pumpjack mechanism was developed and studied thoroughly. The pumpjack is expected to operate in the oil fields, exposing it to chemicals from the extracted oil. The surrounding environment is also expected to be a desert with sand storms. The initial requirements list for the pumpjack is mentioned in Table 1. The pumpjack design aims to resist wear from sand abrasion, chemical corrosion, and fatigue failure. Based on the findings of our previous reports, this report presents the final design, material selected, actuator, and bearings selected for the pumpjack. The bill of materials and an estimate of the cost of the machine is also presented. This report focuses on our team's learning outcomes, challenges while designing heavy-duty machinery, and how computer-aided tools made the process easier to grasp.

Table 1: Pumpjack requirements list

Requirements	Value	Level	Measure
Load capacity	13840 kg	Demand	From MBS simulation
Max. cycle time	6 sec.	Demand	From MBS simulation
Maximum weight	7 tons	Demand	From MBS simulation
Maximum length	10 meters	Demand	From MBS simulation

2 Components selection

2.1 Bearings

Bearings are machine components that facilitate the smooth rotation of the joints between the linkages. They reduce friction and wear by providing a low-friction interface between moving parts. Common types of bearings include ball bearings, roller bearings, and plain bearings. In order to choose the correct bearings, we need to know the dimension of the joints themselves. The required specification of bearings and the motor is according to the MBS simulation.

Table 2: Specifications for Joint Motors

Specs	Joint 1	Joint 2	Joint 3	Joint 4 (Motor)	Unit
Motor torque	167624	0	1723187	6714176	Nmm
Motor power	X	X	X	70310.6	W
Max joint force	377120	120590	62780	52059	N
Max joint angular velocity	17	21	71	0	degree/s
Motor speed	X	X	X	60	degree/s

To choose the bearing machine component, we use an online tool of SKF, a Swedish manufacturing company. The tool can be accessed at this hyperlink: https://www.skf.com/group/support/engineering-tools.

In order to choose the bearing component, it is required that we measure the dimensions of the joint. Since all joints share the same dimensions, it suffices to measure only 1 joint and use the same bearing component for all joints that are not the actuator. The required dimensions are bearing inner and outer radius, bearing thickness and shaft length. Using Measure Tool from ANalysis tab in NX, we can obtain the dimensions of the joint as follows.

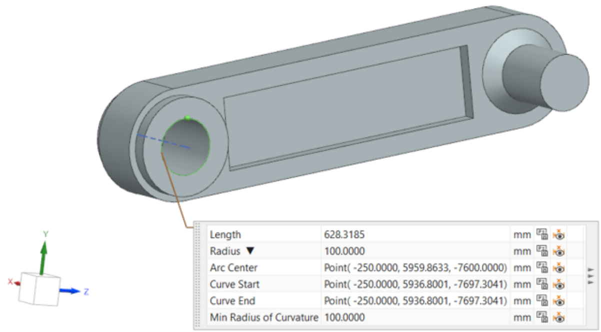

Figure 1: Bearing inner radius, d = 200mm

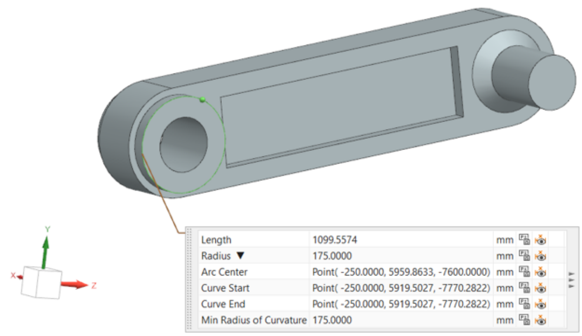

Figure 2: Bearing outer radius, D = 350mm

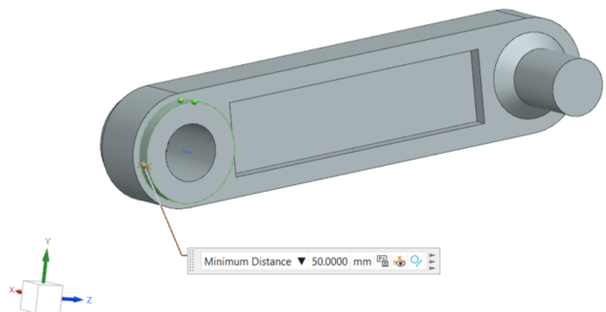

Figure 3: Bearing thickness, B = 50mm

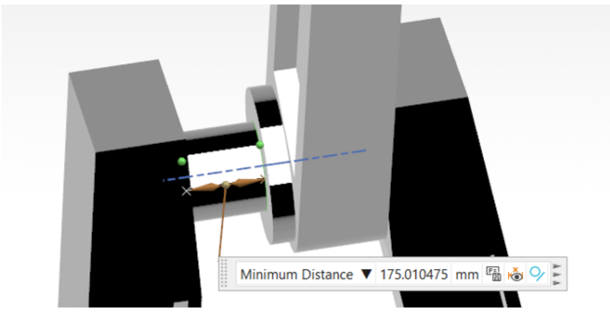

Figure 4: Shaft length connecting the bearings, L = 175 mm

After we have obtained the dimensions d, D, B and L, we can plug them into the tool and let it choose an appropriate component.

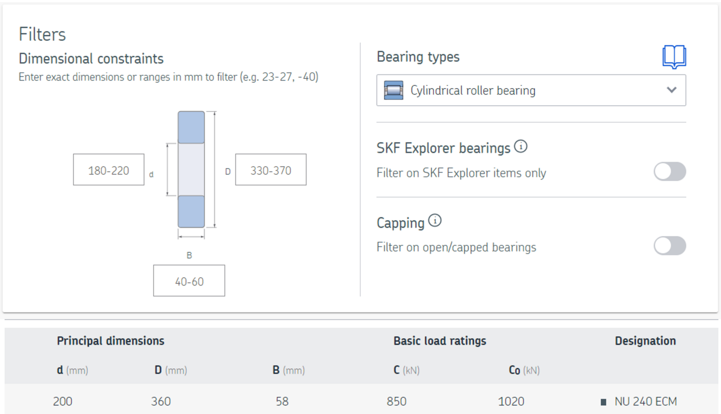

Figure 5: Bearing Selection for the actuator

The bearing type is chosen as the NU 240 ECM cylindrical rolling. This bearing can withstand heavy radial loads and high speeds. Additionally, it has high stiffness, low friction and long service life. The rollers are also protected from contaminants, water and dust, while providing lubricant retention and contaminant exclusion, which fits the working conditions of the pumpjack. This provides lower friction and longer service life [1].

Figure 6: Cylindrical roller bearing illustration

Then, we need to input the radial and axial force applied on the. From MBS report, axial force (Fx) is 0 N, since there is no transverse force. The radial force can be taken as the maximum joint force for Joint 1,2 and 3, which is 377120 N or 377.12 kN. The speed can be derived from the joint with maximum angular velocity, which is 71 degrees per second, or $71 \times 60/360 = 11.83$ rounds per minute. We can plug in this info for the configurations.

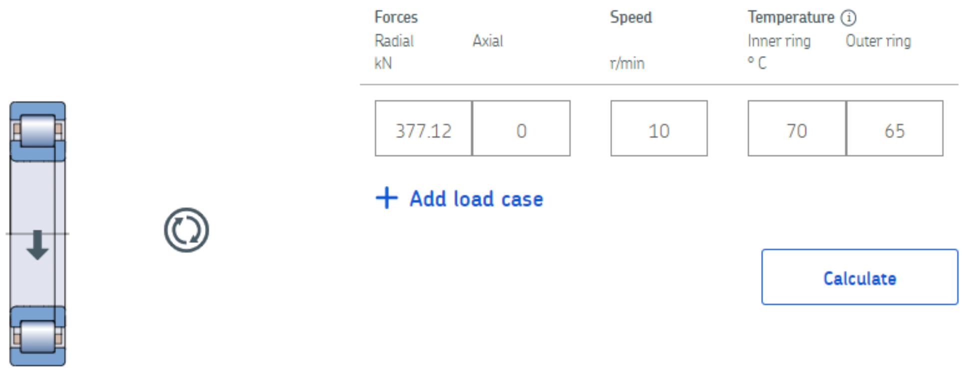

Figure 7: Bearing settings given the information from MBS

Then we calculate the results for all entries. The figure below shows that this type of bearing has satisfied all criteria, except that viscosity is a little bit low in bearing rating life since lubrication has not been chosen.

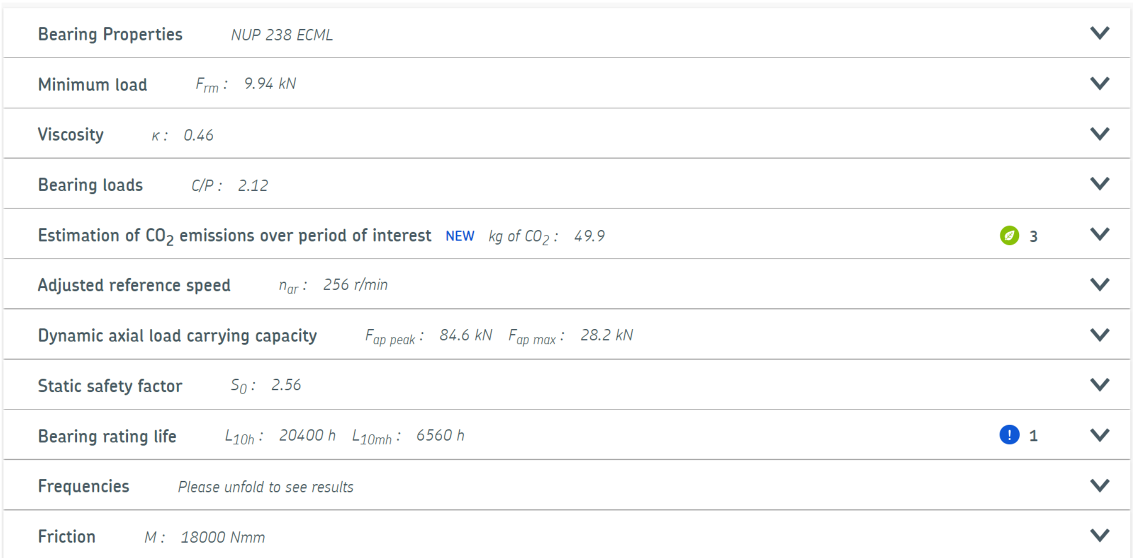

Figure 8: Results of bearing component selection

Conclusion: We choose cylindrical roller bearing, code NU 240 ECM for all the joints to reduce friction and increase lifetime service of the pumpjack.

2.2 Actuator

The same procedure can be applied for the actuator. However, the forces and speed are different. From table 2, we know that the maximum radial force applied on the motor is 52059 N, or 52.059 kN. The motor speed would be $60 \times 60/360 = 10$ rounds per minute. We plug the numbers into the calculations.

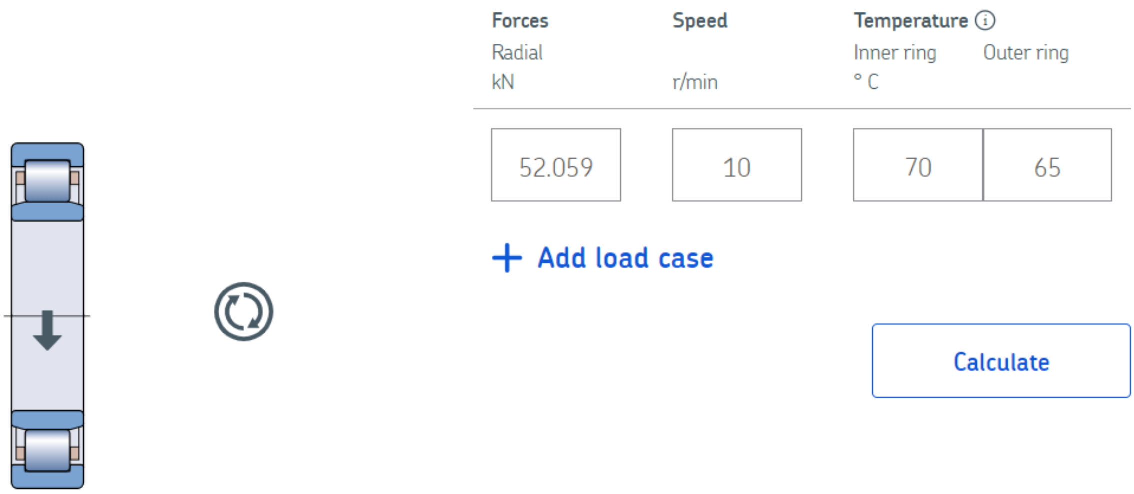

Figure 9: Bearing settings for the actuator given the information from MBS

The result yields all acceptable criteria. Therefore, we also uses the cylindrical roller bearing, code NU 240 ECM for the actuator.

2.3 Lubricant

On SKF, there are many types of oils, but they are categorized in 3 main groups: grease, oil with and without filter. Greases are just oils but with an added thickener. At room temperature, greases are usually solid, while oils are usually liquid [2]. We used the ISO VG grade oil, which stands for "International Standards Organization Viscosity Grade". The grade number is a number ranging from 2 up to 1500, which is critical because a lubricant's viscosity is the most important factor when selecting the right oil [3]. Because the pumpjack requires the high viscosity, we choose the maximum grade lubricant, which is ISO VG 1500 lubricant, which is an oil equipped with a filter, whose purpose is to remove contaminants from engine oil. This is important since the pumpjack operates in a dusty, chemical-present environment.

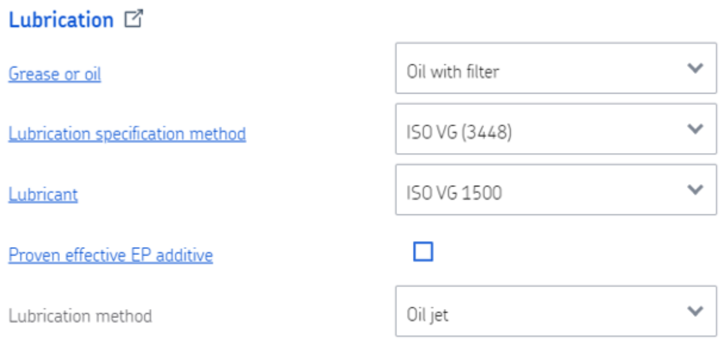

Figure 10: Lubrication choice: ISO VG 1500 oil with filter, using oil jet

In VG 1500 oil, very strong EP additives are added to ensure that the bearing is perfectly suitable for heavy loads and high temperatures [4]. This oil also functions very well when the gears are working under heavy or shock loads, which is true in the pumpjack's heavy loading conditions.

3 Material selection

For a pumpjack, the material needs to be of high strength, corrosion resistant, and durable in salt water. Based on these requirements, the material used for the simulations is AISI 410 stainless steel. The material mainly consists of iron, a high percentage of chromium, and other alloying elements like manganese and silicon, costing approximately 2 euros per kilogram (Granta EDUPACK). This grade of steel is primarily martensitic, which is a phase type that contributes significantly to strength and hardness. It can reach an ultimate tensile strength of 500-1400 MPa depending on the different heat treatments used in its production. The material shows good resistance to corrosion in air, water, and some chemicals [5]. This material is suitable for pump jacks, as it is highly durable in saline water, i.e., the material does not degrade even in high exposure to saline water. This material is economical as it is a low-alloy steel and is typically used in bolts, nuts, screws, coal mining equipment, pump parts and shafts, steam, and gas turbine parts, etc. Properties of AISI 410 stainless steel are shown in table 3.

Table 3: AISI 410 stainless steel material properties

Property	Value
Young's Modulus (E)	219.36 GPa
Poisson's ratio	0.268
Yield strength	483.1 MPa
Ultimate tensile strength	678 MPa
Thermal expansion coefficient	$9.68\times 10^{-}6^{\circ}C^{-}1$

4 Lifetime of selected components

In this report, we consider the lifetime of the chosen bearing NU 240 ECM and the lubricant ISO VG 1500. The actual lifetime of the bearing would be dependent on the rotating speed of the motor and how many times the pumpjack is turned on for gushing up the oils. Though, the pumpjack should be expected to last about 40-50 years, which can still operate without failure [6]. The cylindrical bearing NU 240 ECM is stated to be extremely durable and last a very long lifetime, but no concrete number is given since the wearing is dependent on different cases. Lubricant oil is applied once in a while to reduce friction, further increasing the lifetime of the bearing component.

5 Mechanism renderings

Rendering refers to the process of generating a visual representation from a model. It plays a crucial role in creating realistic and visually appealing graphics. It simulates the interaction of light with objects, textures, and materials, resulting in lifelike images. In product design, rendering helps communicate ideas and concepts to clients or stakeholders effectively. It provides a visual representation of what a final product or building will look like, allowing for better understanding and decision-making. Rendered images and animations are also extensively used in marketing and sales of products where the visual appeal is highly important. It serves as a cost-efficient way to create virtual prototypes, try out different designs and analyze how the different parts of the mechanism/product move.

Figures 11, 12, and 13 show the rendering images of the pumpjack from different angles. This pumpjack model does not include the actuators or bearings and will still need modifications to those components. Different effects like background, shadow, color, etc. were tried out to see which would optimize the visual appearance of the mechanism. Since the material chosen for our pumpjack is AISI 410 stainless steel, this same material was chosen in the rendering as well, which gives the gray, shiny metal finish. However, in order to protect the pumpjack from surround environment, paint finish will be applied to it.

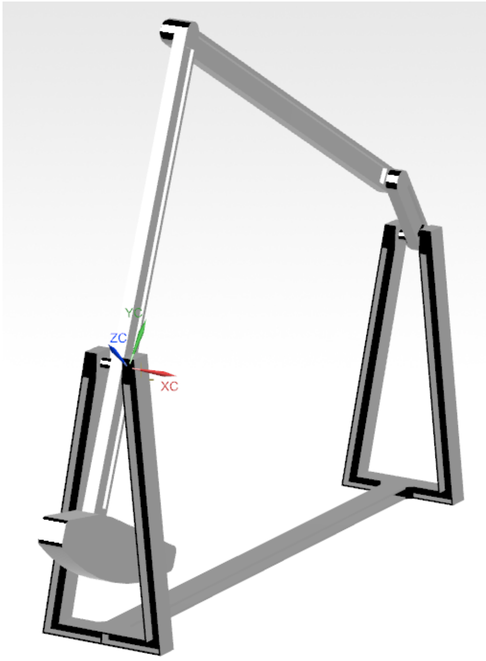

Figure 11: Pumpjack rendering side image

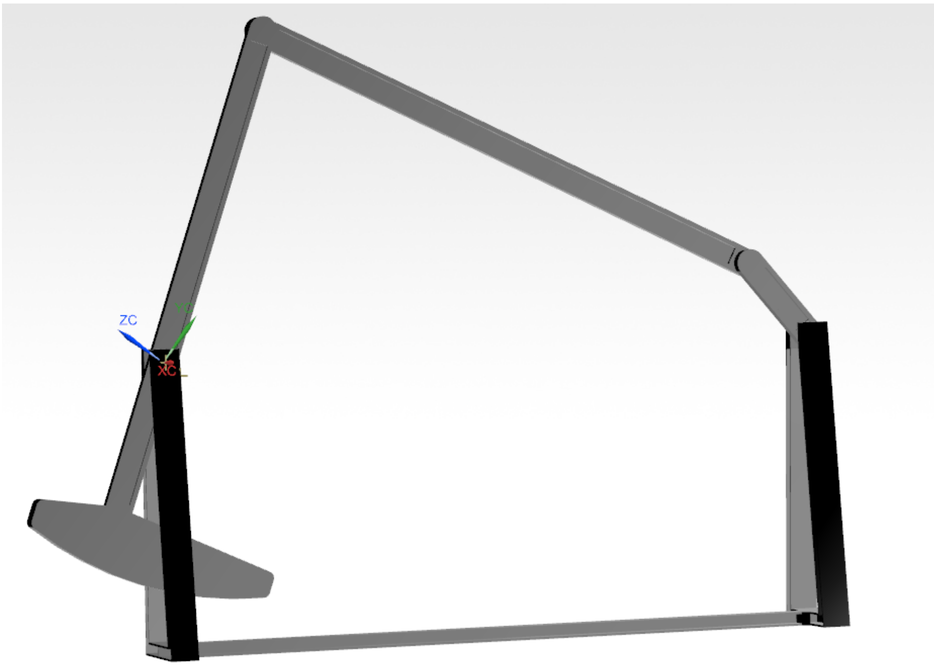

Figure 12: Pumpjack rendering front image

Figure 13: Pumpjack rendering back image

6 Consideration of original requirements

The total weight of the pumpjack mechanism parts without bearings, motor, and lubrication oil is 34,356 kg. This is well over 7000 kg, mentioned in the requirements list. This underestimation of weight shows the lack of understanding we had regarding the weight of heavy machinery components. However, we believe that with further FEM analysis and design optimization, the pumpjack components' weight can be further reduced.

The height of the pumpjack mechanism is around 9300 mm, and the width is slightly less than 11200 mm. These dimensions also exceed the original requirements presented in Table 1. This is simply proof of how focused our team was on ensuring the mechanism works instead of whether it fits within our required dimension. The level of both the maximum length and maximum weight was non-demand. Hence, once we are satisfied with our mechanism and have optimized the shape of each component, we can scale the design down or up based on customer needs. While scaling the model, we will keep the critical areas where the actuator mounts or bearing connections the same; only the overall length of the pumpjack and its carrying capacity will change.

7 Design process and application of computer tools

Product development can be done via hand sketching and hand calculations. Many historical constructions have been created without any or very little computer aid. However, if we want to make machines as efficient as possible with no materials wasted and the maximum performance possible, there are no substitutes for computer-aided tools.

The use of computer-aided tools has revolutionized the fields of product development and machine design. These tools encompass a range of software and technologies that streamline and enhance the entire product development and machine design process. From ideation to production, computer-aided tools play an indispensable role in accelerating innovation, improving efficiency, and ensuring the overall success of projects.

For the pumpjack design, we started with sketching and trying to explain the model to each other. However, we only fully grasped the model when we saw the first linkage simulation. Simulations and 3D models make technical communication much easier, especially when talking with customers. Our team started by sketching the mechanism on paper. However, on the same day, we moved on to the computer-aided tools, and an animation of the linkage mechanism was created. This is done via the Linkage open source software. Free body diagrams were drawn with the pictures from the linkage simulation and PowerPoint presentation tool. Once we had a basic understanding of the mechanism, joint selection was done using the Kutzbach criterion.

Skeleton models are used to understand the fundamental structure of a mechanical system without having all the details. They are highly efficient for visualizing the concept. They offer a clear and simplified visual representation of a machine's primary components, such as frames, linkages, joints, and critical connections. At first, we created a skeleton model of the pumpjack mechanism and then used it to carry out a kinematic simulation. Kinematic simulation is a powerful computational tool that focuses on understanding the motion and behavior of mechanical systems. It is used to understand the movement of components within mechanical systems, focusing on positions, velocities, and accelerations while disregarding the forces and torques responsible for this motion. A kinematic simulation of our pumpjack mechanism was done with Siemens NX to ensure that the mechanism works. The simulation was carried out successfully, and the results ensured that the mechanism would move as the team expected.

After confirming the pumpjack mechanism with the kinematic simulation, a 3D model of the pumpjack was created using Siemens NX. Dynamics simulation is used to study the time-dependent behavior of machines. Dynamics simulation delves deeper by considering the intricate forces, torques, and motion-related variables that impact the motion of objects or components within a system. It encompasses the interactions between bodies, as well as their responses to external forces and internal interactions. A dynamic simulation of the pumpjack mechanism was done, and an animation of the pumpjack's dynamic simulation was created with Siemens NX. The most important learning outcome of the dynamics simulation was understanding the direction and values of forces and torques on each joint. The results were similar to what we expected from the pumpjack's force body diagram.

FEM is extensively used in structural analysis for understanding how structures deform and distribute stresses. It is vital for ensuring safety, optimizing designs, and identifying failure points. FEM analysis is a numerical simulation method used to analyze complex physical systems and calculate their various engineering aspects. It is utilized to understand the behavior of structures under various load and boundary conditions. Based on the values of different loads' and their direction on each joint, we carried out FEM analysis using Siemens NX and Ansys. After looking at FEM results and understanding the components with maximum load and deformation, we moved on to optimizing the design. We removed extra materials from the areas with sufficient strength and added more material to the areas with stress values close to the material's ultimate strength. The FEM results were beneficial for visualizing stress and deformation in our model and optimizing the design.

Lastly, Siemens NX was used to create the rendering and bill of materials. Both of these tools help ease the communication between the designer and the manufacturer. Computer-aided tools also make the selection of components, such as bearings, motors, screws, nuts, bolts, etc., easier. Adding the models of these components to the design will also help the designer ensure that the design can be manufactured and assembled.

8 Cost estimate

There are multiple factors to consider the cost estimate of a pumpjack machine. Although we do not have a specific budget, it is still important to come up with a solution that is as cost-efficient as possible. The main contributor to the cost of our pumpjack machine is material cost. The material used, as previously mentioned, is AISI 410 stainless steel. The cost per kg of this material is 2 euros (Granta EDUPACK). Table 4 shows the total mass of each of the linkages of our mechanism. This value is multiplied by the cost per kg of the material. The costs for each of the linkages are also mentioned in table 4.

Table 4: Weight of the pumpjack linkages

Linkage name	Weight (kg)	Costs
AB	11343.9	22687.8 €
BC	2884.9	5769.8 €
CD	929.4	1858.8 €
DE	19197.6	38395.2 €

The cost of NU 240 ECM bearing component is estimated at 1484 €per one item. Its price can be referred from this link. Additionally, the cost of one bottle of VG1500 oil is estimated at 6 euros. We assume to use at least 30 bottles during its lifetime. Its price can be referred from this link. Finally, the labor cost to build this pumpjack is estimated to be at 450000 USD (427 972 €) based on its power capacity, which is estimated at 70kW, or 0.7 MW [7]. Along with material and labor costs, it is important to consider processing costs. Most of our components need to be welded together, so this would also be a factor to consider in our cost estimate. Therefore, the total estimated costs of building the pumpjack is

$$22687.8 + 5769.8 + 1858.8 + 38395.2 + 1484 \times 2 + 6 \times 30 + 427972 = 499831.6€$$

Half a million euros is required to build this pumpjack, which is expected given its very long lifetime. It is clear that most of the total cost is labor cost.

9 Bill of materials (BOM figures)

A Bill of Materials (BOM) is a comprehensive list of all the components, parts, and materials required to manufacture a product. It serves as a structured document that provides detailed information about the product's composition, including part numbers, quantities, descriptions, and reference designators that indicate where each item is used in the assembly. BOMs are commonly used in various engineering industries to ensure accurate production, inventory management, and product documentation. Overall, a well-structured BOM is a fundamental tool for efficient and accurate manufacturing and assembly operations. In a BOM, there are many views, such as the top or isometric view. Our mechanism is in meters, so we need to scale it by 100, since the original BOm drawing is in millimeters. In order to change to scale, we click on little triangle under New Sheet, then click Edit Sheet. Then we change the scale from 1:1 to 1:100. To edit the information table, we click on Menu tab under New Sheet icon, Format, Layer Settings. Hover on the information table and click OK. To turn off the Black Wireframe, go to Menu, Preferences, Drafting, then find the Wireframe and turn it off. Below are two drawings of our pumpjack: The dimension drawing and the BOM drawing. We are stuck at how to suppress the datum plane in the BOM plane. It would be nice if the professor would help us how to turn it off in the feedback

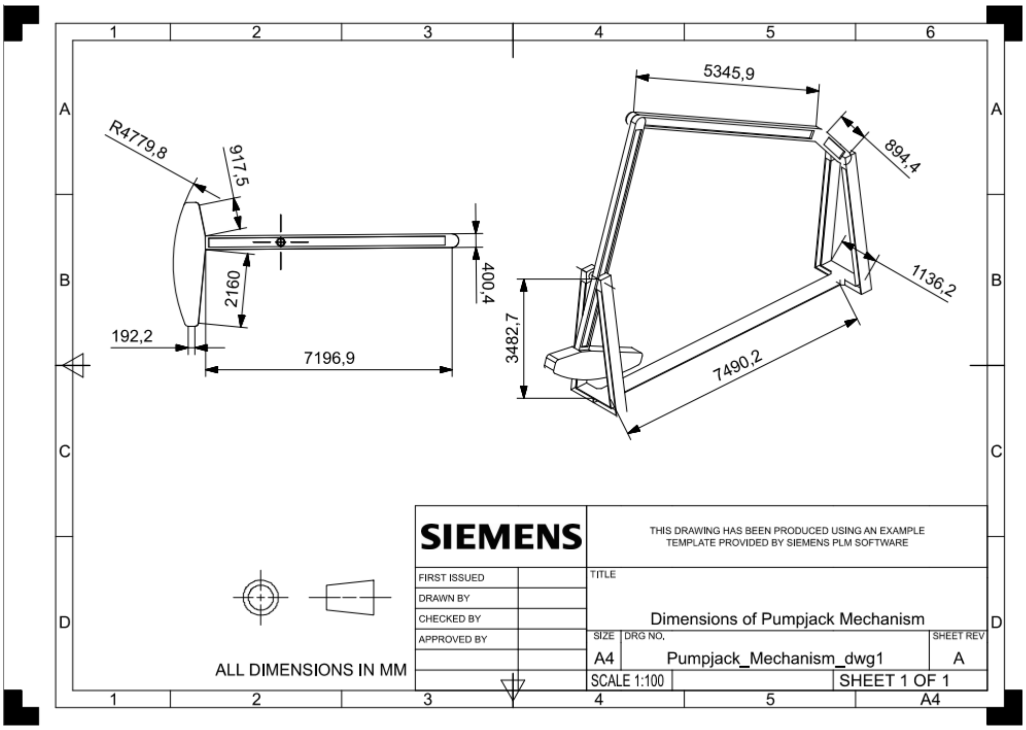

Figure 14: Dimensions drawing of the pumpjack mechanism

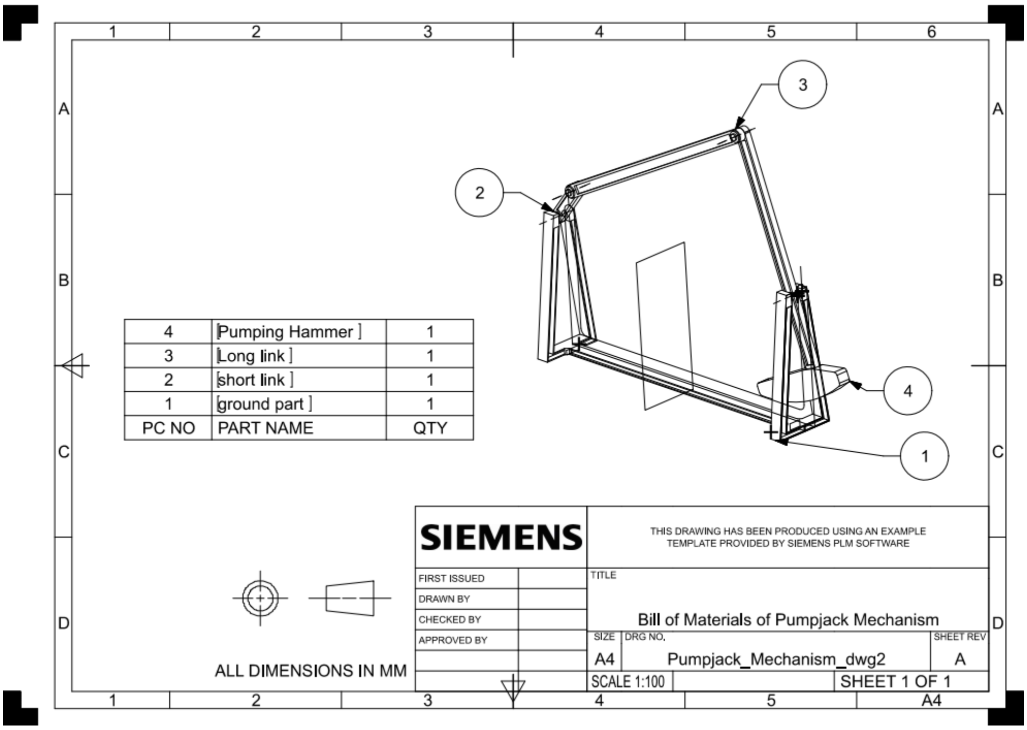

Figure 15: BOM drawing of the pumpjack mechanism

10 Animation

The animation for the mechanism has been created using the Animation Design tool in the NX software. Figure 16 shows the final mechanism along with the joint names. Joint 1 and 4 are revolute joints, joint 2 is cylindrical and joint 3 is spherical. The different joints were decided during the kinematic simulation of the MBS phase. In the animation design tool, each of the four linkages were defined as a rigid body, and the joints and associated vectors and points were selected. A speed motor was set at joint 4 to drive the mechanism and the animation was allowed to run. The animation can be viewed from the file 'pumpjack_animation.avi'.

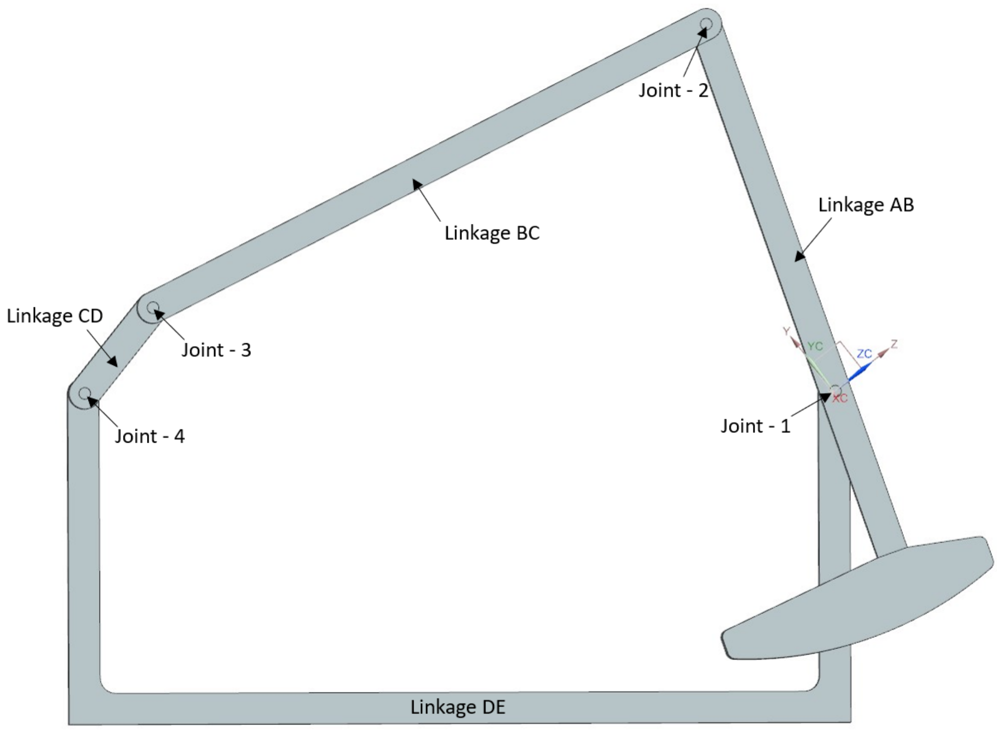

Figure 16: Pumpjack linkages' and joints' names

11 Discussions

This week was the first time our team looked at the maximum weight and length requirements we had agreed on during week one. We were all surprised that even though we ensured that our mechanism worked and was strong enough to carry the load, it exceeded both the maximum weight and length requirements. These requirements could have been confirmed at quite an early stage of the design. This made us realize the importance of constantly checking the requirements list rather than focusing on only one design aspect at a time. It is a balance of multiple design aspects that must be met.

12 Learning outcomes

The most important part of this course was learning about computer-aided tools for machine designing, how they are used in the industry, and how to use them. Although we understand that our pumpjack is far from being good in any way, designing a very simple mechanism and focusing on how to use the computer-aided tools is our most valued learning outcome. Our knowledge of which tool to use for what and how to use these tools has increased drastically. Even though we have only learned how to use Siemens NX, we believe it is learning how to use the tool that is important, and once we know how to use one, we can slowly figure out how to operate other software relatively easily.

After having written several reports, we understand how these tools can assist us in designing and removing one uncertainty at a time. This course also taught us what exact questions to ask while designing anything and how to answer one question at a time. Iterating the requirements list and the design process is also easier if the computer tools are adequately utilized. We had a first-hand experience of this while trying to optimize our model during FEM analysis. Because of our combined efforts, we expect to receive a grade of 5 for this report. We extend our thanks to the teaching assistants who had greatly helped us during this course.

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