Adaptive Grease Level Monitoring System

Lukas Nilsson

DIVISION OF INNOVATION | DEPARTMENT OF DESIGN SCIENCES
FACULTY OF ENGINEERING LTH | LUND UNIVERSITY
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MASTER THESIS

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Lukas Nilsson

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Abstract

Today, Sandvik does not measure the grease level in one bushing housing in their rock crushers. They use high-viscosity grease, and this master's thesis aims to measure when the level becomes too low.

Many industries, including rock processing, focus on sustainability. On that mission, reducing waste and energy usage and improving efficiency are essential. A well-lubricated system is vital to maximizing efficiency and minimizing wear. When the grease level becomes too low, friction will increase, and there is also the risk of catastrophic failure, resulting in prematurely swapping parts.

Measurement technologies were researched to determine which could be suitable. Needs and requirements were gathered, and concept selection methods were used to narrow them down. Then, different mounting solutions were also researched and evaluated similarly.

Three different sensors were tested. An ultrasonic distance sensor did not perform nearly as well as predicted and had to be scrapped. A capacitive sensor was decent but had some drawbacks. A tuning fork-type level sensor was deemed the most suitable solution, fulfilling all the requirements.

There is not much research done on measuring high-viscosity grease, and certainly not in such an extreme environment as a rock crusher. This thesis researched many possibilities and compared their pros and cons. Three completely different technologies were also tested, and two were compared in the rock crusher. This thesis shows that it is possible to measure grease in this environment; you just have to find a suitable sensor.

Keywords: level-sensing, high-viscosity grease, cone crusher, product development

Sammanfattning

Idag mäter inte Sandvik smörjfettnivån i ett bussningshus i sina stenkrossar. De använder ett högvisköst smörjfett och målet för detta examensarbete är att mäta när nivån blir för låg.

Många industrier, inklusive stenkrossning, fokuserar på hållbarhet. För att uppfylla de målen som är satta är det viktigt att minska avfall och energianvändning och förbättra effektiviteten. Att alltid ha ett välsmort system är avgörande för att maximera effektiviteten och minimera slitaget. När fettnivån blir för låg ökar friktionen och det finns även risk att bussningen skär, vilket leder till att den behöver bytas ut i förtid.

Olika mättekniker undersöktes för att avgöra vilka som kan vara lämpliga. En behov och krav-analys gjordes och olika metoder användes för att avgränsa urvalet. Efter det undersöktes och utvärderades även olika monteringslösningar på liknande sätt.

Tre olika givare testades. En ultraljudsgivare testades som inte alls presterade så bra som förväntat och gick därmed inte att använda. En kapacitiv givare som testades var användbar men den hade några nackdelar. En stämgaffelgivare ansågs vara den mest lämpliga lösningen och den uppfyllde även alla kraven.

Det finns inte tillräckligt med forskning gjord på att mäta högvisköst fett, och absolut inte i en så extrem miljö som en stenkross. I rapporten undersöktes många olika alternativ och deras för- och nackdelar jämfördes. Tre helt olika mättekniker testades också, och två jämfördes i stenkrossen. Rapporten visar att det är möjligt att mäta fett i denna miljö, det gäller bara att hitta en lämplig givare.

Nyckelord: nivåmätning, högvisköst smörjfett, konkross, produktutveckling

Acknowledgments

I want to thank my university supervisor, Axel Nordin, for providing feedback and support during my master´s thesis.

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Lund, May 2024

Lukas Nilsson

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1 Introduction

This section introduces the company, the problem itself, and the objectives.

1.1 Background

Sandvik is a world-leading industry group in three different business areas: "Mining and Rock Solutions," "Rock Processing Solutions," and "Manufacturing and Machining Solutions." This master's thesis has been performed in the business area of "Sandvik Rock Processing Solutions" (SRP), which specializes in equipment for processing rocks and minerals in the mining and infrastructure industries. [1]

Sandvik is focusing on delivering more sustainable solutions to its customers and has a goal that rock processing should reach a net-zero climate impact. To achieve net zero, the industry needs to be circular and productive. A part of that is looking at resource efficiency and how it can be improved. Another part is reducing energy usage and improving efficiency. [2]

Sandvik SRP AB is a company specializing in rock processing solutions. In Svedala, Sandvik manufactures different types of rock crushers, mainly cone crushers. The cone crusher uses a conical mantle that rotates eccentrically to crush rocks. It is made in various sizes and is used in the mining and infrastructure industries.

At the moment, Sandvik is developing its offerings to become more sustainable. Two specific areas that Sandvik prioritizes are reducing waste and maximizing energy efficiency. [3]

1.2 Problem description

In this master´s thesis, a level monitoring system must be developed for the spider bushings' round grease chamber. The spider bushing is one of the main bushings for the axle. The grease chamber has a moving axle in the center, which rotates and moves axially. Depending on its position, the top of the axle will either be dry or submerged in grease. Although different grease variants will be used depending on the crusher's application, all the grease variants will be highly viscous.

Measuring the grease level is essential for several different purposes. The first is to maximize operational time. The second is to make the cone crusher more connected and easier to monitor. Finally, the last purpose is to monitor the state of the grease level to plan preventative maintenance.

1.3 Objective

The objective is to develop multiple concepts of and finalize a functional level-monitoring system. The solution must consider the axle's axial movement and the highly viscous grease.

1.4 Thesis structure

The report has been structured in a similar order to the steps that were performed. First, the literature study was done, which can be found in Chapter 2. Then, the methods used in the project were gathered in Chapter 3. It is also essential to clearly understand the needs and requirements throughout the development process. Therefore, they were gathered at the project's beginning and are shown in Chapter 4. Based on the gathered theory, the measuring technology chapter (5) could be started with brainstorming, screening, and testing. After deciding on which technologies to move forward with, the mounting system for the sensors could be developed. This was done by brainstorming, screening, and testing, and the results are gathered in Chapter 6. Then, the final concept could be constructed based on the earlier tests, and it is presented in Chapter 7. Finally, the final results are discussed and concluded in Chapter 8.

2 Theory

This section presents the necessary theory about how a cone crusher functions and various measuring technologies.

2.1 Cone crusher

A cone crusher is a specific type of crushing equipment used in industries such as mining and infrastructure. Cone crushers are a popular type of rock crusher, and a likely reason for that is their simplicity, with few moving parts. The few moving parts make them easy to maintain and less likely to break. [4]

A cone crusher works by having a conical mantle rotating eccentrically with a predefined gap to another fixed surface called a concave. The feed drops down from the top, and the eccentrical motion of the mantle crushes the rock each rotation, causing the rocks to fall further into the chamber until they become smaller than the gap, causing them to fall through. Figure 2.1 shows this process. [4]

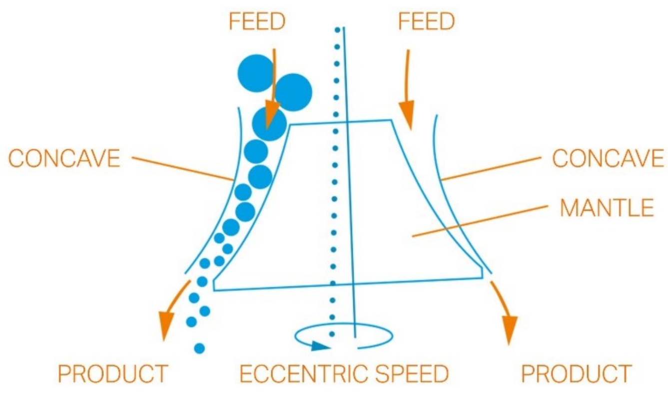


Figure 2.1 Material flow in the cone crusher. [5]

Figure 2.2 shows a section view of one of Sandvik’s cone crushers. The arrow in the upper part of the figure points to the bushing housing that will be the focus of this master's thesis. It is different from the other lubrication points of the main shaft as it is the only point that needs to be greased.

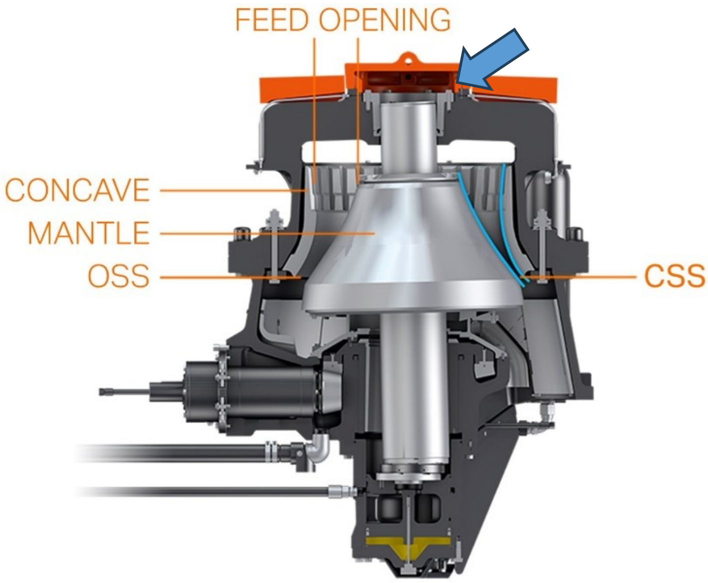


Figure 2.2 Section view of a Sandvik CH cone crusher. [6]

2.2 Measurement technologies

There are many different measurement technologies integrated into many different types of sensors. All sensors work in different ways and can measure different things. For this project, sensors that can measure distance, level, proximity, and weight have been researched.

In Figure 5.1 and Figure 5.2, the researched sensors are categorized by their measurement technologies and what they measure.

2.2.1 Capacitive sensors

A capacitive sensor is commonly used to measure the presence of non-metallic objects. It can be used for several different applications, including measuring fluids. The sensing distance will depend on the target's dielectric constant. The distance that can be measured will increase with a larger dielectric constant, and therefore, the material needs to be accounted for when calibrating the sensor. The sensor measures changes in the electrostatic field. [7]

Capacitive sensors can measure the position of a conductive target with great precision and are not affected by the target's thickness. They are known for high resolution, frequency, and temperature stability. However, they are sensitive to the material between the sensor and the target and will, therefore, not always function in a dirty environment. [8]

2.2.2 Conductive sensors

A conductive sensor can measure when a fluid passes a set level. Using two electrodes, a signal can be carried between the electrodes when the distance is bridged by a conductive fluid. This is a reliable way to measure as it is not affected by environmental changes, and the state of the fluid will not affect it either, as long as it is still conductive. The output will act like a switch, being on when fluid is present and off otherwise. [9]

2.2.3 Electromagnetic radiation sensors

Electromagnetic radiation, more commonly known as light, is used to measure proximity, level, and distance. Depending on the type of sensor used, different frequencies will be used for the measurements.

Time-of-flight (ToF) is one way to measure distance with electromagnetic radiation. This type of optical sensor normally uses infrared laser or infrared LEDs. [10] To measure the distance, it outputs a light signal and measures the time it takes to bounce back. [11] As the speed-of-light is very fast, they are generally used to measure greater distances with high accuracy. [11]

Infrared LEDs are also commonly used for proximity measurements. Using infrared light and a phototransistor, the light will trigger the transistor when a certain amount of light bounces back. This threshold will be calibrated depending on the environment but can vary between 0 and 2 m. [11]

Radar uses microwaves to measure distance. It is a proven technology used when measuring levels and is not affected by changes in the environment, such as obstructions, steam, temperature, and turbulence. Radar works by outputting a microwave signal at the liquid surface and measuring the phase difference of the reflected signal. As it uses microwaves, licenses may be needed to operate it. [12]

Guided wave radar (GWR) is similar to through-air radar, but instead of using the air as a transmitter for the microwaves, the waves are guided through a probe. A radar pulse is sent through the probe, and when that pulse hits the fluid, it reflects it back to the sensor. Then, the time between those events is measured and converted to a level. GWR is unaffected by changing environmental conditions such as pressure, temperature, and density. The sensor is usually mounted at the top of the tank. [13]

Inductive proximity sensors can measure the position of a conductive target. They emit an electromagnetic field into the target, inducing a small electrical current that the driver can measure. They are used for both ferrous and nonferrous metals. [8]

2.2.4 Mechanical wave sensors

Ultrasonic sensors are commonly used to measure the level of highly viscous liquids. They work by the time-of-flight principle: They send out a sound wave, detect when it has bounced back, and calculate the distance based on the time difference. They can be used to measure the surface level of the liquid both from above and from the bottom. [12]

2.2.5 Piezoelectric sensors

A piezoelectric sensor can be used in the format of a vibrating level sensor or switch. The vibrating level sensor works by having a hollow tube generating vibrations at its resonant frequency. The resonant frequency of the probe will vary with how much of it is submerged in the fluid. A circuit will be used to change the excitation frequency to find the new resonant frequency, thereby detecting the depth of submersion. The sensor is somewhat affected by buildup on the probe. A variant of the sensor is the vibrating level switch which detects when there is a step change in the vibration frequency. [12]

2.2.6 Piezoresistive sensors

Pressure can be measured by using a piezoresistive pressure transducer. They are based on a diaphragm that can be made from materials such as plastic, metal, or silicon. The chosen material will depend on the environment and the needed accuracy. The most common diaphragm is made of silicon with diffused resistors on the diaphragm and is very small. They can be accurate up to ±0.1% and can have automatic temperature compensation and calibration procedures built in when they are combined with an analog-to-digital converter. [14]

There are a few ways to implement a pressure-measuring device. If it is a sealed unit, it can measure the differential pressure by using tubes or adding air, which is called a bubbler. If it is an open chamber, it can just measure the air directly. [12]

Figure 2.3 shows schematics of three different ways to implement a pressure transducer.

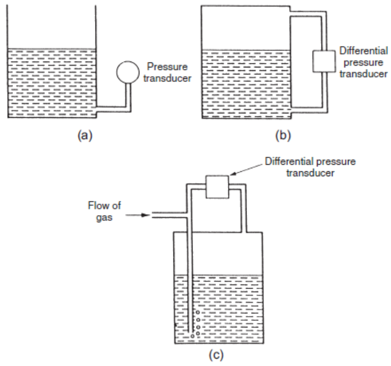


Figure 2.3 Schematic of different pressure transducers. [12]

2.2.7 Nucleonic sensors

A nucleonic sensor uses a radiation source and a detector. It is two separate parts that both can be located outside of a tank. The absorption of the rays depends on the current level in the tank and can, therefore, easily detect level changes. Common sources of gamma rays are caesium-137 or cobalt-60. The intensity varies by the length of the ray traveling through the liquid. It is a relatively expensive technology, and very strict safety regulations apply when using this technique. The advantages are that it can be mounted on the outside and it can measure any fluid or solid. [12]

2.2.8 Switch sensors

A floater can be used as a switch for when the liquid surpasses a predetermined level. It consists of a float and some kind of transducer or switch, depending on the specific sensor. It is a simple and cheap system, but it can only give rough measurements. The main drawback is high maintenance. [12]

3 Methods

This section contains the methods used in this project. It specifies the methods used for planning and designing and how they were applied during the project.

3.1 Project plan

When starting the project, a plan had to be made. The project's main activities were first specified, and a Gantt chart was created. All the steps were carefully assigned weeks that they should be worked on. All the deadlines for the report and the presentations were used to figure out when the project had to be finished. During this phase, the project's depth was considered to ensure enough time to complete the project. All the supervisors also verified the plan to be reasonable. The Gantt chart has been attached in Appendix A.

3.2 Design and development process

The design process methodology used in this project was based on the book "Product Design and Development" by Ulrich, K. T. & Eppinger, S. D. Figure 3.1 highlights the main steps needed when developing a new product. [15]

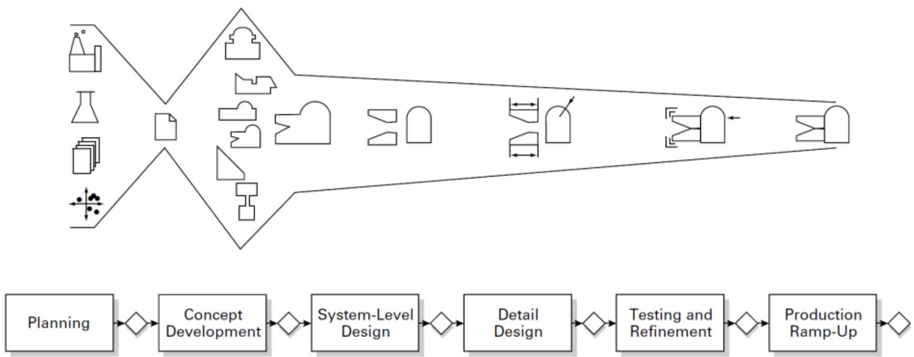


Figure 3.1 The main steps in the product development process. [15]

The process has been altered to suit this master's thesis as it is not a new product but rather a modification to an already existing product that will be designed. The problem has also been condensed into two different parts: the measurement technology and the mounting solution.

This master´s thesis focuses on the concept development process shown in Figure 3.2. The first two steps in the figure, "Identify Customer Needs" and "Establish Target Specifications," have been condensed into one step for this project. This is because the needs were already established before Sandvik announced this subject. The thesis only needed to clarify the needs and create the target specifications in close collaboration with the stakeholders.

The later steps would be more closely followed for the project's different parts: generating, selecting, and testing concepts, followed by setting the final specifications. Sandvik also wanted to focus more on creating and testing multiple different concepts rather than focusing on one and making it production-ready.

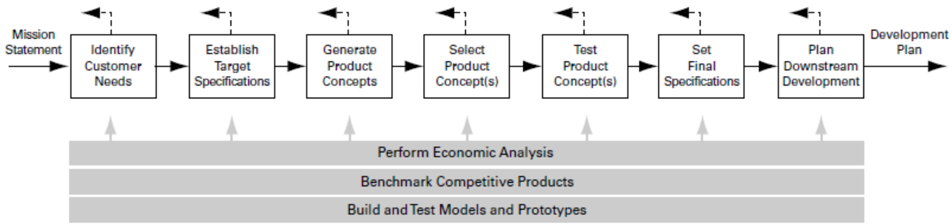


Figure 3.2 Concept development process. [15]

The following subchapters describe which methods can be used for the different development steps. In those chapters, there will also be descriptions of how those methods have been used and adapted to suit this thesis.

3.2.1 Planning

The scope, budget, and planned development time are key decisions that need to be made to create a good project plan. After those have been decided, the project needs to be broken down into a task list of all the tasks that make up the project. At this point, there will not be enough information to go into all the details, but with an experienced team, the tasks can be estimated. [15]

A Gantt chart can be made when a task list has been created. Gantt charts are a common tool for planning the timing of all the tasks for a particular project. The Gantt chart does not show how the tasks depend on each other, and overlapping tasks may be done in parallel, sequentially, or iteratively. [15]

3.2.1.1 Applied in the thesis

As the thesis can only take 20 weeks to complete, the development time had a hard limit. Therefore, the scope of the project was considered to ensure that there would be enough time for completion. The main tasks of the project were gathered and used in a Gantt chart to allocate different amounts of time to the different steps of the project. The resulting Gantt chart is seen in Appendix A.

3.2.2 Customer needs

Some raw data must be gathered to create a good list of customer needs. The data can be retrieved from interviews, focus groups, and observing the product in use. The customer statements then need to be interpreted and categorized. The needs will be organized by primary and secondary needs and rated by importance. [15]

3.2.2.1 Applied in the thesis

The stakeholders were interviewed, and they received direct feedback from Sandvik's customers. A maintenance procedure was observed, and maintenance technicians were also questioned. Then, a group of Sandvik experts was gathered to discuss possible implementations. Finally, the needs and requirements were interpreted and categorized.

3.2.3 Product specifications

Product specifications are often based on the customer's needs, but instead of focusing on the customer's opinions, they provide a precise description of what the products must accomplish. A specification should consist of a metric and a value, making it measurable. The product specifications should then have targets that the concepts can be measured against, ensuring they fulfill the requirements. [15]

3.2.3.1 Applied in the thesis

This project had many different needs and requirements that needed to be converted into specifications. Many of the needs and requirements were mostly true or false which made it difficult to come up with metrics and values. Instead, many of them were described in the text how they would be achieved.

3.2.4 Concept generation

First, the problem must be clarified and broken down into subproblems if necessary. Then, the search for solutions can begin. It is important to search internally and externally to gather as many possible concepts as possible. Many possible solutions can be found by interviewing lead users and consulting experts, searching for literature, and researching existing patents. A thorough internal search should also be conducted through brainstorming sessions. When brainstorming, it is important to suspend judgment, generate many ideas, welcome ideas that may seem infeasible, and create sketches to mediate your ideas. [15]

Figure 3.3 shows a concept classification tree, which is one way to explore the concepts and categorize the possible solutions systematically.

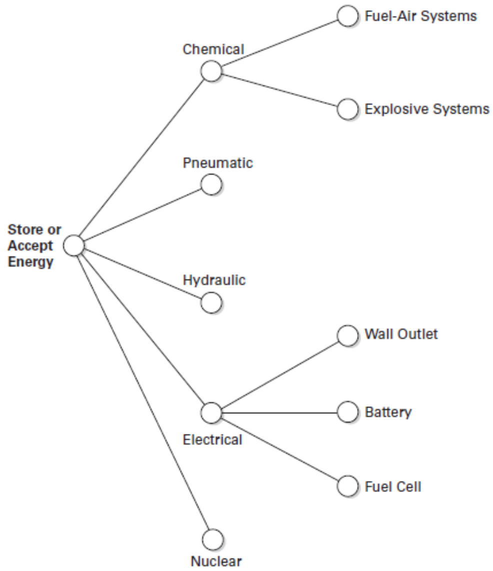


Figure 3.3 Concept classification tree. [15]

3.2.4.1 Applied in the thesis

The project was divided into two subproblems: measurement technologies and mounting solutions. The possible solutions were carefully researched by conducting a literature study, searching for online articles, books, and patents, and also searching internally at Sandvik. The results were categorized using a concept classification tree that was optimized for viewing many solutions, as the figure would otherwise be very large and difficult to view. An example of that implementation can be seen in Figure 5.1.

3.2.5 Concept selection

After the initial brainstorming, selecting the right concepts to move forward is a critical step in getting a good result from the development process. Therefore, it is also important to do it methodically. A concept screening matrix, such as the one seen in Figure 3.4, is a great way to pick out one or a few concepts to move forward with. The selection criteria are crucial in getting a good result and are selected based on the customers' needs. [15]

	Concepts						
Selection Criteria	**A Master Cylinder**	**B Rubber Brake**	**C Ratchet**	**D (Reference) Plunge Stop**	**E Swash Ring**	**F Lever Set**	**G Dial Screw**
Ease of handling	0	0	–	0	0	–	–
Ease of use	0	–	–	0	0	+	0
Readability of settings	0	0	+	0	+	0	+
Dose metering accuracy	0	0	0	0	–	0	0
Durability	0	0	0	0	0	+	0
Ease of manufacture	+	–	–	0	0	–	0
Portability	+	+	0	0	+	0	0
Sum +'s	2	1	1	0	2	2	1
Sum 0's	5	4	3	7	4	3	5
Sum –'s	0	2	3	0	1	2	1
Net Score	2	–1	–2	0	1	0	0
Rank	1	6	7	3	2	3	3
Continue?	Yes	No	No	Combine	Yes	Combine	Revise

Figure 3.4 Concept screening matrix. [15]

3.2.5.1 Applied in the thesis

The concept screening matrix was used in the thesis to determine the best measurement technologies and mounting solutions to proceed with developing and testing. As there was no previous solution to use as a reference, the "+", "0", and "-" were defined in a separate table.

3.2.6 Concept testing

To create a robust design, it must be tested thoroughly. One way to organize the testing to ensure a good combination of tests has been done is to use the Design of Experiments method. First, the control factors, noise factors, and performance metrics need to be identified. Secondly, an objective function has to be formulated, which can have different targets such as maximizing, minimizing, a target value, or measuring signal-to-noise ratio. With all this in mind, an experimental plan will be created to ensure good coverage of different parameter combinations will be tested. A different type of matrix will be chosen depending on the time constraints and the difficulty of running the tests. A few examples of how to select tests are shown in Figure 3.5. Then, the experiment will be run according to the experimental plan previously developed, and the results will be analyzed. [15]

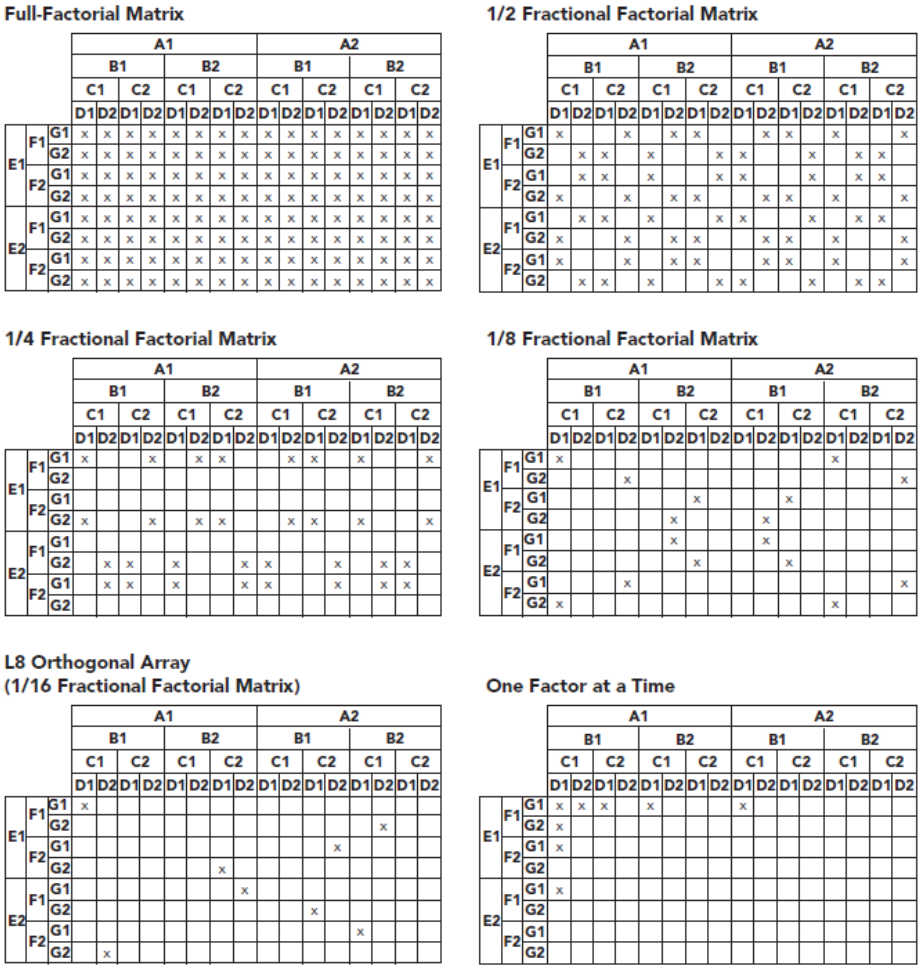


Figure 3.5 Alternative experimental plans for seven factors. [15]

3.2.6.1 Applied in the thesis

Design of Experiments was used when testing inside the cone crusher. The different parameters were identified, and an experimental plan was made to ensure that all the relevant parameter combinations were tested. The final results were then analyzed and discussed.

4 Needs and Requirements

This section contains the needs and requirements. To get a clear picture of these, the problem description was scrutinized, and meetings with employees were scheduled.

The needs and requirements were mostly set from the start in Sandvik's problem description. They were then discussed, clarified, prioritized, and organized into a list. Then, the list was assessed to determine if it had to be expanded to cover any needs that Sandvik may not have specified. Some needs were added after discussing them with Sandvik's mechanical design engineers, crusher specialists, hydraulic engineers, and service technicians, some of whom have had direct contact with customers about their needs. The cone crusher's technical specifications have also been investigated.

4.1 Requirements

The system needs to fulfill several requirements, all of which are listed in Table 4.1. The following subchapters provide detailed descriptions of the individual requirements.

Table 4.1 List of requirements

Requirements
Measurements
The device can measure high-viscosity grease.
The device can measure both clean and dirty grease.
The device can detect when the grease level becomes too low.
The device provides accurate measurements.
Axle movement
The device will work with a rotating axle moving both eccentrically and axially in the fluid.
Environment
The device will work when covered in grease.
The device will work in a mining environment.

4.1.1 Measurements

Measuring high-viscosity grease can be challenging, but it is essential for this project. Texaco Marfak 00 is the grease commonly used in the cone crusher, and thereby, it is also the grease that needs to be measured.

The state of the grease can vary; for example, the viscosity will change depending on the temperature. The grease will also behave differently depending on whether it is new grease or dirty grease ready for a swap. In the cone crushers, the grease can be contaminated by dust, water, and even metal. It is important that the grease can be measured regardless of what state it is in at that particular time, so the measurements will be reliable and trustworthy. The grease is normally swapped when the mantels are due for a change, which can be upwards of 800 hours of running time, depending on the hardness of the rock being crushed and the wear it causes.

The main task of this thesis is to measure when the grease level becomes too low. It is, therefore, of high importance to be able to differentiate between when there is enough grease and when it is running out.

The accuracy of the measurements is also important. If the result is not accurate, it is not trustworthy and cannot be relied upon. Therefore, the final solution needs to provide an accurate reading of the grease level.

4.1.2 Axle movement

In Figure 4.1 the left schematic shows a cross-section view of the axle (blue) in its lowest position in the grease chamber (black), with the grease marked in red. A few measurements have been taken to calculate how much the grease level on the sides increases when the axle moves up.

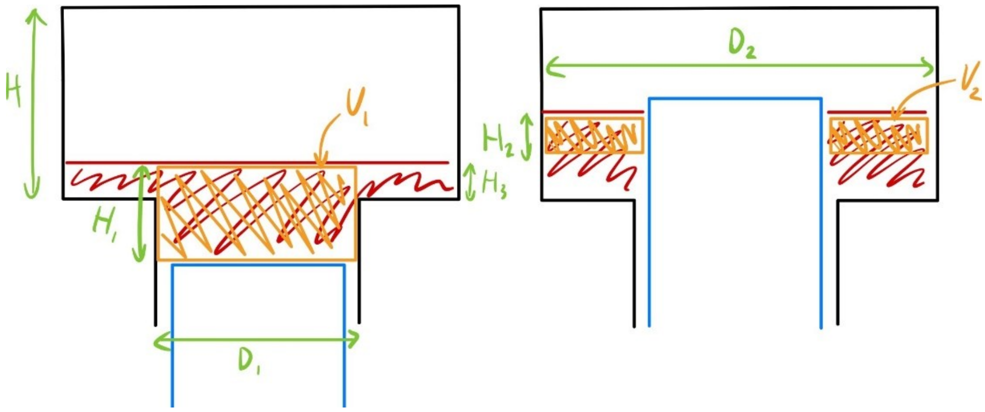


Figure 4.1 Grease volume calculations.

The grease is refilled when the axle is in the lowest position to $H_3 \approx 16\ mm$. When the axle moves up, the grease moves to the sides. The highest grease level can be derived by calculating the orange volume in Figure 4.1.

$$V_1 = V_2 => \frac{\pi * {D_1}^2}{4} * H_1 = \frac{\pi * \left({D_2}^2 - {D_1}^2\right)}{4} * H_2$$

$$=> \ H_2 = \frac{{D_1}^2 * H_1}{\left({D_2}^2 - {D_1}^2\right)} = \frac{246.4^2 * 36}{(360^2 - 246.4^2)} \approx 31.7\ mm$$

By adding H_2 and H_3 together, a maximum grease level of approximately 48 mm was given. This means the grease level varies between 16 and 48 mm depending on the axle position.

The axle moves up and down, rotates, and moves eccentrically. The measurement system, therefore, needs to account for that kind of movement in the grease. The system also needs to withstand some lighter forces from the grease moving around in the chamber.

4.1.3 Environment

Figure 4.2 shows the grease chamber and the cap; as expected, everything is covered in grease. This means that any integrated system needs to work even when it is covered in grease. As a lot of grease moves around in the chamber, there is a risk of air vents being clogged by grease, leading to increased pressure in the chamber. The system, therefore, also needs to handle pressure increases.

Figure 4.2 Grease chamber and cap.

The mining environment is normally in outdoor conditions. Therefore, the system must withstand harsh weather, such as rain and humidity, and different altitudes. According to the technical specifications, the cone crusher is designed to work in an ambient temperature range of -20℃ to +40℃ and at altitudes ≤ 1,000 m, which means that this system also has those same requirements. To work in the rain and high humidity, the solution must also be water resistant.

4.2 Needs

Except for the requirements, there are a couple of needs that would be nice if they could be accomplished. All the needs listed in Table 4.2 are related to the measurements, more "*" equals higher priority. The following subchapters will describe the needs.

Table 4.2 List of needs

Priority	Needs
	Measurements
*	The device can detect the actual grease level.
**	The device can detect when the grease level becomes too high.
***	The device measures with high frequency.
***	The device measures the grease level close to the axle.
	Integration
**	The device shall be easy to integrate.
**	The device shall be easily serviceable.

4.2.1 Measurements

Having the system detect the actual grease level would be good, as it is easier to monitor the current grease level and see when it is starting to run low. However, having the system detect both a too-high grease level and a too-low level can also be a good compromise.

High-frequency measurements are not strictly needed. This is because the cone crusher moves quite slowly, and there is a natural tendency for the grease to diminish over time, which means that there will be enough time to refill even if the low level is caught later. But although it is not needed, it is, of course, preferred to get a fast response to the grease running low, leaving more time for the maintenance technician to fix the issue. It will also be beneficial as the grease level varies depending on the axle position, and the result will be more reliable if many measurements can be taken to calculate the mean level. A high frequency, in this case, will be a few hundred Hz.

The grease level is most important to monitor closer to the axle, as it is the surface between the axle and the bushing that needs to be kept properly lubricated. Therefore, it is of high importance that the system can measure the grease level as close to the axle as possible.

4.2.2 Integration

It is important to make the device easy to integrate into the cone crusher. As the environment has many constraints and is well-established, it is desirable to make as few changes as possible to existing parts. This device may also come as an add-on to the cone crusher, which in turn makes it desirable to be easy to integrate depending on the customer needs for that specific crusher.

Installing this device shall not negatively impact the cone crusher's serviceability. This means that the service procedure can not differ too much from how it is done today. Only making small changes to the service procedure will minimize the risk of the technicians making any mistakes.

5 Measurement technologies

This chapter covers all the researched measurement technologies, brainstorming, screening, and testing.

5.1 Brainstorming

After doing a thorough brainstorming session and scouring the web for all relevant measurement technologies suitable for this problem, the following list was gained:

- Capacitive
- Conductive
- Electromagnetic radiation
- Mechanical waves
- Piezoelectric
- Piezoresistive
- Radiation
- Switch

All technologies have advantages and disadvantages, and a literature study has been done to narrow down the alternatives.

Figure 5.1 differentiates between different sensor types based on the same fundamental technology, and Figure 5.2 categorizes the sensor types by what they measure. These figures were helpful in the next screening step.

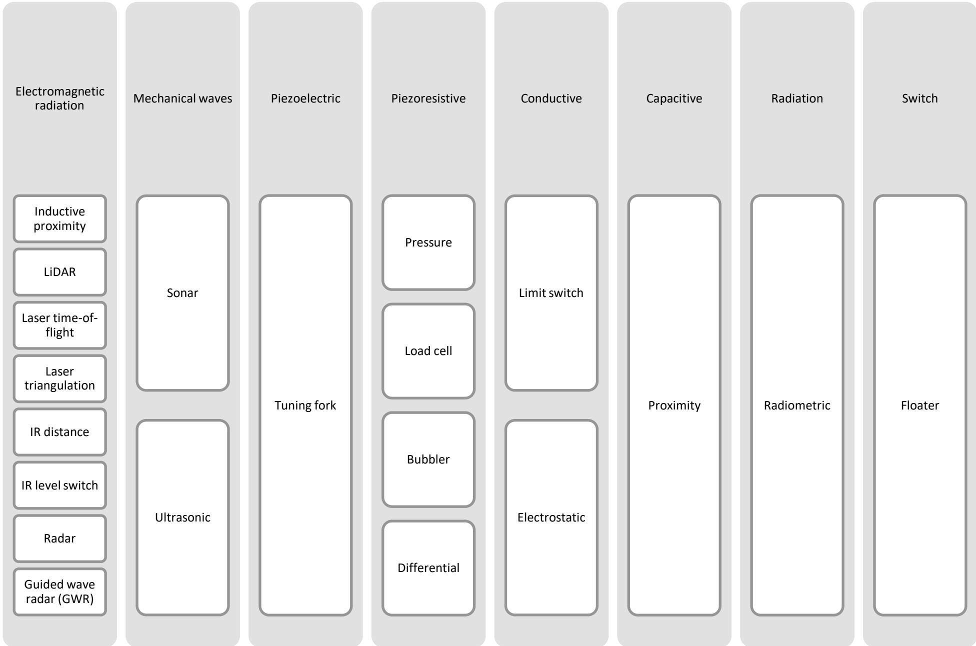


Figure 5.1 Sensor types categorized by their fundamental measurement technology.

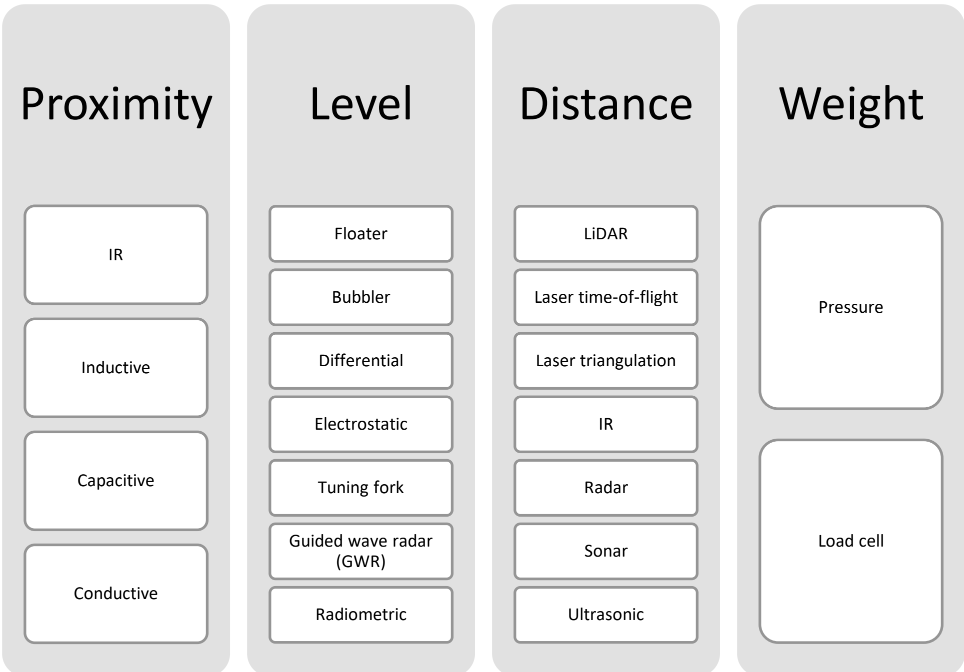


Figure 5.2 Sensor types categorized by what they measure.

5.2 Pre-screening

In Figure 5.1, all the different sensor types are gathered. As some technologies have clear downsides, such as radiation, which requires special licenses and is dangerous, there was no need to continue with that solution.

Figure 5.3 assisted in figuring out what positions the sensors could be mounted in. Proximity must be measured either from the side or from the bottom. A level sensor's position strictly depends on the sensor type. Distance measurements must be taken from above or below, depending on whether it can be measured through grease or not. Weight has to be measured from below. Using this information, along with the assistance of Figure 5.2, helped determine which sensors could be feasible.

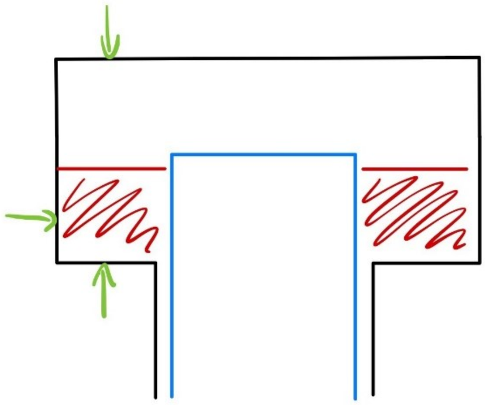


Figure 5.3 Top, side, and bottom are the possible mounting locations.

Using these categories and the earlier research, one-third of the concepts were discarded before proceeding to the next screening step. This helped save time, but many concepts still remained to be screened.

5.3 Screening

To make a good screening, the selection criteria need to be carefully selected, making sure that they also correlate to the needs and requirements in Chapter 4. Most of them correlate directly to a requirement or a need, but there are a few exceptions, for example, “handling of buildup,” which is not a direct requirement or a need, but it is still related to two requirements: “can measure high-viscosity grease” and “provides accurate measurements”. As there was no reference the “+”, “0”, and “-“ for the screening matrix were instead defined according to Table 5.1.

Table 5.1 Selection criteria interpreter.

Selection Criteria	+	0	-
Easy to integrate	Bottom/side	Bulky not top	Top
Measures high-viscosity grease	Yes	Not stable	No
Measures up to 100 mm	Yes	Not really	Only proximity
Handles moving grease	Yes	Somewhat	No
Unaffected by humidity	Unaffected	Somewhat	Affected
Unaffected by elevation	Unaffected	Somewhat	Affected
Insensitive to dirt & metal particles	Insensitive	Somewhat	Sensitive
Handling of buildup	Can handle buildup	Partially affected	Cannot handle buildup
Accuracy	High	Medium	Low
Updating frequency	High	Medium	Low

The screening was done using a screening matrix. The concepts are named with letters in Table 5.2, and the same letters are used in Table 5.3 for easy identification.

Table 5.2 Concepts in screening matrix.

A	Capacitive proximity
B	Time-of-flight IR Laser
C	Radar
D	Guided wave radar (GWR)
E	IR proximity
F	Ultrasonic distance top
G	Ultrasonic distance bottom
H	Tuning fork
I	Bubbler
J	Differential pressure
K	Pressure transducer
L	Floater

Table 5.3 Concept screening.

	Concepts											
Selection Criteria	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
Easy to integrate	+	**0**	-	-	+	-	+	**0**	-	-	-	**0**
Measures high-viscosity grease	+	+	+	+	+	+	+	+	**0**	+	+	+
Measures up to 100 mm	-	+	+	+	-	+	+	**0**	+	+	+	**0**
Handles moving grease	+	-	+	**0**	+	+	+	**0**	+	+	+	**0**
Unaffected by humidity	+	+	+	+	+	+	+	+	+	+	+	+
Unaffected by elevation	+	+	+	+	+	+	+	+	+	+	-	+
Insensitive to dirt & metal particles	-	+	+	+	+	+	+	+	**0**	**0**	**0**	+
Handling of buildup	+	-	-	+	-	-	+	**0**	-	-	-	**0**
Accuracy	+	+	**0**	**0**	+	+	+	+	-	**0**	-	**0**
Updating frequency	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Sum +'s	7	6	6	6	7	7	9	5	4	5	4	4
Sum 0's	1	2	2	3	1	1	1	5	3	3	2	6
Sum -'s	2	2	2	1	2	2	0	0	3	2	4	0
Net Score	5	4	4	5	5	5	9	5	1	3	0	4
Rank	2	7	7	2	2	2	1	2	11	10	12	7
Continue?	Yes	No	No	No	MB	MB	Yes	MB	No	No	No	MB

The scoring was done according to the results from the literature study and by doing a workshop with a couple of experts at Sandvik. As some of the concepts got a similar score, they were investigated further, and if they had a big downside, they were dismissed. For example, the radar-based concepts “C” and “D” were dismissed based on size. The size would make them significantly harder to integrate, and they were also much more expensive than some of the other concepts.

Choosing which concepts to move forward with was also discussed in that same workshop, which led to the capacitive concept “A” and the ultrasonic distance concept “G” moving on. Later on, the tuning fork concept “H” was also tested.

5.4 Testing

5.4.1 Test setup

The sensors would first be tested in a lab environment to figure out if they work for measuring grease. As the sensors will be used in the rock crusher surrounded by steel components, it was important to simulate that as closely as possible while still being able to do the tests in a lab. Therefore, a steel tube was welded to a bottom plate, and two holes were drilled through the tube, see Figure 5.4. The holes will be used to attach the sensors. The lower hole will be for the sensors mounted close to the bottom of the tank, submerged in grease, and the upper hole was intended for the sensors to measure the distance to the grease. They were placed at a distance of 160 mm from each other, similar to the grease chamber's height.

Figure 5.4 Steel profile for testing.

A Dewesoft Sirius unit was used to connect the sensors to a computer. It is a powerful data-gathering system with modules for connecting many different sensors. For the testing conducted in this project, the modules for connecting a standard 4-20 mA output sensor and a switch type of sensor were used. The Sirius unit only supplied 12V, which was not enough for some of the tested sensors; they were instead supplied with power by a 24V external power supply. The testing setup can be seen in Figure 5.5.

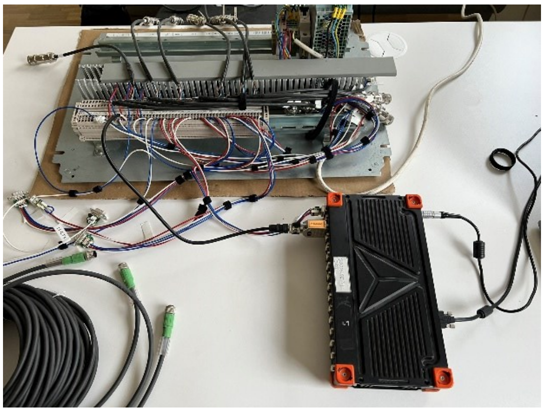


Figure 5.5 Testing setup for connecting sensors to the computer.

5.4.2 Grease

To ensure that the final solution would work regardless of the state of the grease, a few different grease samples were gathered. Texaco Marfak 00 is the grease that is commonly used in the cone crusher; therefore, the tests were done with that specific grease.

The easiest sample to get a hold of was the clean grease. The dirty grease sample was old grease that had been used for complete cycles in cone crushers, and it was full of dirt particles and some water. The viscosity was very high, and compared to the clean grease, it almost did not flow at all; see Figure 5.6, where it did not even move out of a glass held upside down. The final sample was grease taken from a cone crusher with a severely damaged bushing. It was full of metal particles and even some metal chunks. As shown in the picture in Table 5.4, it shimmers because of all the metal it contains. This grease had not been used for as long as the other dirty sample, as it was swapped prematurely because of the damaged bushing. The viscosity, therefore, differed and appeared close to the new grease. This grease was received later in the project; therefore, the first tests did not include it. The different qualities of grease are shown in Table 5.4 for a visual comparison.

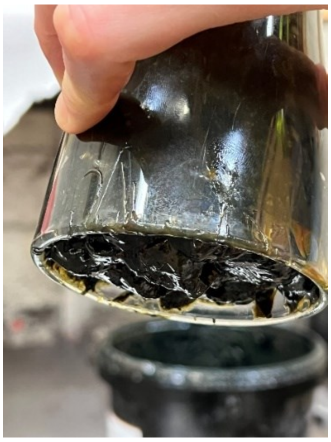


Figure 5.6 Dirty grease not flowing from glass.

Table 5.4 Different grease qualities.

New grease	*Dirty grease*	*Grease with metal particles*
		

5.4.3 Testing parameters

The testing parameters are very closely related to the needs and requirements in Chapter 4. The tests will focus on whether the sensor can even measure high-viscosity grease, both clean and dirty. For the ultrasonic sensor, the distance to the grease surface will be tested, and for the other sensors, only a specific level will be tested. The sensors will also be covered in grease to see if that affects their functionality. As the ultrasonic and capacitive sensors will somewhat be affected by being close to steel, they will also be set up to test that.

5.4.4 Ultrasonic sensor

Many different manufacturers were contacted to find an ultrasonic sensor that could measure the grease level from below. Unfortunately, none of them had tested their sensors in this specific application before, and they could not guarantee that their sensors would work.

One of the manufacturers, Pepperl+Fuchs, a German sensor manufacturer, supplied a UB300-18GM40A-I-V1 to test ultrasonic measurements. The supplied sensor was not guaranteed to work in this environment by Pepperl+Fuchs, but since the theory suggested that it could work, it was tested anyway. This would be the first sensor to be mounted at the bottom, pointing upwards. The specific sensor that was tried was set up with a lower measurement limit of 50 mm and a higher limit of 300 mm. The limits were tested in the air with the help of a ruler and a metal object. This verified that the sensor was indeed working as intended and that it had been connected properly to the measurement equipment.

The next test was to see how the sensor reacted to grease. The sensor was placed in the bottom hole of the testing setup, see Figure 5.7. Then, grease was put into the steel tube, and the sensor output was closely monitored as more grease was put into the steel tube. As soon as the sensor was covered in grease, the measured distance was ~300 mm. This value remained the same even when the steel tube had been completely filled with grease, as seen in Figure 5.8.

Figure 5.7 Ultrasonic sensor mounted in steel profile.

Figure 5.8 Ultrasonic sensor output.

A finer test was needed to determine how much grease the sensor could handle before sending an incorrect value. Therefore, the sensor was placed in the upper hole, making it easier to access. Then, grease was carefully put on top of the sensor until it no longer gave an accurate reading. Figure 5.9 shows how much grease was needed to make the sensor stop working. This is way too sensitive when compared to the pictures taken in a used cone crusher, see Figure 4.2, where the chamber was completely covered in grease.

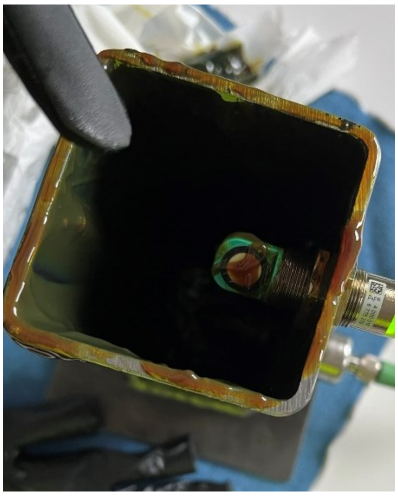


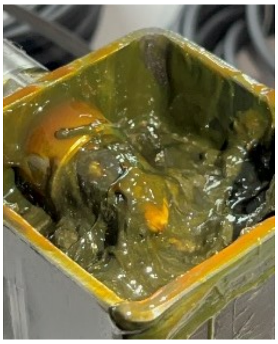
Figure 5.9 The amount of grease that stops the ultrasonic sensor from working properly.

5.4.5 Capacitive sensor

Ifm, a German sensor manufacturer, supplied an LMT110 sensor to test a capacitive sensor. The sensor was placed in the upper hole in the previously used steel tube. This made it easy to fill up grease and find out when the sensor activated. The sensor was tested by directly mounting it to the steel and also by electrically isolating it with the help of some 3D-printed plastic spacers. All the pictures in Table 5.5 show the moment that the sensor reacted to the grease except when isolated with dirty grease, as it never reacted, not even when it was completely submerged in the grease.

Buildup was not an issue when using clean or dirty grease. The main difference was that dirty grease, because of its much higher viscosity, stuck more easily to the sensor. However, as the sensor was less sensitive to dirty grease, the risk of it causing problems was low.

Table 5.5 Capacitive sensor tested in different ways.

	Non-isolated	*Isolated*
New grease		
Dirty grease		

5.4.6 Tuning fork

Sick, a German sensor manufacturer, supplied an LFV200 sensor to test the tuning fork type of sensor. This sensor would be compared to the LMT110, which previously showed promising results. A new grease type had also been supplied with many metallic particles and fragments, as it had been taken from a cone crusher with a severely damaged bushing. The steel profile used in the previous tests did not work with the LFV200 as it was too big, and as a new type of grease had been gathered, the tests with the LMT110 were redone to be able to compare the results.

The LFV200 was received much later than the other sensors, as the initial plan was not to test it. That decision changed when the ultrasonic sensor did not work even remotely as intended, and the capacitive sensor showed significant differences in responsiveness depending on how dirty the grease was. Getting the sensor that late meant there was no time to construct a new testing rig; therefore, improvisation was needed.

In Table 5.6, just as before, the LMT110 shows a clear distinction between new and dirty grease, where it is clearly less sensitive to the dirty grease. On the other hand, the sensitivity of the grease with metal particles is very similar to the new grease. The LFV200 has less of a difference between the different qualities of grease and showed negligible differences. This is logical as it cares about the density of the liquid, which is very similar, as the amount of dirt in the grease is always quite small compared to the overall mass. Grease contaminated with water is also not an issue as the grease has a similar density to water.

Table 5.6 LMT110 vs. LFV200 in different qualities of grease.

	New grease	***Dirty grease***	***Grease with metal particles***
LMT110			
LFV200			

The capacitive sensor had not previously been tested for grease buildup with metal particles, so it was tested now instead. This was important as it showed a different result from before. The LMT110 is sensitive to buildup, but only if it is full of metal particles; see Figure 5.10.

Figure 5.10 Buildup of grease with metal particles on LMT110.

A test was also conducted to determine whether grease buildup would be an issue with the LFV200 sensor. The dirty grease had the highest viscosity and was used for this test as it was most likely to stick to the sensor. As seen in Figure 5.11, the grease is mostly stuck between the forks. The amount of grease shown in the figure is also the point at which the sensor outputs a signal of there being grease. This is quite a lot and is unlikely to cause any problems.

Figure 5.11 Buildup of dirty grease on LFV200.

6 Mounting system

This chapter covers all the researched mounting positions, screening, and testing at Sandvik's research facility.

6.1 Brainstorming

After doing a brainstorming session and carefully assessing the existing CAD model of the cone crusher, the following mounting positions have been found:

- Top
- Side
- Bottom

Figure 6.1 shows a sketch of the positions in relation to the grease chamber.

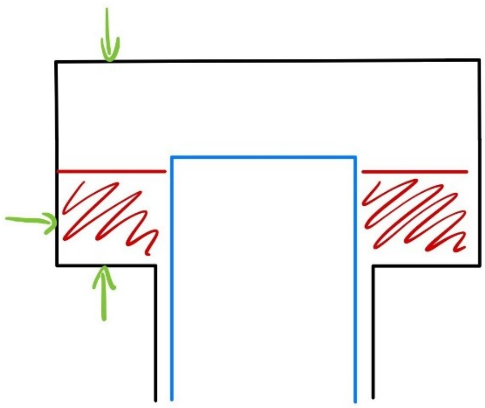


Figure 6.1 Top, side, and bottom as possible mounting locations.

A brief description of the positions and their main benefits and drawbacks are described in the following subchapters.

6.1.1 Top

One solution to mounting a sensor from the top is to mount it to the cap. Mounting a cable-bound sensor to the cap, which is the first thing that opens, usually with a crane as it is very heavy, is not optimal. This means that either the cable needs to be very long, detach itself when pulled on, or it needs to be disconnected by putting your arms in between the heavy cap lifted by a crane to unplug it. All of these solutions have clear downsides. A long cable will probably entangle itself in the moving axle. A cable that detaches by itself will most likely not be sealed and risk being contaminated with grease, isolating the connections. Reaching in beneath a heavy cap is a safety risk.

Another solution is to mount the sensor using a bracket on the bushing. This will allow the cable to be connected after the cap has been removed, and it will be easier and safer to do so.

6.1.2 Side

To mount the sensor from the side, a hole could be made from outside the chamber into the chamber. This will most likely be difficult, as a lot of steel has to be drilled out to do that. It will also be harder to install the sensor, and it will need protection from rocks falling on it on the outside.

A bracket could also be added on the inside on top of the bushing. This will mount the sensor tangentially instead of radially. It will have the same benefits as before, with easy and safe installation.

6.1.3 Bottom

Mounting the sensor from the bottom will require even more steel to be drilled out than from the side, now reaching approximately 190 mm deep. This will make the sensor even harder to install and connect.

6.2 Screening

All the locations have advantages and disadvantages, and a screening has been done to investigate which one is the most suitable.

The selection criteria were carefully selected to correlate to the needs and requirements in Chapter 4, although most of the requirements were based on how the measurements were done and not how the sensor should be mounted. Therefore, this was discussed with experts at Sandvik to figure out which criteria are suitable. For example, one new criterion that was added is “not affecting structural rigidity.” This is important as it makes the integration easier without having to do any advanced new simulations to figure out how other parts have to be adapted. Changing other parts will also make this project significantly more expensive and take longer time. It is also important not to make the rock crusher weaker than it is today. Although there is not a single need or requirement related to just this criterion, it can be connected to a few others, such as “will work in a mining environment” and “easy to integrate”.

In Table 6.1, the concepts have been weighed against each other with one clear winner, which is concept B, “bracket on bushing. This concept is the clear winner; it will be the easiest to integrate and service, it will not affect any existing parts on the rock crusher, and it will allow a wide variety of mounting positions depending on how the bracket is constructed.

Table 6.1 Mounting concepts.

	Concepts			
	A	**B**	**C**	**D**
Selection Criteria	**Top cap**	**Bracket on bushing**	**Hole through side**	**Hole through bottom**
Easy to integrate	**0**	+	-	-
Easily serviceable	-	+	**0**	**0**
Handles moving grease	+	**0**	+	+
Not affecting structural rigidity	**0**	+	**0**	-
Not causing buildup by sensor	+	**0**	**0**	**0**
Sum +'s	2	3	1	1
Sum 0's	2	2	3	2
Sum -'s	1	0	1	2
Net Score	1	3	0	-1
Rank	2	1	3	4
Continue?	Maybe	Yes	No	No

6.3 Prototype

A few different adjustable brackets have been designed to test various mounting positions on top of the bushing. The brackets will accommodate both the LMT110 and the LFV200 sensors.

6.3.1 Requirements

6.3.1.1 Adjustability

For the prototype, it was important to make it as adjustable as possible. Adjustability, both rotationally and translationally, therefore, became an important requirement.

6.3.1.2 Works with both sensors

The prototype has to work equally well with the LMT110 and LFV200 sensors. It also has to enable both sensors to be mounted in equal positions so a comparison can be made.

6.3.1.3 Electrically conductive

According to previous testing, the LMT110 did not perform as well when mounted electrically isolated from the grease container. Therefore, it is important that the prototype is electrically conductive.

6.3.1.4 Rigid and durable

It is also important for the sensor to be rigidly mounted, as it should always measure in the same position. As the sensor is mounted before the cap, it should be able to withstand a smaller hit from the 100 kg cap. Due to the cap being installed with a crane, there will often be a slow swinging movement that could cause the mount to be hit.

6.3.1.5 Allow grease to move freely

The mounting solution shall allow the grease to move as freely as possible. It is important as otherwise, there is a risk of buildup around the sensor. Buildup can lead to the sensor giving a false positive when reading the grease level.

6.3.2 Solutions

The adjustability has been solved by having slots that allow mounting in different positions, one of which will be radial, so the sensors can also be rotated. Slots will be easy to implement and will allow a large range of adjustments.

Both sensors have threads, so they can be mounted similarly. The main difference is that the LMT110 has a G1/2" thread, and the LFV200 has a G3/4" thread. Therefore, the hole must be bigger to accommodate the LFV200 sensor.

The mounting solution can be made electrically conductive by either making it out of metal or grounding the sensor with a cable. The easiest solution is to make the mount out of metal, which will also help in fulfilling the next requirement of making it rigid and durable.

Steel is a common material to use when something needs to be durable. Steel is also cheap and easy to manufacture. As the environment the sensors will be mounted in will get covered in grease, corrosion is not a concern. Steel has, therefore, been the chosen material for this mount.

There are many suitable methods for manufacturing a prototype using steel. Some of the most common methods are using a mill, lathe, water cutter, laser cutter, or hand tools. For this specific use case, the tolerances and shapes that can be accomplished by using a mill or a lathe are not needed. By using sheet metal, the manufacturing time will be reduced, and a functional design can still be achieved. Sheet metal can also be bent to achieve semi-complex shapes. Using sheet metal will also aid in not obstructing the grease flow if oriented correctly, as it will only be a thin sheet.

6.3.3 Calculations and Simulations

Ansys was used to perform four different finite element analyses (FEA). Figure 6.2 shows the geometry that will be used in all the following simulations. The geometry includes the fasteners and the largest of the sensors (LFV200), mounted in the uppermost position at 45 degrees, as it will provide the most leverage. The LFV200 sensor was simplified as it was not the focus in these simulations; this will also make the mesh and the calculations simpler and faster.

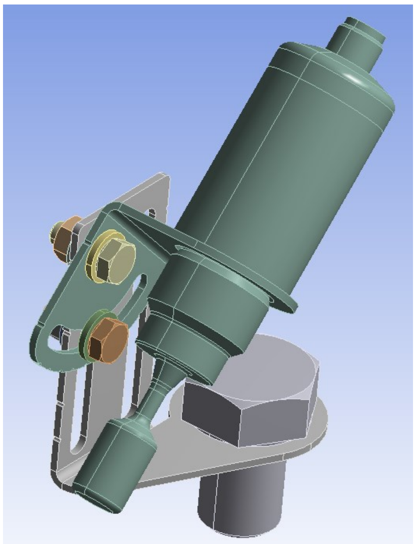


Figure 6.2 Geometry in Ansys

The contacts between the washers and the steel bracket, as well as between the two different steel brackets, have been put as frictional while the other contacts were bonded.

Figure 6.3 shows the mesh used in the simulations. The mesh was refined in several specific areas. An important area to refine was where the bolts contact the steel brackets. The overall steel brackets were also refined, and the sensor was refined where it had small radiuses.

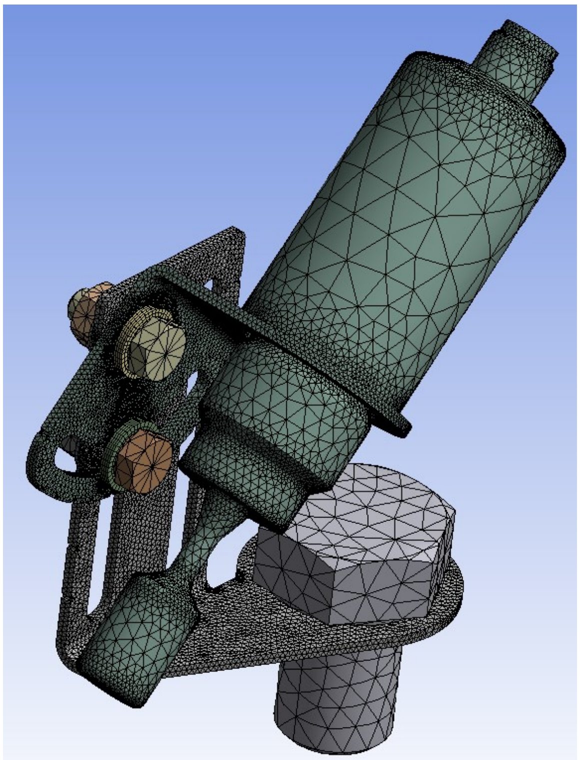


Figure 6.3 The mesh used in the simulations.

6.3.3.1 Simulating the mount being hit by the cap

The first simulation will be done to simulate a cap swinging into the mount when doing maintenance. A few estimates must be made, to calculate the stopping force required to stop the cap swinging into the bracket. The cap weighs $m = 100\ kg$. The cap swings slowly at a speed of $0.1\ m/s$. The maximum deformation that the bracket can handle is $5\ mm$. The force that the brackets need to withstand can be calculated, by using the following formulas:

$$W = F * d, E = \frac{m * v^2}{2} \ => F = \frac{m * v^2}{2 * d} = \frac{100 * 0.1^2}{2 * 0.005} = 100\ N$$

Figure 6.4 shows where the individual forces and supports have been applied. A pre-tension of 2500 N has been applied to the bolts. The big bolt has been set as a fixed support, as that is the bolt that will mount everything to the bushing. The underside of the bottom bracket has been set as a compression-only support, as it will rest on the bushing. The external force of 100 N has been placed on the outside of the upper bolt as that is the part that protrudes the most and is most likely to get hit by the cap.

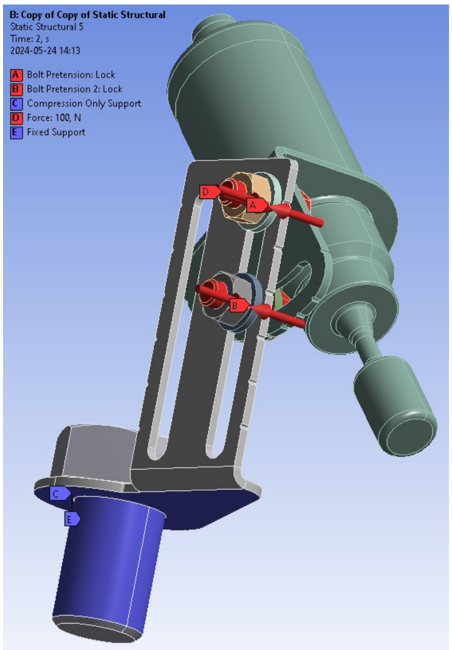


Figure 6.4 Applied forces on the geometry for the simulation.

In Figure 6.5, the stresses and deformations are shown when applying the previously mentioned force of 100 N. The stress peaked at 1140 MPa in one element, which is most likely due to singularities and a small radius. Otherwise, the stress in the part was mostly around 300 MPa, with some smaller areas approaching 500 MPa. This means that if common construction steel with a tensile strength of 350 MPa is used, there will be some permanent deformations. This could be solved by increasing the thickness of the steel further from the now-used 2 mm. However, as this is a prototype, it is not strictly necessary to handle those forces, and the cap can be installed carefully instead. When doing the final concept, the slots will be removed as there is no longer a need for adjustability, this will increase the strength of the part further. The deformation when a force of 100 N was applied was, as expected, around 5 mm, which further reinforces the simulations.

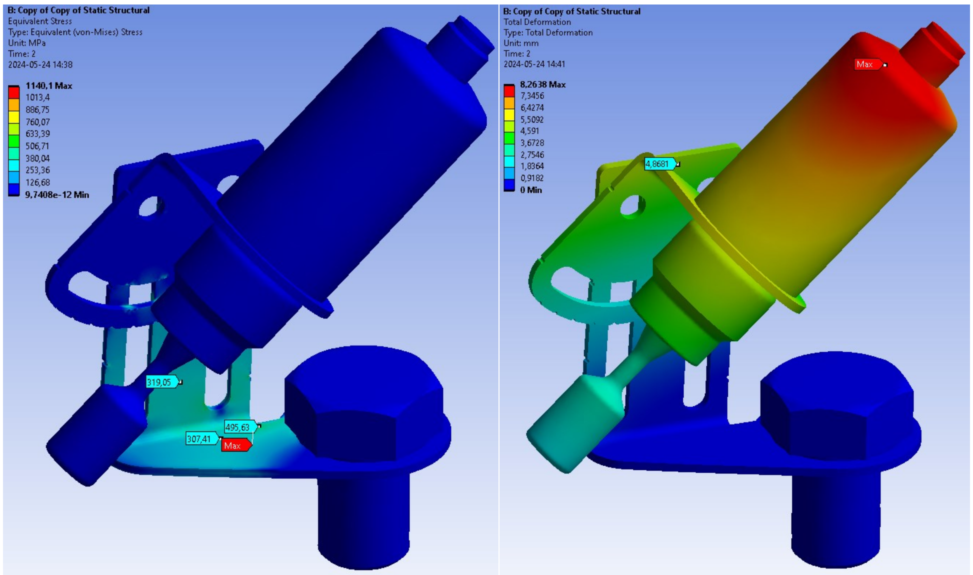


Figure 6.5 Stresses and deformations in the brackets when applying a force of 100 N.

6.3.3.2 Simulating the grease exerting force on the sensor

The next three simulations will be run with a force exerted on the tip of the sensor. The forces applied to the sensors were estimated to be 50 N; this is likely more than enough, as only the moving grease will exert force on the sensor. Figure 6.6 shows the applied forces in the first of these three simulations.

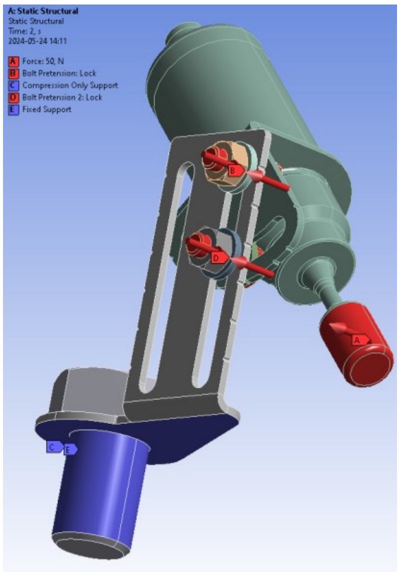


Figure 6.6 Applied forces on the geometry for simulation one.

In Figure 6.7, the stresses and deformations when applying a force of 50 N are shown. The stress approaches 555 MPa due to singularities between the edges of the slots where the screws are. Otherwise, the stress is around 100 MPa and 160 MPa in the bend on the upper bracket. The deformation is 1.8 mm at the sensor tip, which is more than acceptable.

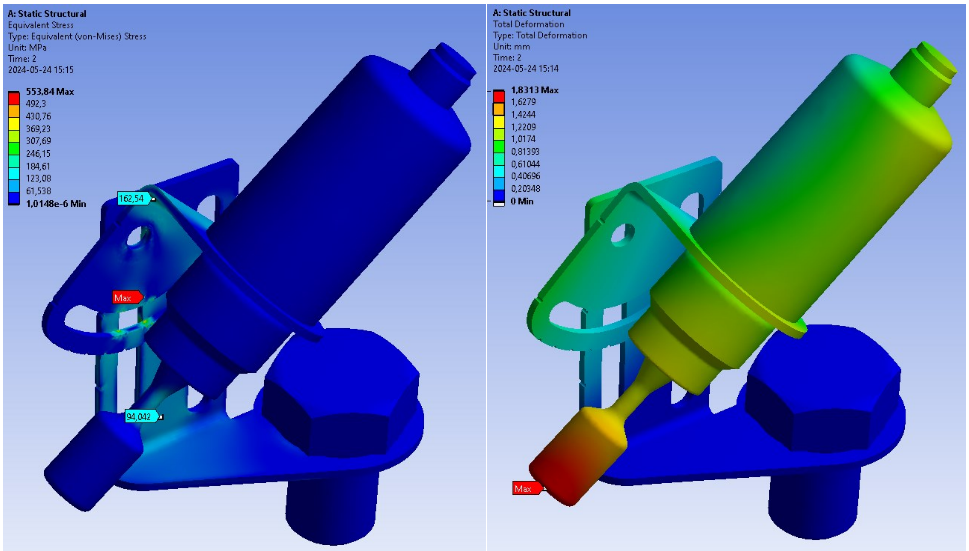


Figure 6.7 Stresses and deformations in the brackets when applying a force of 50 N.

Figure 6.8 shows the forces applied in the second simulation, with the 50 N force in a different direction than before. Figure 6.9 then shows the stresses and deformation it resulted in. The stress approaches 615 MPa due to singularities between the edges of the slots where the screws are. Otherwise, the stress is around 80 MPa and, in one area, 150 MPa. The tip of the sensor got a deformation of 1.1 mm, which is less than before.

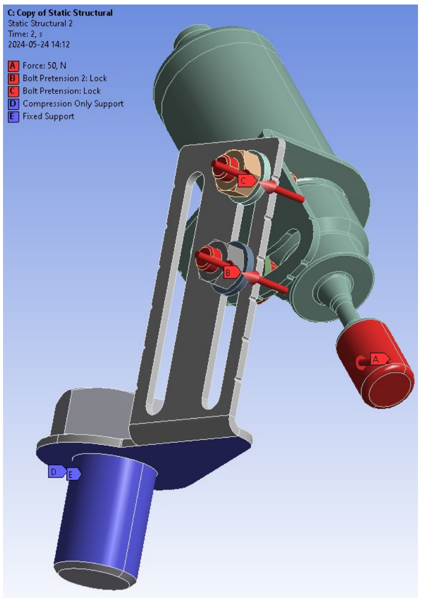


Figure 6.8 Applied forces on the geometry for simulation two.

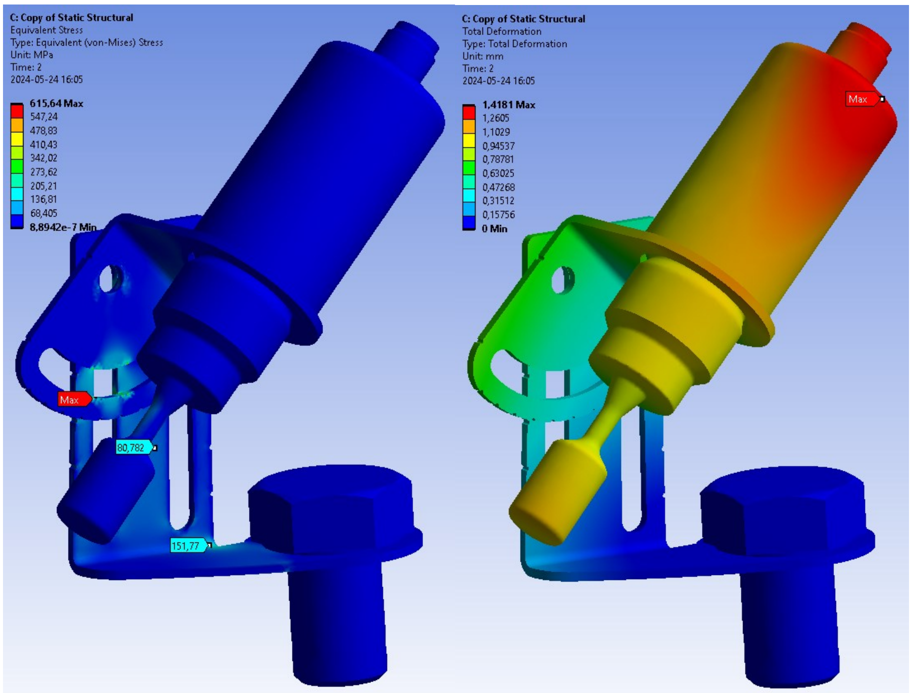


Figure 6.9 Stresses and deformations in the brackets when applying a force of 50 N.

Figure 6.10 shows the forces applied in the third simulation, with the 50 N force in a different direction than before. Figure 6.11 then shows the stresses and deformation it resulted in. The stress approaches 585 MPa due to singularities between the edges of the slots where the screws are. Otherwise, the stress is around 85 MPa and, in one area, 110 MPa. The tip of the sensor got a deformation of 1.1 mm, which is the same as in the previous test.

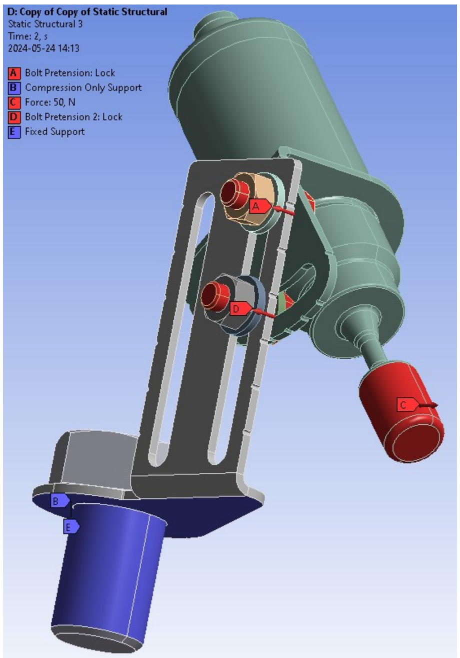


Figure 6.10 Applied forces on the geometry for simulation three.

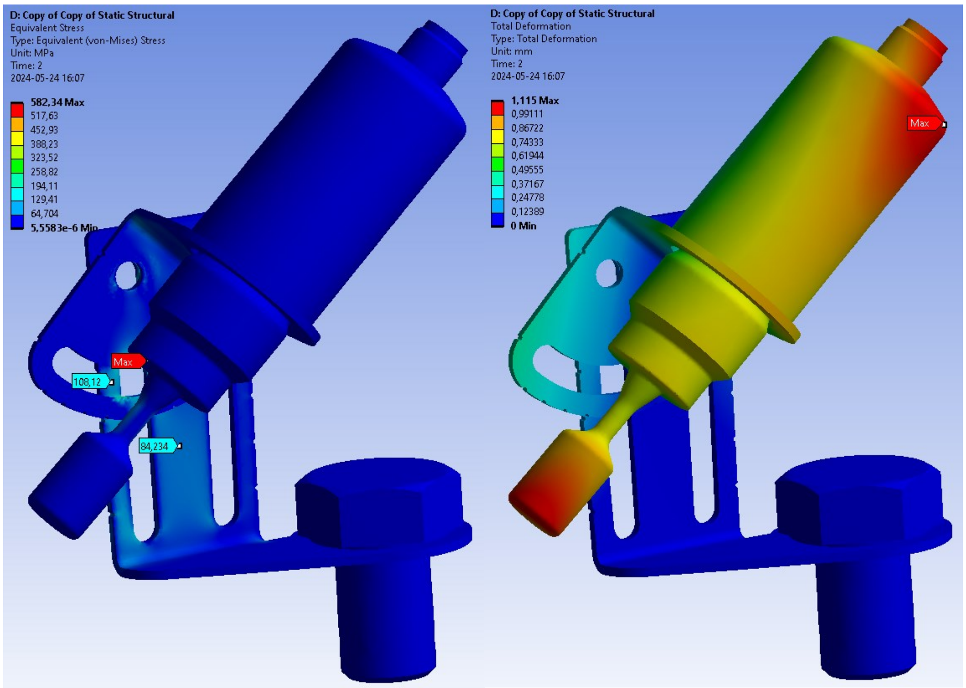


Figure 6.11 Stresses and deformations in the brackets when applying a force of 50 N.

6.3.4 Result

Four different brackets were designed to be manufactured using laser cutting and bending of 2 mm sheet metal. Two different bottom brackets were designed, allowing the sensors to be mounted and angled tangentially (Figure 6.12) and radially (Figure 6.13) to the moving axle. Two different top brackets were constructed to facilitate the different thread profiles of the sensors. The LFV200 has a G3/4” thread, and the LMT110 has a G1/2” thread. The brackets have large slots to allow installation at different heights and angles. For the asymmetrical brackets, a decision was made to manufacture two variants to allow for even more mounting positions. This was especially important for the bracket in Figure 6.12 as it allowed mounting the sensor both clockwise and counter-clockwise. Drawings of the prototypes are shown in Appendix B.

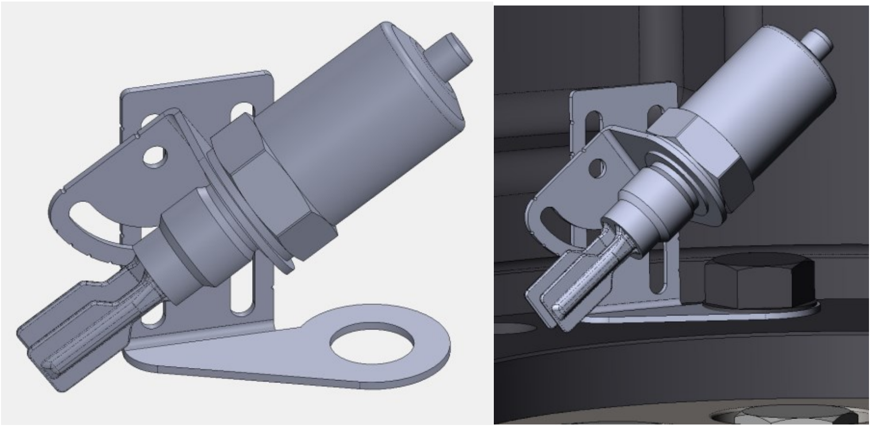


Figure 6.12 Brackets that allow the sensors to be mounted tangentially.

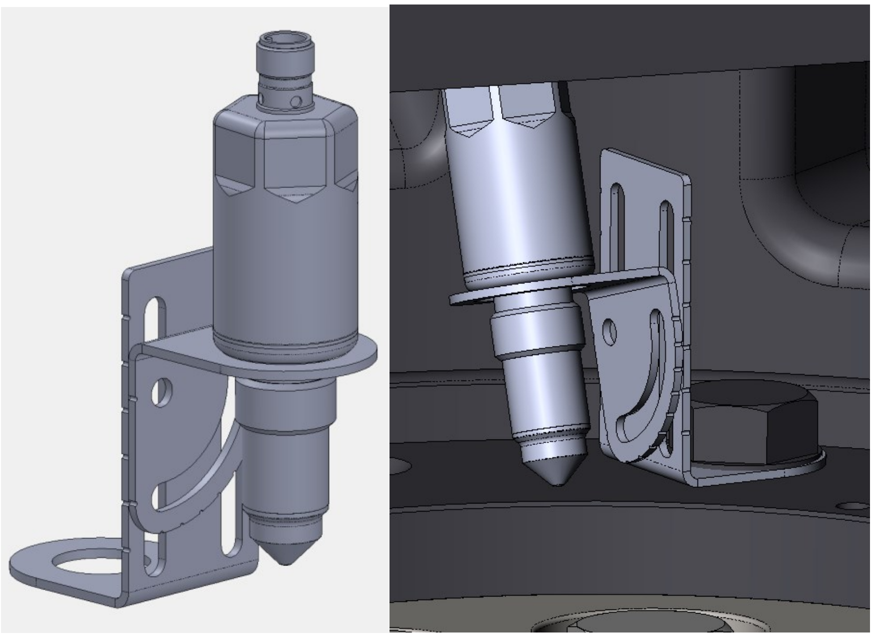


Figure 6.13 Brackets that allow the sensors to be mounted radially.

6.4 Testing

The tests will be conducted at Sandvik's testing facility in a CH430 cone crusher. Design of Experiments will ensure that a good mix of the different design parameters will be tested.

6.4.1 Test plan

First, the testing parameters had to be decided, and as this test would focus on the mounting position in the cone crusher, most of the parameters are related to that. In Table 6.2 the parameters have been gathered.

Table 6.2 Test parameters.

	No.	Description
Sensor	A1	LMT110
	A2	LFV200
Rotation of fork	B1	Towards flow
	B2	Against flow
Height	C1	Low
	C2	High
Lower bracket	D1	Straight
	D2	Twisted
Direction	E1	Clockwise
	E2	Counter-clockwise
Angle	F1	90 degrees
	F2	75 degrees
	F3	45 degrees
	F4	30 degrees

Both sensors will be connected and mounted simultaneously to allow easier comparison between their measurements. As the LFV200 allows the grease to flow through in one direction and not in the other, both directions will have to be tested. Two different heights will also be tested: 5 and 15 mm above the bushing for the LFV200 and 15 and 25 mm above for the LMT110. This is because the LFV200 sensor needs to be submerged approximately 10 mm to activate while the LMT110 activates much quicker, as tested previously. The lower bracket has been designed in two variants, as mentioned in Chapter 6.3. Both variants will be tested, and the tangentially mounted brackets will be tested both clockwise and counterclockwise.

The angle largely correlates to which bottom bracket is used, and two different angles will be tested for each bottom bracket.

This resulted in the testing matrix shown in Table 6.3. As the sensors will be tested simultaneously, the A1 and A2 columns will be covered simultaneously, resulting in 24 separate tests.

Table 6.3 Planned testing matrix.

			A1		**A2**			
					B1		**B2**	
			C1	**C2**	**C1**	**C2**	**C1**	**C2**
D1		**F1**	X	X	X	X	X	X
		F2	X	X	X	X	X	X
D2	**E1**	**F3**	X	X	X	X	X	X
		F4	X	X	X	X	X	X
	E2	**F3**	X	X	X	X	X	X
		F4	X	X	X	X	X	X

A parameter that won't be tested is running the cone crusher both under load and unloaded. The tests will only be done when running the cone crusher unloaded. This is because testing all different mounting positions requires easy access to the grease chamber. Therefore, the regular cap could not be used, and another cap had to be used for the tests. This cap was not as structurally robust and could not handle constantly dumping rocks on it. The cap used for the tests was taller to allow testing all the planned mounting positions, and it also had an acrylic window on top to allow for documenting how the grease moved and how the sensors interacted with the grease.

For each test, the rock crusher will be run unloaded with the axle rotating; while doing that, the axle will be raised from its lowest position to its highest and, soon after that, move down to its lowest position again. While raising the axle, the grease level will rise, where the sensors measure the grease, allowing the sensors to be activated and compared to the axle position. This will then be used to derive the sensor's responsiveness based on how long the grease sticks to the sensors when the grease level decreases.

The axle position will be measured by measuring the axle offset. When the axle is flush with the bushing, the axle offset will be set to 0 mm; the axle will then have a negative offset value at its lowest position and a positive offset value at its highest position.

The tests will be done with clean grease, as the differences between clean and dirty grease have already been tested. Testing dirty grease will also substantially increase the time to perform the tests, as it is not quick and easy to change grease.

6.4.2 Test results

These tests were conducted at Sandvik's testing facility, which is located in a quarry. At the facility, one of their CH430 cone crushers is set up with all the necessary accessories for running it.

Eleven tests had been conducted after spending a whole day at Sandvik's testing facility. Table 6.4 shows which tests were completed. As can be seen, not all the tests were done as planned, and some tests were done that were not planned, such as testing a few more heights. All the acquired data from the individual tests can be found in Appendix C.

Table 6.4 Resulting testing matrix.

			A1		A2			
					B1		B2	
			C1	C2	C1	C2	C1	C2
D1		F1	X	X	-	X	X	X
		F2	-	X	-	X	-	-
D2	E1	F3	-	-	-	-	-	-
		F4	-	-	-	-	-	-
	E2	F3	X	X	X	X	X	-
		F4	-	X	-	-	X	-

Although not all the planned tests were conducted, careful consideration was given to ensure that a good mix of the parameters was tested. Specifically, the testing parameter E1 was not tested at all. As the E parameter was the direction in which to mount the sensor in the chamber, and the grease did not move as much as expected, it was deemed unnecessary to test both directions.

The first test was made with the sensors mounted low and pointed straight down. This was deemed too low as the sensors activated directly and stayed active for the whole test duration. The test was also important for calibrating the height of the axle and finding out how the grease moves in the chamber. The grease moved a lot less than expected, and it did not rotate as much as expected with the axle. Most of the grease movement was in and out radially with the eccentrical motion of the axle. A schematic of the movement is shown in Figure 6.14.

Figure 6.14 Grease movement.

In the second and third tests, the sensors were raised until they worked as intended. In the fourth test, the height was untouched, and instead, the tuning fork sensor was turned radially to see if that would decrease the grease buildup, which it did.

All the previous tests were done with the sensors pointing straight down, measuring roughly in the middle of the bushing. As the grease moved more closer to the axle, the fifth test, therefore, consisted of angling the sensors radially against the axle, roughly 15 degrees, thereby also coming closer to the axle. This test showed even more promising results, and the difference between activation and deactivation became very small for the LMT110 and almost halved for the LFV220 compared to the previous test, as seen in Table 6.5. This is, therefore, without any doubt, the best mounting position when measuring from above.

Table 6.5 Sensor activation points related to axle offset.

		Axle offset [mm]		
		On activation	**On deactivation**	**Difference**
Test 1	**LMT110**	Activated from beginning	Stayed active	**-**
	LFV200	Activated from beginning	Stayed active	**-**
Test 2	**LMT110**	-1	-24	**23**
	LFV200	Activated from beginning	Stayed active	**-**
Test 3	**LMT110**	1	-19	**20**
	LFV200	-4	-37	**33**
Test 4	**LMT110**	0	-18	**18**
	LFV200	2	-28	**30**
Test 5	**LMT110**	12	7	**5**
	LFV200	-8	-25	**17**
Test 6	**LMT110**	Never activated		**-**
	LFV200	5	-13	**18**
Test 7	**LMT110**	-11	Never deactivated	**-**
	LFV200	-8	Never deactivated	**-**
Test 8	**LMT110**	-2	-14	**12**
	LFV200	2	-37	**39**
Test 9	**LMT110**	-1	-12	**11**
	LFV200	-3	-13	**10**
Test 10	**LMT110**			**-**
	LFV200	0	-13	**13**
Test 11	**LMT110**	13	0	**13**
	LFV200	8	1	**7**

For the sixth test, the bottom bracket was swapped, allowing the sensor to be mounted tangentially to the axle. The sensors were mounted high at a 45-degree angle, and the tuning fork was turned flat. Tests seven and eight were done with the same settings but first lowered by 10 mm and then in between. For the ninth test, the only setting that changed was the orientation of the fork, which would now be standing.

The tenth test did not test the sensors in a new way but rather the inputs to the computer. Throughout the testing, there had been some strange artifacts in the signal. The signal should have been on or off as both sensors work as switches, resulting in an output of 24V or 0V. But throughout the day, a middle ground of 7V had been seen on all the tests when only one of the sensors was activated when it should logically have been 0V. To rule out what caused this, a test was done with only the LFV200 sensor plugged in, which did not have that same problem.

The issue was thereby traced to the inputs of the testing equipment next to each other sharing the ground signal and, in some way, causing this problem. When finally figuring it out, one of the sensors was moved to another input channel, fixing the signal issue.

The eleventh test continued test nine, but the angle was changed from 45 to 30 degrees. This proved to be the best overall result for LFV200, getting the least difference between activation and deactivation heights, as seen in Table 6.5.

7 Final concept

Showcases the final concept, how it works, what parts will be used, how it meets the needs and requirements, and its pros and cons.

For the final concept, the chosen sensor was the LFV200 manufactured by Sick. It was deemed good at detecting both new and dirty grease and did not suffer from significant buildup. Mounting it at a 30-degree angle tangentially to the axle was also the preferred position according to the testing. Figure 7.1 shows how the final concept looks when mounted in the cone crusher. As can be seen, there is more than enough room to mount it without changing any other parts.

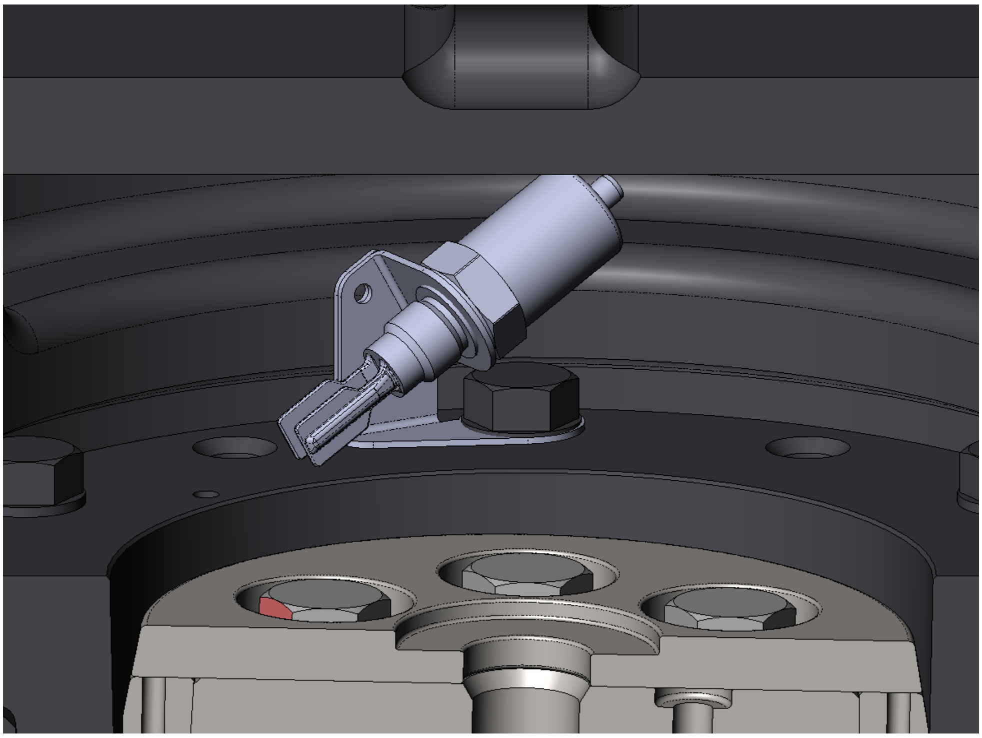


Figure 7.1 Final concept view in the cone crusher.

Figure 7.2 shows what the position of the sensor in the final concept looked like when performing the tests in the cone crusher.

Figure 7.2 Picture of the mounting position of the LFV200 from test eleven.

The plan is to manufacture the final brackets similarly to the tests but without the slots, leaving no room for error when mounting it. It will still be made from sheet metal, approximately 2 mm thick, as it is sturdy enough to take some beating when installing it, as seen in the simulations done earlier. As the grease moves very slowly, the forces exerted on the mounting brackets are small, and the only real concern is hitting the mount when installing the cap. This mounting bracket is also easy to install, only requiring two M6 screws and nuts. The sensor will then be mounted with a nut to the bracket and connected by an M12 sensor cable.

A steel tube will also be installed to pass the cable out of the grease chamber and connect it to the controller. This will protect the cable and provide an easy path through which to pass it. The steel tube will be mounted similarly to how the air vent is constructed now.

This concept will only detect when the grease falls below a specific preset level. As this level varies depending on the height of the axle, both values need to be checked against each other to be certain whether the grease level is low or not.

7.1 Advantages

This measuring system has the advantage of being equally sensitive to high-viscosity grease regardless of whether it is dirty or not. It is also easy to integrate and mount. When servicing the cone crusher, the sensor does not interfere with the regular maintenance process, making it easy to do it right. The cap can be lifted as usual, and then the sensor will reveal itself. The sensor must also be removed before lifting out the bushing, leaving no room to damage the sensor during that operation.

The mount also uses one of the bushing bolts to fasten the bottom bracket. This is important because that bolt is already known to be sufficient in this environment and will, therefore, also work to fasten the bracket.

The mounting system also allows the sensor to be mounted close to the axle, which is the most important place to keep lubricated.

7.2 Disadvantages

This sensor does not easily detect the maximum and actual grease levels, in addition to the required minimum level. An additional sensor has to be added to measure the maximum level. The mount also has two angles that are not keyed: the angle around the bolt attaching the bracket to the bushing and the angle at which the sensor is mounted in the brackets. This means it will most likely be installed slightly differently every time, leading to slightly different measurements.

7.3 Fulfilling needs and requirements

This section compares the needs and requirements from Chapter 4 with how the final concept performed.

7.3.1 Measurements

By carefully selecting and testing different sensors, the final concept has no issues measuring high-viscosity grease, whether clean or dirty. The chosen sensor is a level sensor and will, therefore, detect when the grease surpasses a distinct level; by placing the sensor so that the level coincides with where the level is too low, this requirement is also fulfilled. The measurements also proved to be accurate.

The needs were not strictly needed and were, therefore, not all fulfilled. Unfortunately, the sensor cannot detect the actual grease level, but if you would like to detect both minimum and maximum levels, two sensors can be installed. The sensor itself does not limit the frequency of the measurements, which is, in this case, limited by the controller that the sensor is plugged into. The sensor has a response time of 500 ms, limiting how fast the controller can pick up the signal. The final solution will allow measuring the grease level close to the axle.

7.3.2 Axle movement

The system shall work when the axle is moving. The tests done with the sensor mounted in the cone crusher showed no issues with the moving grease, so this requirement is, therefore, fulfilled.

7.3.3 Environment

The sensor is IP67 rated, can handle an overpressure of 64 bar, and can be used at -40°C - +70°C. These specifications are more than enough for the environment this sensor will be subject to. This requirement is thereby fulfilled.

7.3.4 Integration

The final concept is easy to integrate and only requires an additional pipe to be added for the cable. It also proved to be easily serviceable as it is easy to access when doing the regular maintenance procedure and does not interfere with any existing parts. These needs are, therefore, fulfilled.

8 Discussion and Conclusions

Discuss how the testing went, how this project ties into sustainable development, and what the future development steps look like.

8.1 Testing

There are always ways to improve a test, and there are always error sources. One significant error source was the temperature of grease when testing. All of the tests were done with grease at approximately 15°C; the grease gets significantly more and less viscous in the outer regions of the cone crushers temperature specification of -20°C - +40°C. When the viscosity increases, it can possibly stick easier to the sensor, resulting in false positive readings.

Other equipment could have more precisely compared how the sensor reacted to the different grease qualities. The results were adequate since the test focus was mostly on how the sensor reacted and how the activation point differed between the different grease qualities. The dirty grease was also a lot thicker than expected, and if that had been known, the testing could have been better prepared. It could also have helped narrow down the selected concepts more easily.

The tuning fork sensor was also received almost last minute, so the tests using that sensor could not be planned as well as the tests with the other sensors.

Testing the final concept would also be good and doing that in a cone crusher in active use for an extended period would be preferred. This would allow long-term testing in the correct environment and retrieve much data from the sensor. This would preferably be done with a cone crusher that leaks so that the grease will run low several times, testing what the system is designed for. Using an active cone crusher will also result in a lot of testing with different loads, which has not been done before. It will also provide testing when the cone crusher is subject to more vibrations thereby testing if those vibrations will be an issue.

8.2 Sustainable development

This master’s thesis topic can easily be tied to sustainable product development. Designing a level monitoring system for a cone crusher might not seem like a sustainability question at first, but it certainly can be when exploring why the system is needed.

Today, the lubrication for the spider bushing is not monitored, and it is, therefore, challenging to find out if the grease is running out. It is important to catch when the grease is running out, as when it does, the bushing will wear excessively. The grease leaking from the bushing can also be a sign that the bushing has already worn out and needs to be replaced, as more grease will slip out when the bushing gap gets bigger. Failing to catch this moment can result in complete failure and a seized bushing. This will negatively impact production, and more extensive maintenance will be needed.

An improperly greased bushing will almost certainly affect energy efficiency, as it will require more energy to rotate when there is more friction to counter. Wear will also increase when the bushing is improperly greased, resulting in more worn-out parts and, therefore, more waste. Improving this will help Sandvik develop more sustainable offerings and reach their sustainability goals.

8.3 Has the objective been solved?

The objective of this master's thesis was to develop multiple concepts and finalize a functional level-monitoring system. This was done by researching many different measurement technologies and testing three different sensors, two of which were tested in a rock crusher. Finally, the LFV200 sensor was chosen as the most suitable one, and a mounting solution was also developed for that specific sensor.

The solution also had to consider the axle’s axial movement and the highly viscous grease. The final sensors were tested with the grease, and they definitely fulfilled that requirement. The final concept will also work even when the axle is moving axially, although it can only measure one specific level right now.

8.4 Future development

The final concept should also be optimized by doing FEA. This will ensure they have the required strength without using more material than needed. After that, a final prototype should be made for long-term testing in a rock crusher to see if it gives the desired results.

Vibrations should be investigated thoroughly to see if the sensor or mounting system will work even when subject to vibrations when running the cone crusher. It would be beneficial to do a “Failure modes and effect analysis” (FMEA) to find out what potential issues can arise when the newly developed measuring system fails. The finite element analysis can also be extended with a modal analysis to see what effect resonance will have on the mounting system and what the resonance frequency will be.

The LFV200 can also be bought with IO-link, which unlocks some more possibilities, such as retrieving the resonance frequency and temperature from the sensor. Exploring these possibilities might facilitate an even more reliable system. The temperature could, for example, be used to determine what viscosity the grease can be expected to have at that specific time. Measuring the exact resonance frequency might also allow measuring how far the sensor is submerged in grease or even adjusting the sensitivity in real-time based on the temperature and viscosity of the grease.

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Appendix A Project plan and outcome

This is the project plan for the master's thesis, including how it went and what did not go as planned.

Overall, the project went as planned, and there was enough time to go through all the planned steps. The contact with suppliers and delivery of sensors took a few weeks longer than anticipated, mostly because the suppliers that were contacted did not have experience with measuring high-viscosity grease. Finding many different suppliers and contacting them regarding sensors also took a while, and there was a lot of discussion before finally ordering a few sensors. The ultrasonic sensor did not work as intended, and therefore, a new order was placed for a tuning fork sensor; this also delayed the tests a bit. This resulted in the testing not being done as thoroughly as preferred, leaving less time for prototyping. The final tests at Sandvik's testing facility were done when planned, but left little time to finish the report.

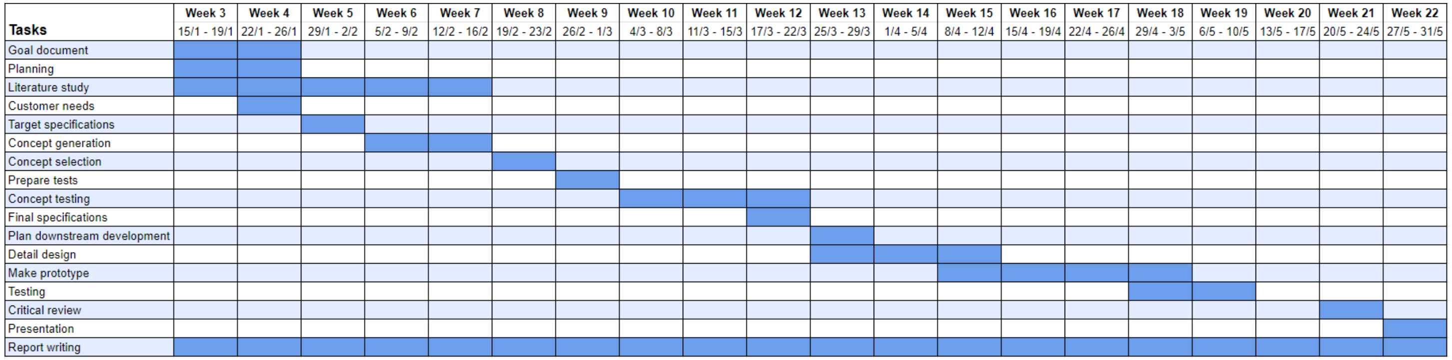


Figure A.1 Project plan.

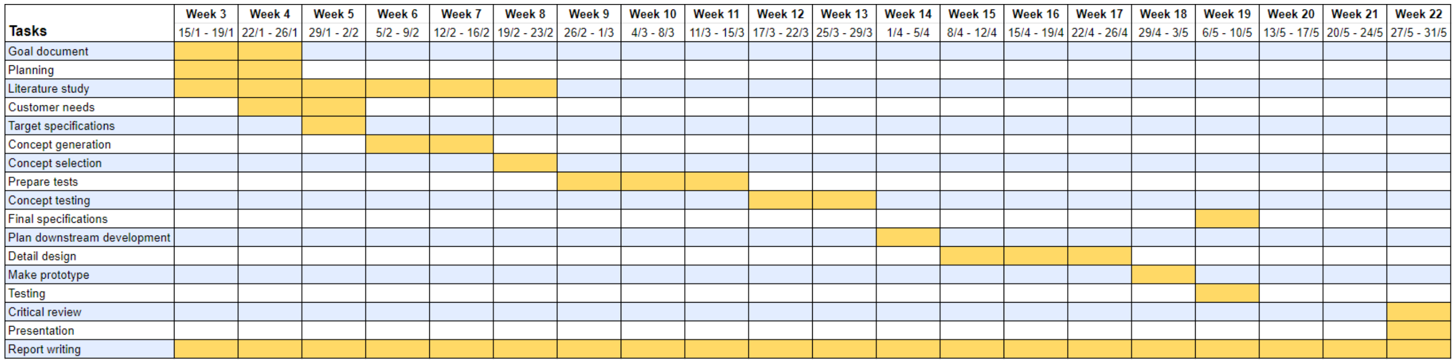
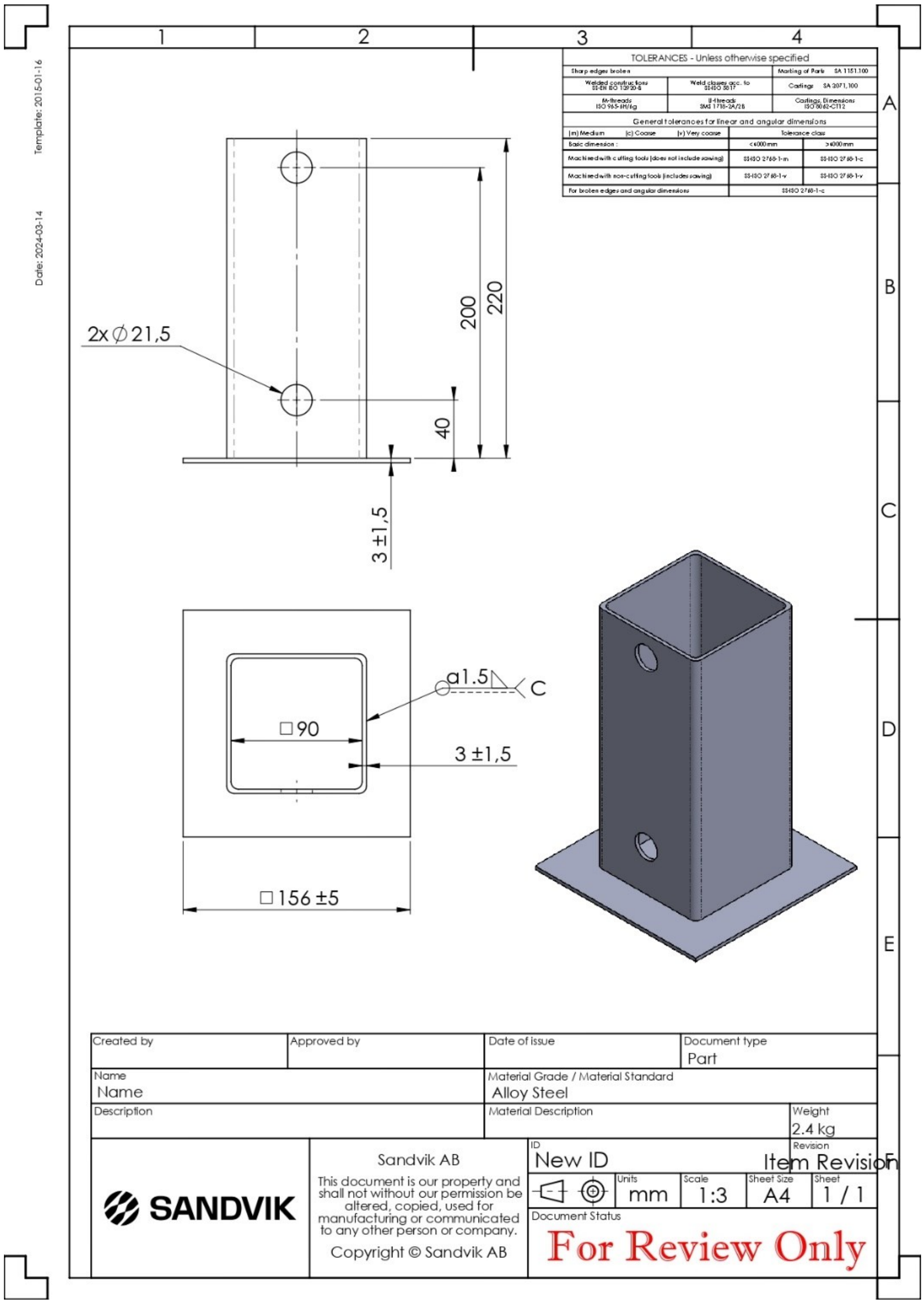


Figure A.2 Project outcome.

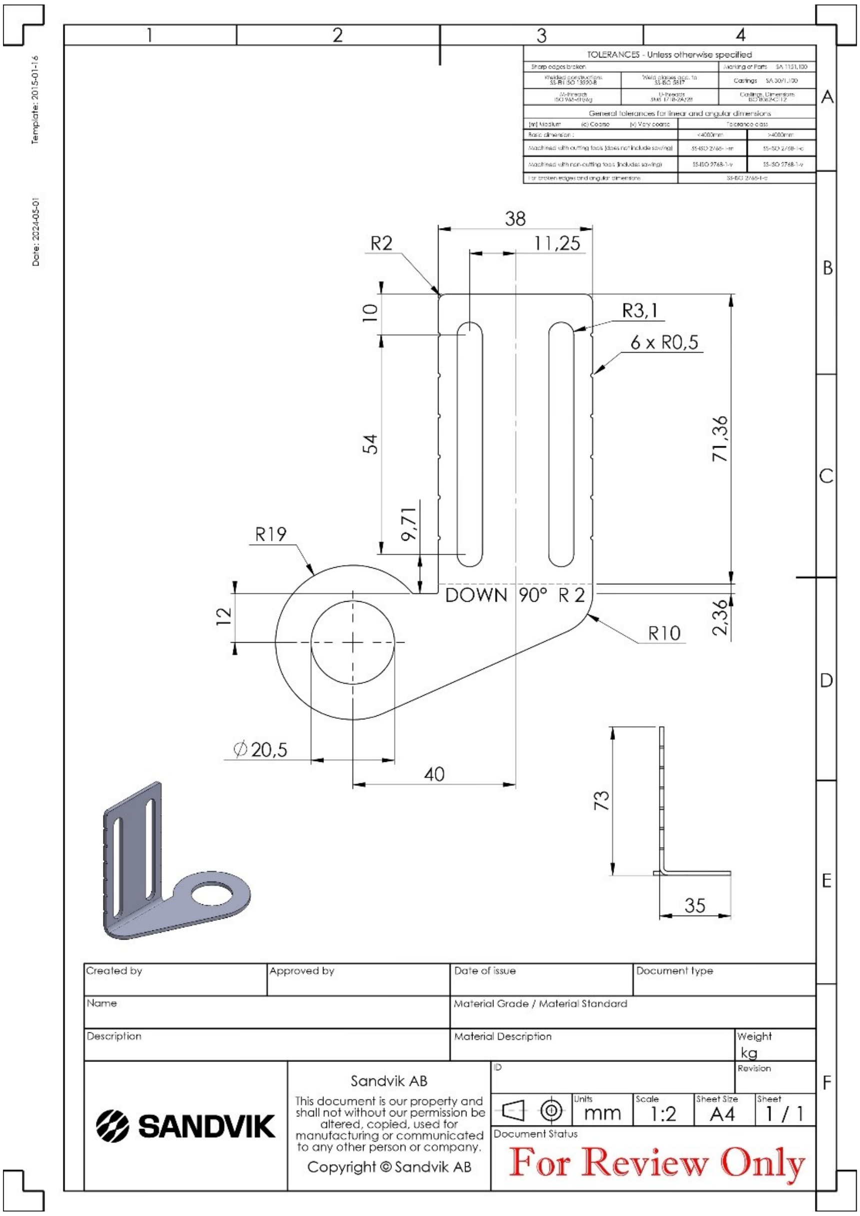
Appendix B Technical Drawings

Technical drawings for all the different brackets used when testing different sensors.

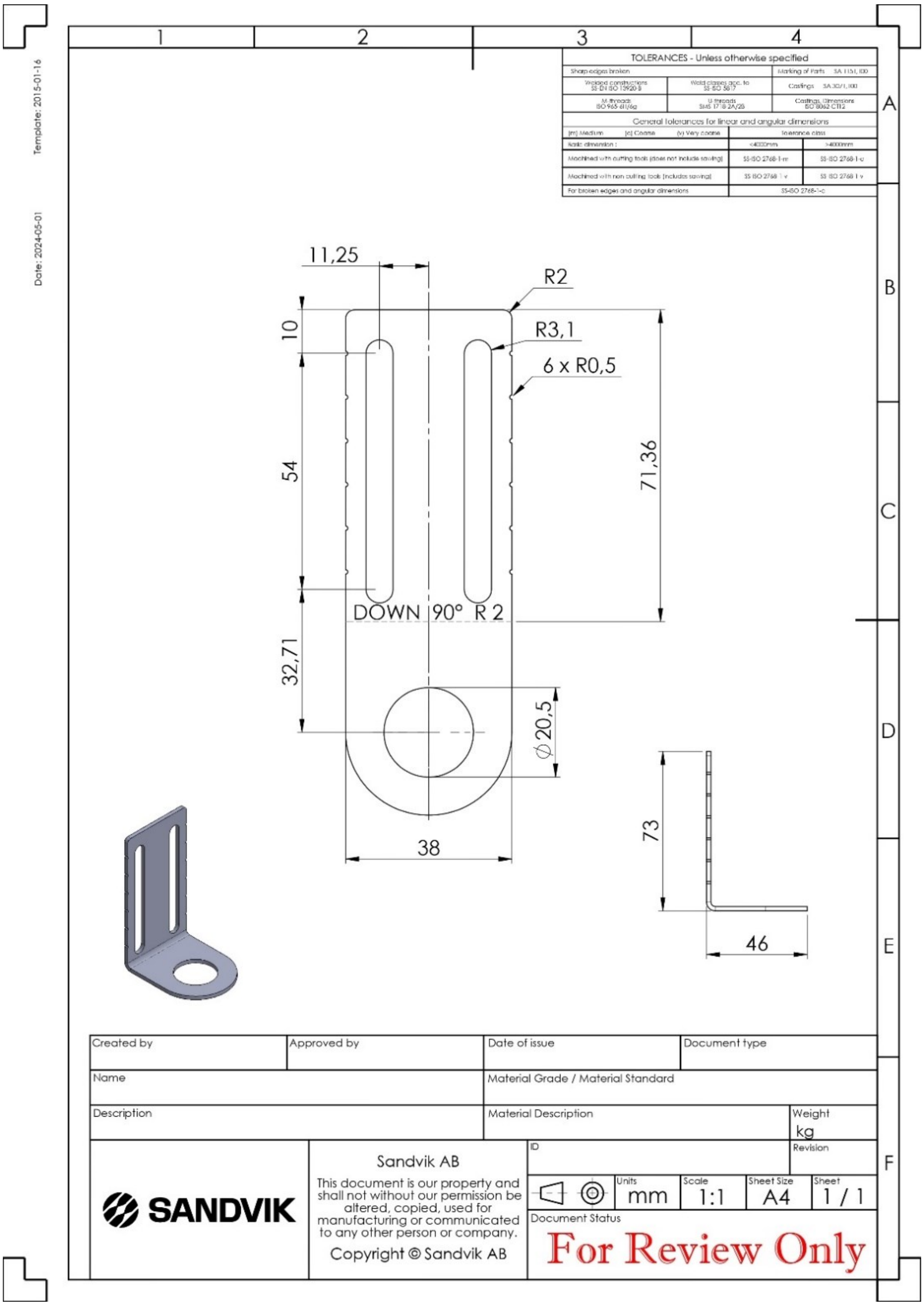
B.1 Testing tower



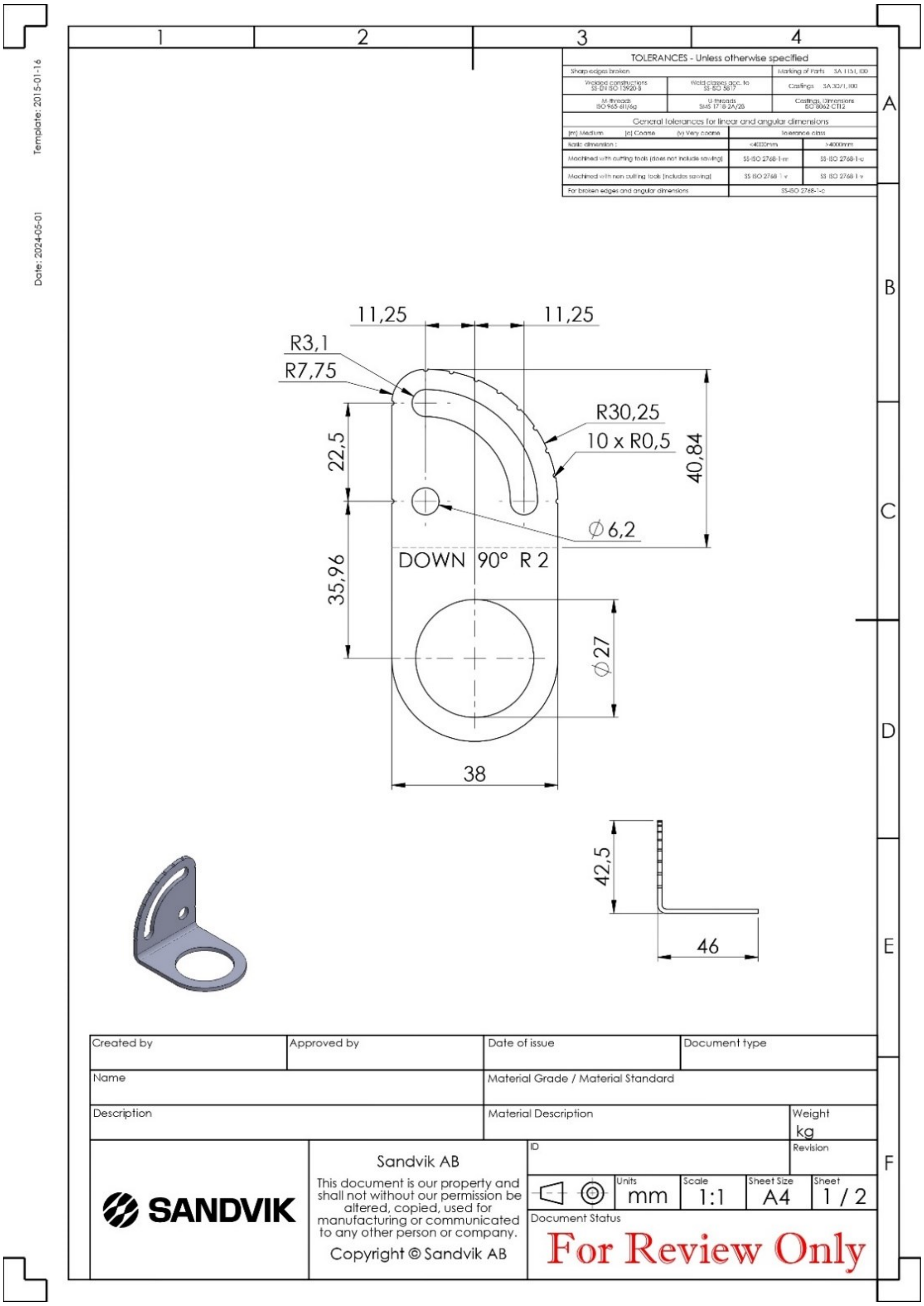
B.2 Bottom side mounting bracket



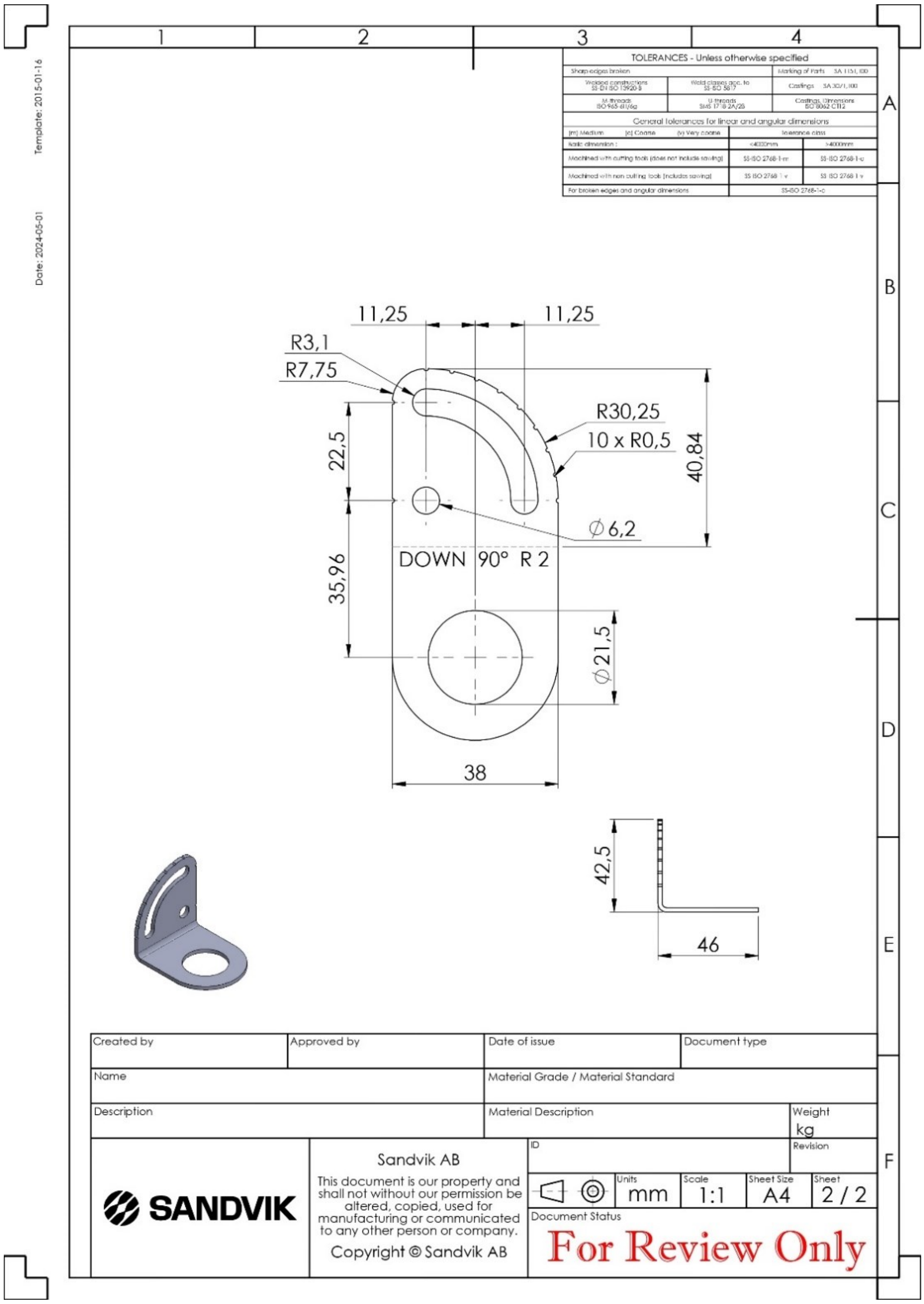
B.3 Bottom straight mounting bracket



B.4 Top mounting bracket LFV200



B.5 Top mounting bracket LMT110



Appendix C Testing Data

Data from the testing done in the cone crusher at Sandvik's research facility.

All the following figures, A.1-A.11, are from the testing done in a running cone crusher at Sandvik's testing facility.

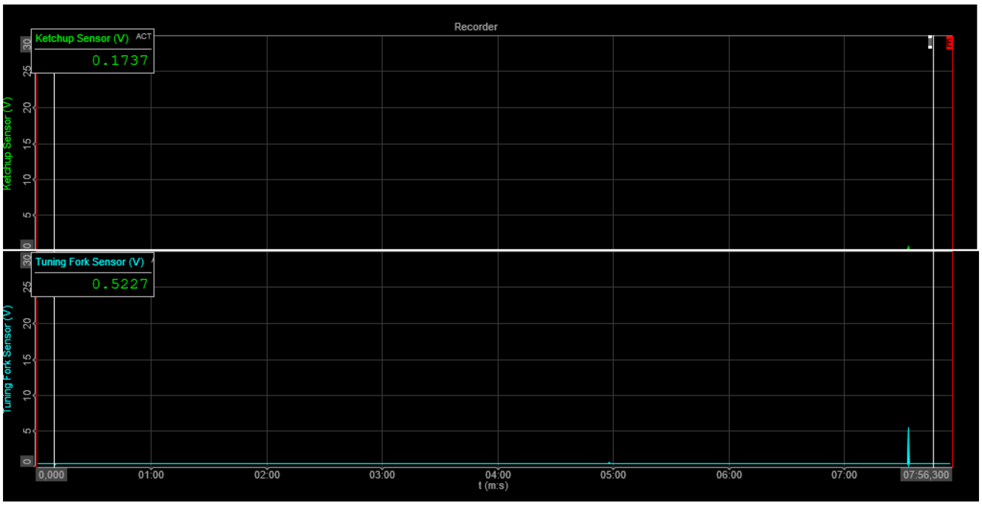


Figure A.1 Graph from test 1.

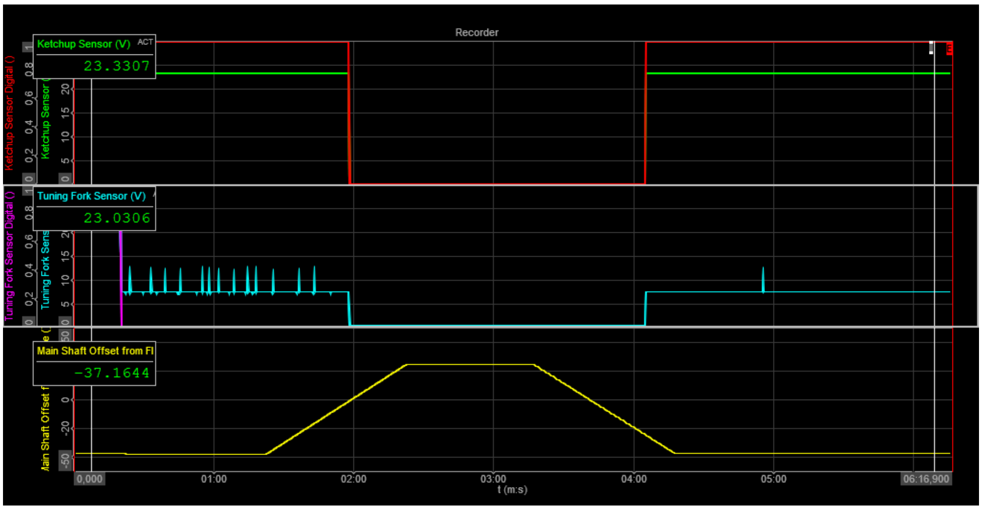


Figure A.2 Graph from test 2.

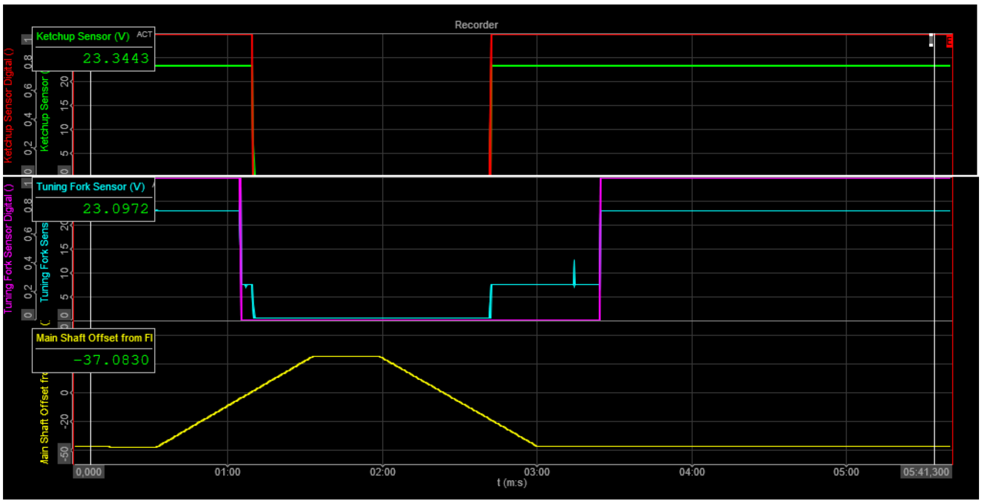


Figure A.3 Graph from test 3.

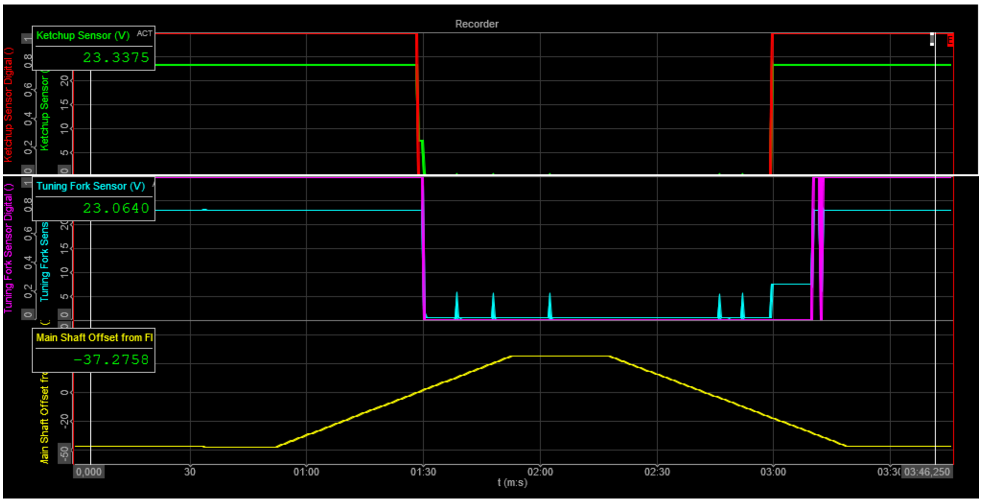


Figure A.4 Graph from test 4.

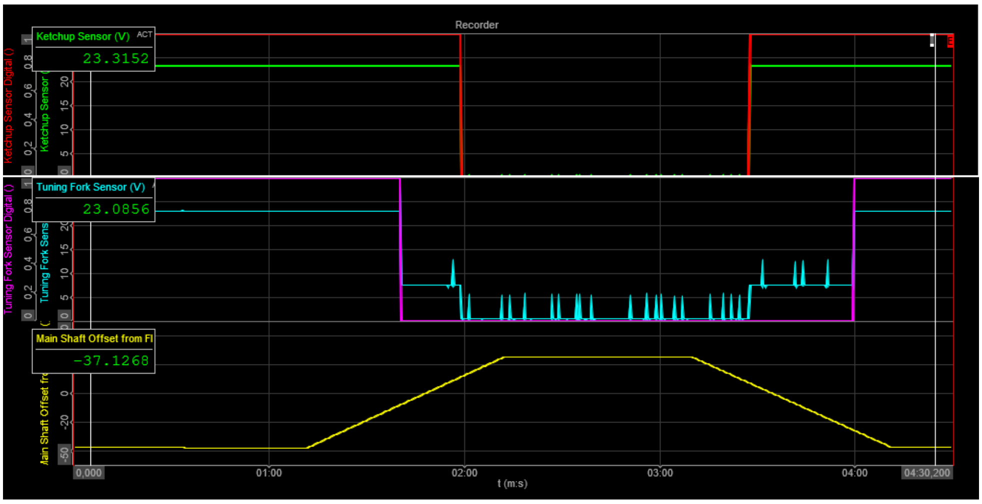


Figure A.5 Graph from test 5.

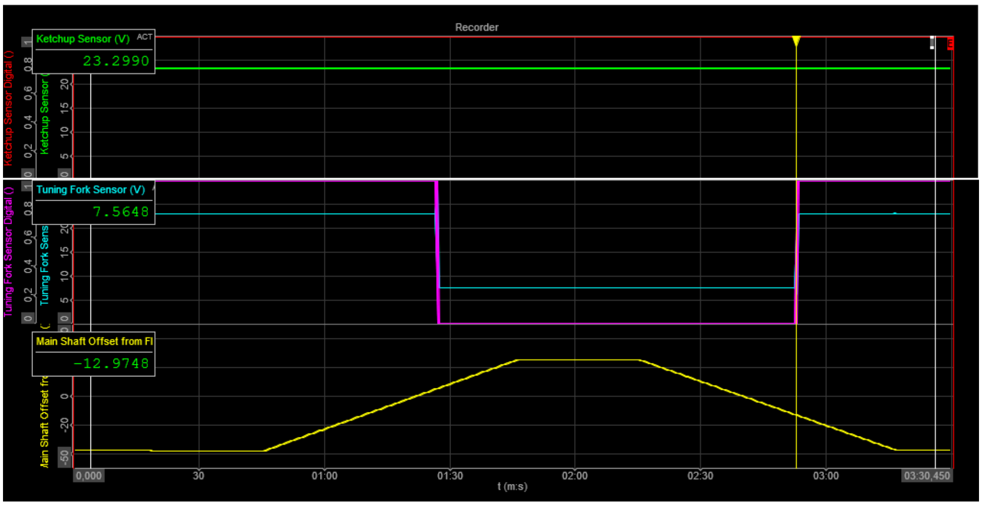


Figure A.6 Graph from test 6.

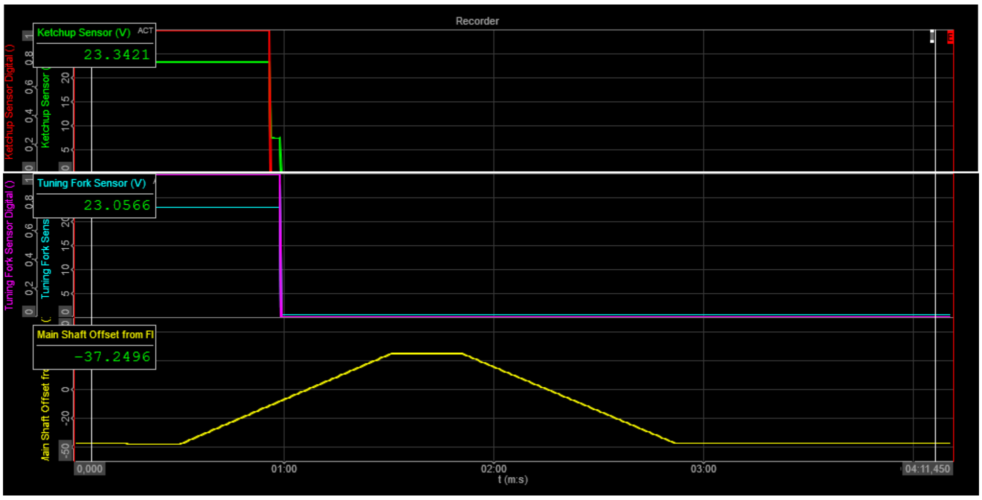


Figure A.7 Graph from test 7.

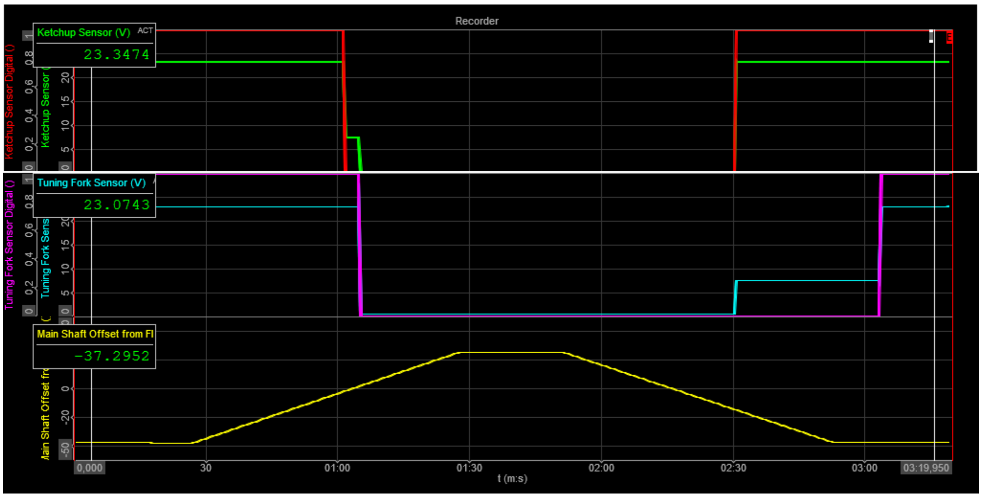


Figure A.8 Graph from test 8.

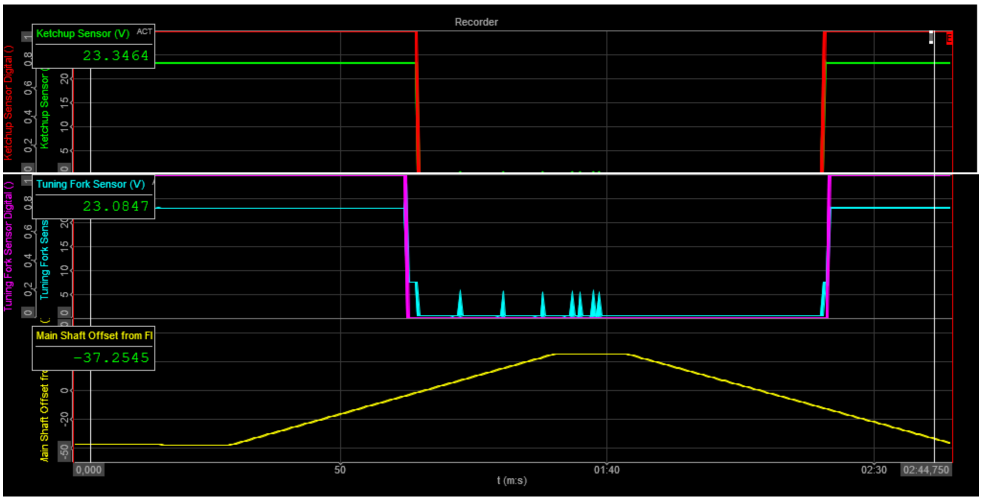


Figure A.9 Graph from test 9.

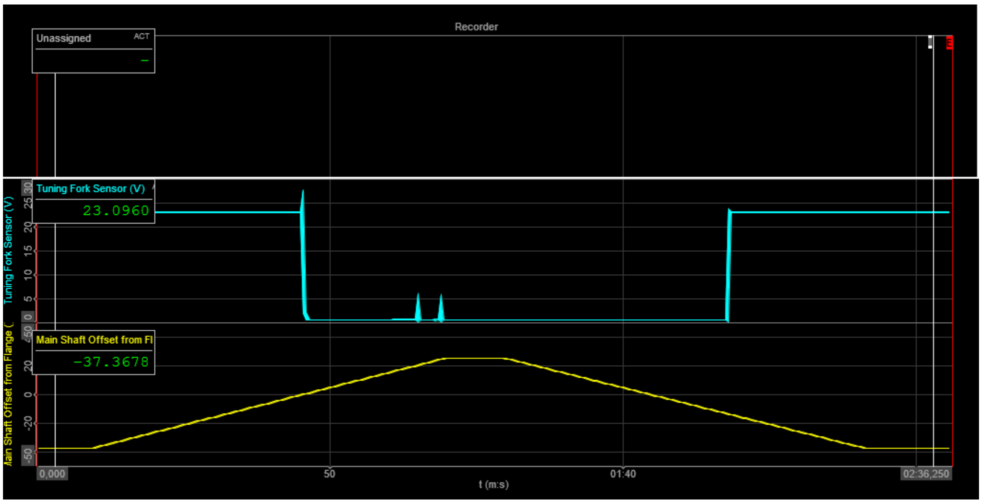


Figure A.10 Graph from test 10.

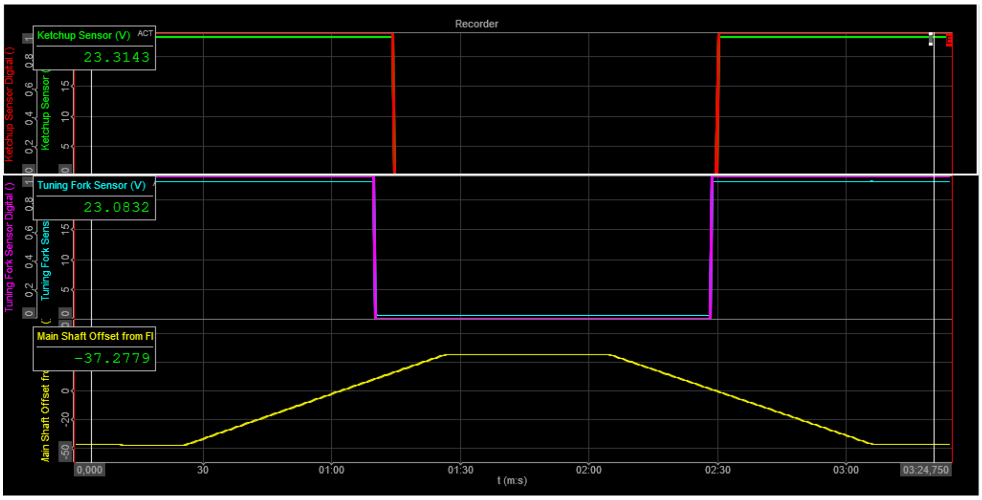


Figure A.11 Graph from test 11.