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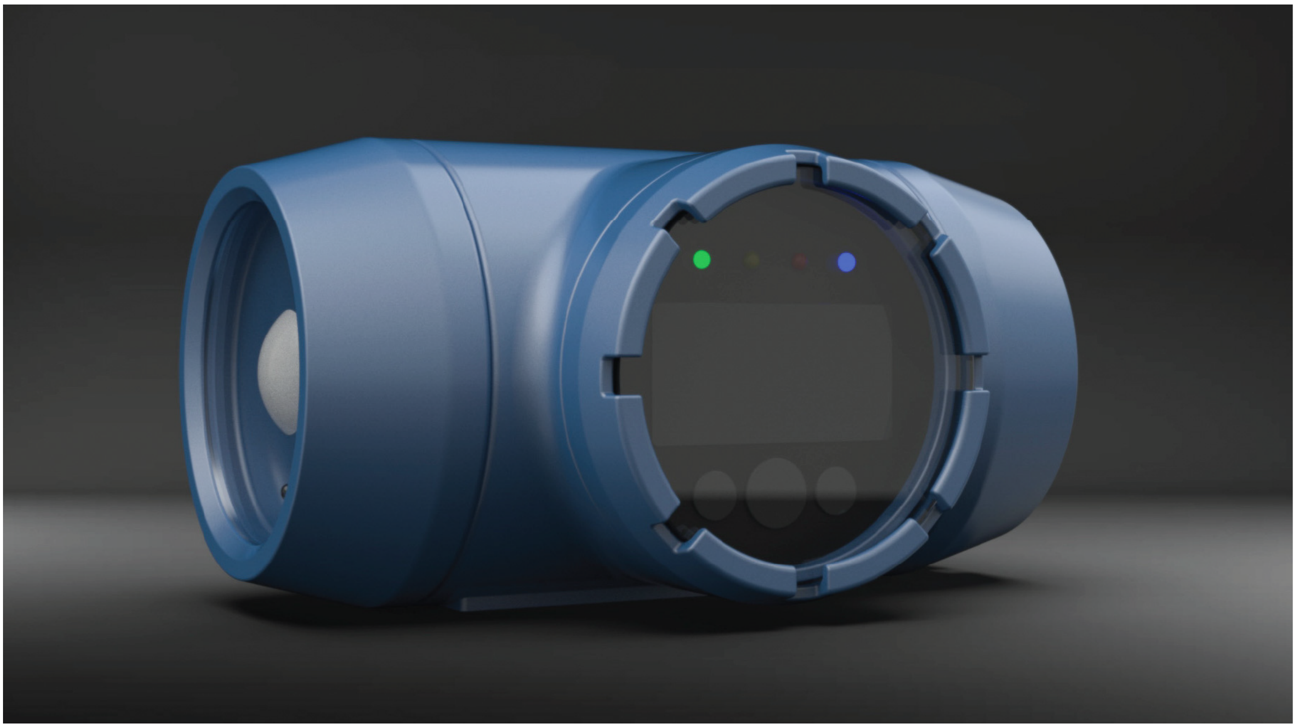

# Radar-based Vibration Monitoring

## A study defining a need for contactless vibration monitoring and the development of a radar-based sensor for industrial settings

Master's thesis in Industrial Design Engineering

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*In collaboration with Emerson*

Supervisor & examiner: Pontus Wallgren

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Cover illustration: The final concept, a radar-based vibration monitoring sensor. Cover illustration made by Isabelle Kjellström & Cornelia Nilsson

# Abstract

Undesired vibrations are a large problem within many industries as they cause damage to structures, machines, and equipment. This can lead to unplanned stops in production resulting in very costly consequences for their businesses. Emerson Automation Solutions has recently been able to modify its radar technology to monitor vibration levels contactless. With this technology, Emerson has the opportunity to be the first on the market with this technology. The aim of the project is to identify a user need and market for a contactless vibration monitoring device, as well as develop a physical concept of a radar sensor that can monitor vibrations and fulfill the needs of the users in the chosen market. To understand the needs of the users, user studies were conducted including interviews with ten companies in two rounds and four company visits. The need was then defined and used as a basis for developing the product. The results showed the users being satisfied with today's cheap and popular accelerometer solutions used for vibration monitoring. However, a need was found for measuring vibrations where today's solutions are not satisfactory. The market gap found was measuring vibrations on rotational equipment in inaccessible, extreme, or dangerous environments. The study visits showed a need for a flexible solution as the production sites could vary greatly between production sites. The results are compiled into a design concept of a semi-permanent radar vibration sensor. It was concluded that the flexibility the final concept offers, including the attachment solutions as well as the different versions, enables its use in many different applications.

**Key words**
Vibration monitoring, radar technology, predictive maintenance

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This thesis would not have been possible without all support and contribution by some people in particular. Therefore, we would like to express our gratitude towards those people.

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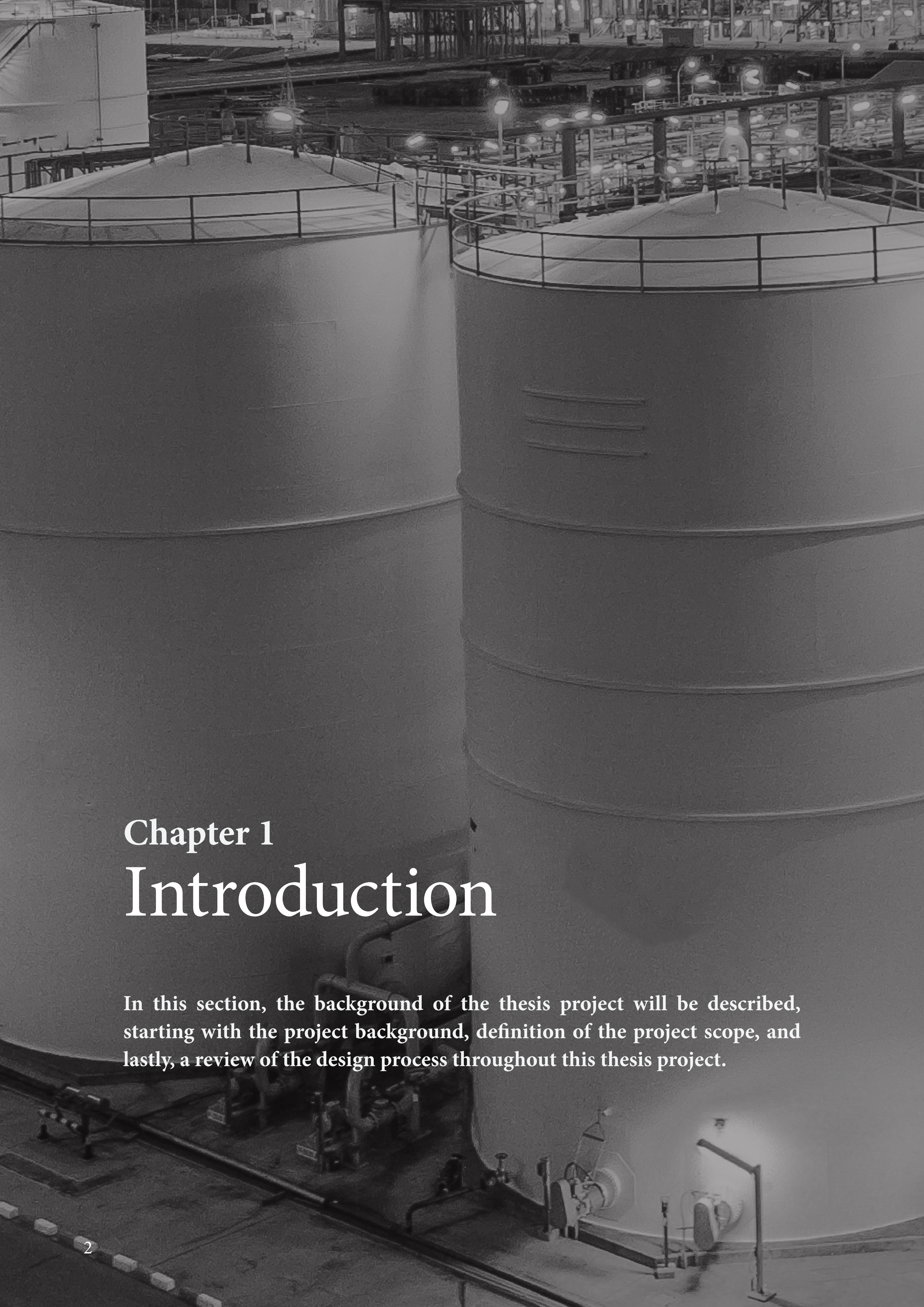
Without all of you, this thesis would not have been possible. Thank you!

Isabelle Kjellström          Cornelia Nilsson

# Vocabulary

| | |
|---|---|
| **Antenna** | Where the radar is transmitted from and received. On Emerson's radar products this is the white spherical glass at the bottom of the product. |
| **Hardware** | Product enclosure and accessories. |
| **Lobe** | The lobe contains the energy and is placed inside the antenna. |
| **Laser** | Referring to laser technology in general. |
| **Maintenance** | Maintaining equipment by, for example, replacing parts. |
| **Measuring point** | A point where vibrations are measured. |
| **Radar** | An electromagnetic sensor to detect objects at a distance. |
| **Sensor** | A measuring device, for example, a product that measures vibration. |
| **Software** | Digital computer & product interface, and software compatibility. |
| **Vibration monitoring** | Measuring vibrations on an object to ensure it is within limit values. |

# Table of Contents



## Chapter 1

# Introduction

**In this section, the background of the thesis project will be described, starting with the project background, definition of the project scope, and lastly, a review of the design process throughout this thesis project.**

## 1.1 Background

Undesired vibrations are a large problem within many industries as they cause damage to structures, machines, and equipment (Roy et al., 2020; Ding et al., 2016). They can also affect product quality and delivery. Vibrations can cause a stop in production that can have severe economic consequences and lead to product and supply shortages. As the economy has grown globally and industries become more specialized, many companies are dependent on each other as they are part of long supplier chains. In addition, citizens are dependent on vital production such as power, food, and water supply, among others.

Currently, many companies apply a variety of maintenance management strategies to prevent production failures. A common strategy is to monitor vibrations with contact-based technology to detect deviating vibrations that could affect machine health, product quality, or eventually lead to failures causing a stop in production. When a vibration deviates from the trend, troubleshooting will be made to find the cause and take action before a breakdown happens. Due to the importance of vibration monitoring, there is always a need for new and developed technology.

### 1.1.1 Emerson

This master thesis project is conducted in collaboration with the Emerson subsidiary Rosemount Tank Radar (RTR) in Mölnlycke, Sweden. Emerson is a global company with roots in Missouri, USA. Emerson has two business platforms: Automation Solutions and Commercial & Residential Solutions, this project is made at the Automation Solutions platform. They offer automation solutions in a variety of industries and applications to help companies achieve its top performance. RTR specializes in radar level measurement solutions. Historically, their customers have been mainly in the oil and gas industry. However, they have recently started investigating how radar can be applied to more industries and applications to broaden their product catalog.

### 1.1.2 Project Brief

Emerson have seen an increasing need for vibration monitoring among their clients who are not satisfied with the current solutions on the market. Based on this, a pre-study was conducted where it was found that vibration monitoring on pipes was a need seen among the current customers. RTR has recently been able to modify its radar technology to monitor vibration levels contactless, which was the basis of formulating the master thesis project. With this technology, Emerson has the opportunity to be first on the market with this contactless vibration monitoring technology. In this thesis project, the market will be examined along with the user need, leading up to a physical product concept applying Emerson's existing radar technology and new software.

## 1.2 Project Scope

In this section, the project scope is defined by presenting the aim, research questions, and project demarcations.

### 1.2.1 Aim

This thesis project aims to identify a user need and market for a contactless vibration monitoring device. In addition, the aim is to also develop a physical concept of a radar sensor that can monitor vibrations and fulfil the needs of the users in the chosen market. The chosen market should have a clear need for non-contact radar monitoring.

### 1.2.2 Research Questions

Based on the project aim, the following research questions were formulated:

- Why is vibration monitoring needed in an industrial setting?
- Where is vibration monitoring needed in an industrial setting?
- What market gap exists for vibration monitoring with radar today?
- What needs and requirements do the users and context pose in a vibration monitoring product?
- How could a product be designed to fulfil these needs?

### 1.2.3 Demarcations

The project's focus is mainly to identify the potential need and market gap for a contactless vibration monitoring device and from there, create a base concept for the sensor. Therefore, the following demarcations have been made:

- The market analysis will be limited to focus on companies in Sweden.
- The development of the concept will be limited to focus on the physical parts of a vibration monitoring device.
- The concept will be limited to presenting a visual concept, representing the functionality, without detailed construction.

## 1.3 Design Process

In this section, the applied design process and the report structure are presented.

### 1.3.1. The Design Thinking Process

Throughout this thesis project, the Design Thinking Process (The Interaction Design Foundation, n.d.) has been followed, see Figure 1.1. The framework is a non-linear process where different stages can take place out of order, in parallel, or in iterative cycles. The framework has been used as it is a suitable explorative process for problems that are unknown or ill-defined.

In the first stage, Empathize, literature studies were conducted along with user studies and field studies to reach an understanding of

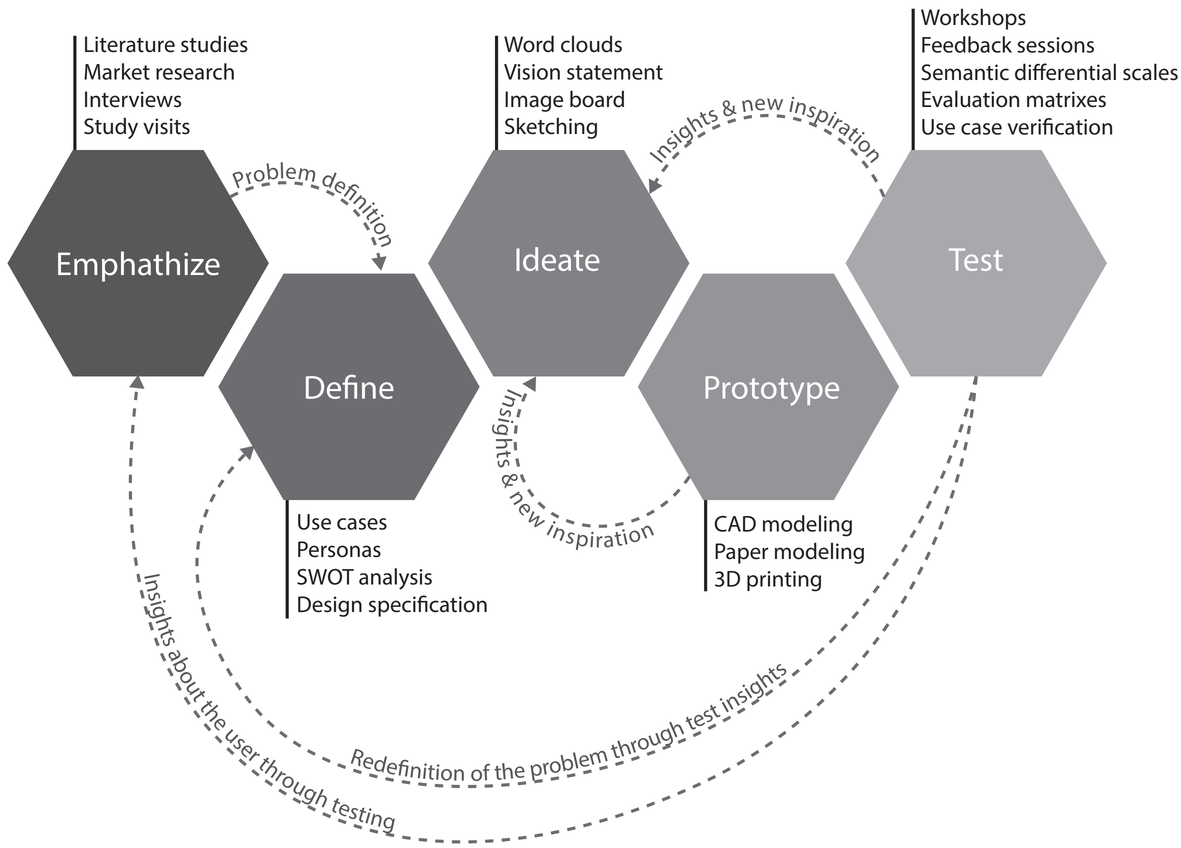



*Figure 1.1. The design thinking process throughout this thesis project.*

the market, users, and potential problems.

In the Define stage, use cases, personas, and a design specification were created. This was conducted to define the users and their needs.

In the Ideate stage, the ideation process took place with inspiration from the define stage. A number of ideation methods were applied, and the ideation process was conducted in iterative cycles with feedback and evaluation sessions.

In the Prototype stage, the early concepts were modeled using CAD. Physical models were also created: a low-fidelity size model and a more high-fidelity 3D printed model of the final concept.

In the Test stage, the ideation and prototype stages were conducted in iterative cycles where the different concepts were evaluated by mechanical engineers.

### 1.3.2 Report Structure

As the design thinking process is non-linear, the different stages often took place in parallel to each other and in iterative cycles. For convenience, the report methodology and results have been divided into two phases, see Figure 1.2.

In chapter 3 the theory behind the methodology is presented. In each phase the methods and how they were applied are presented, followed by the results and lastly, the most important insights from the phase are summarized at the end of the phase chapter.

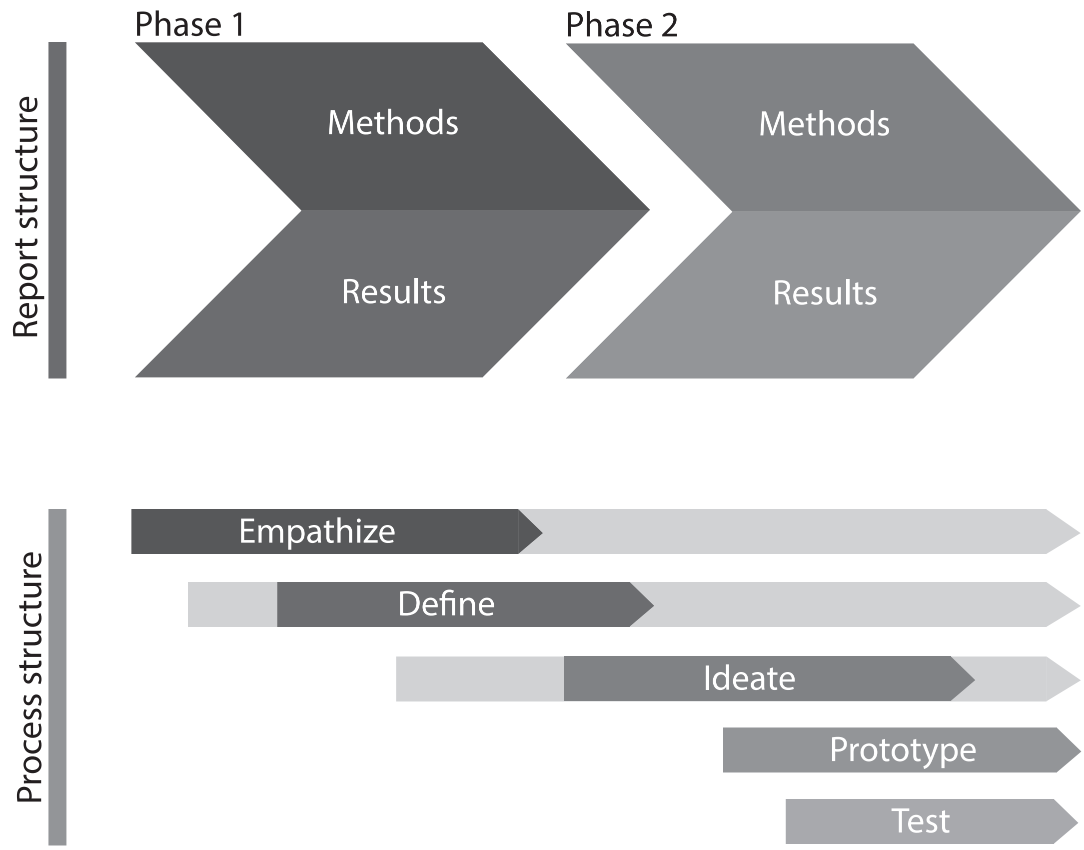



*Figure 1.2. The report structure versus the design thinking process throughout this project.*


## Chapter 2

# Radar Technology & Vibration Monitoring

**In this chapter, theory for the project is presented, starting with theory on radar technology and its current application areas, followed by the existing vibration monitoring technology on the market, and lastly, a presentation of maintenance management strategies used by industries today.**

## 2.1 Radar Technology

In this section, the theory behind radar technology, its preconditions and applications today are presented to create an understanding of the rest of the report.

### 2.1.1 How an FMCW Radar Works

In this section, the basics behind the FMCW radar technology will be explained. It will also cover the principle behind the measurement of multiple objects at the same time, and end with the principle behind vibration monitoring using radar technology.

**Chirp**

FMCW stands for Frequency Modulated Continuous Waves and is used to measure range, velocity, and the angle of arrival of in-front objects (Rao, 2017). The transmitted signal of an FMCW radar is known as a chirp and consists of a sinusoid which is sine wave and with whose frequency increases linearly with time. This can be illustrated in an amplitude vs time plot, also known as an A-t plot, see Figure 2.1. The chirp is a continuous wave with a linearly modulated frequency, which gives the name to FMCW.

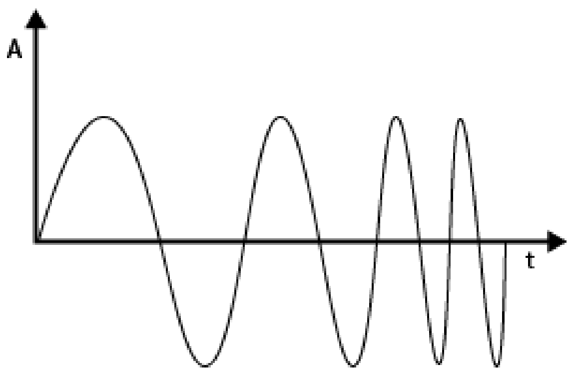



*Figure 2.1. A chirp illustrated in an A-t plot.*

Another convenient way to illustrate a chirp is in a frequency vs time plot, also known as f-t plot, see Figure 2.2, which shows the linear increase of the chirp frequency with time. The chirp has a slope S, illustrating the ramp-up rate of the chirp, and a bandwidth B, illustrating the frequency range of the chirp.

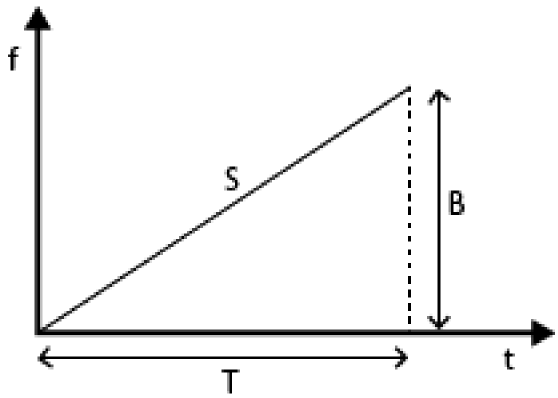



*Figure 2.2. A chirp illustrated in an f-t plot with the bandwidth B and slope S.*

**Technology**

An FMCW radar consists of (1) a synthesizer, (2) a TX antenna, (3) an RX antenna, and (4) a mixer (Rao, 2017), see Figure 2.3. The synthesizer is generating what is known as a chirp, transmitted by the TX antenna. As the chirp hits an object, it is reflected and received by the RX antenna. The TX and RX signal are mixed in a mixer, generating an Intermediate Frequency Signal, also known as an IF signal.

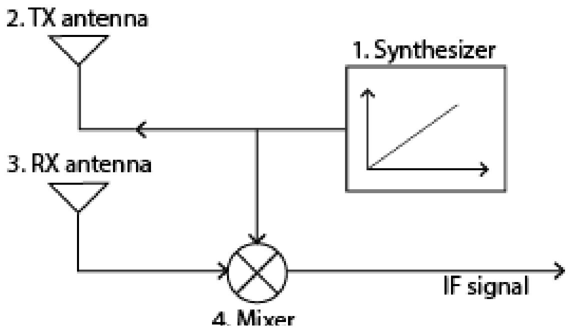



*Figure 2.3. A simplified block diagram of an FMCW radar.*

**Mixer**

The mixer is a 3-port device, meaning that it has 2 inputs and 1 output (Rao, 2017). This means that if two sinusoids are input to the two input ports of the mixer, the mixer sinusoid output will have the following two properties:

1. The instantaneous frequency of the output equals the difference of the instantaneous

frequencies of the two input sinusoids.

$$x_1 = \sin(\omega_1 t + \phi_1)$$

.

2. The starting phase of the output sinusoid is equal to the difference of the starting phases of the two input sinusoids.

$$x_2 = \sin(\omega_2 t + \phi_2)$$

Combining the two inputs gives the output:

$$x_{out} = \sin[(\omega_1 - \omega_2)t + (\phi_1 - \phi_2)]$$

**The IF signal**

Using an f-t plot, the TX-signal and RX-signal can be illustrated (Rao, 2017). As shown, the RX signal is a delayed version of the TX signal. A single object in front of a radar produces an IF signal with a constant frequency of S2d/c, see Figure 2.4.

The IF signal consists of multiple tones, the frequency (f) of each tone being proportional to the distance (d) of the corresponding object. The radar receives a reflected chirp from an object after a round-trip delay of tau. The

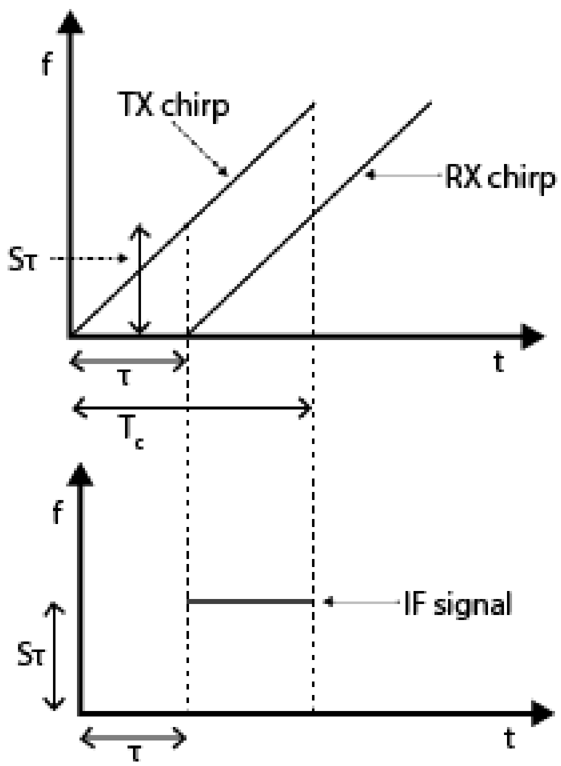



*Figure 2.4. The IF-signal illustrated in an f-t plot.*

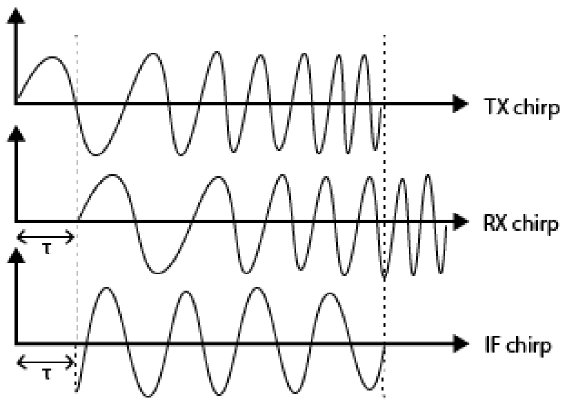



*Figure 2.5. The TX chirp, RX chirp and IF-signal ilstrated in an A-t plot.*

transmit signal and the reflected signal are mixed in a mixer to create an IF signal which has a constant frequency S tau, or equivalently, S2d/c where d is the distance of the object to the radar. The initial phase of the IF signal at the mixer output is the difference of the initial phases of the two inputs.

In Figure 2.5, an A-t plots of the TX chirp, the RX chirp, and the IF signal is shown. The RX chirp is the delayed version of the TX chirp, delayed by an amount tau which is the round-trip delay. The IF-signal is a constant frequency signal

**Fourier Transform**

A Fourier transform converts a time domain signal into a frequency domain (Rao, 2017), see Figure 2.6. A sinusoid in the time domain

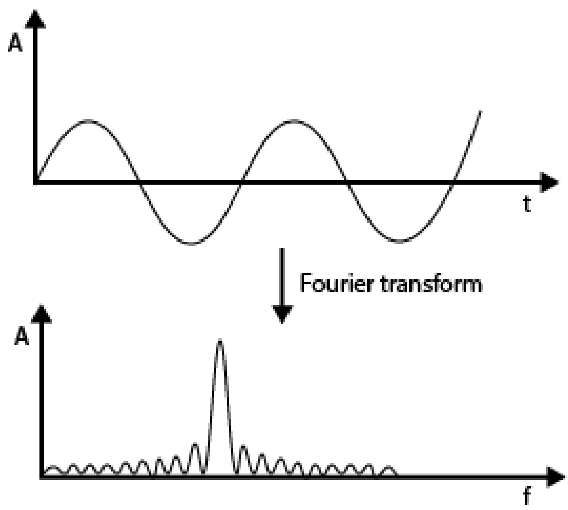



*Figure 2.6. A Fourier transform converts a time domain signal into a frequency domain.*

produces a peak in the frequency domain. The location of the peak corresponds to the frequency of the sinusoid. The signal in the frequency domain is a complex number with an amplitude and a phase.

A complex number can be mathematically represented in the form:

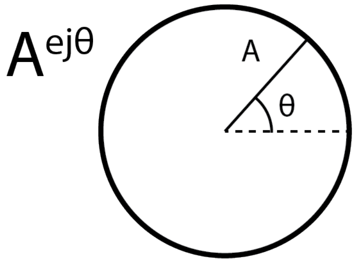



*Figure 2.7. Mathematical representation of a complex number.*

where A is the amplitude and theta the phase. Alternatively, it can also be pictorially represented as a phasor, which is a vector with a length corresponding to the amplitude A and a direction corresponding to the phase theta. An important property of the Fourier transform is that the phase of the peak corresponds to the initial phase of the sinusoid. The mentioned properties are strictly true only for a complex input tone of the form e power j omega t.

**Measuring of vibrations**

A vibration is a small displacement of an object. As the object moves, the phase of the IF signal will also change according to the formula (Rao, 2017):

$$\Delta\phi = \frac{4\pi\Delta d}{\lambda} = \pi = 180^{\circ}$$

An object at a certain distance produces an IF signal with a certain frequency and phase. Once an object moves, it changes the phase but not the frequency. In this way, it is possible to measure vibrations over time, see Figure 2.8.

Basically, a radar measures the changes in the distance of an object in one dimension, meaning only the direction of which the radar is sent out from. Because it only measures the changes in distance, measuring with radar can

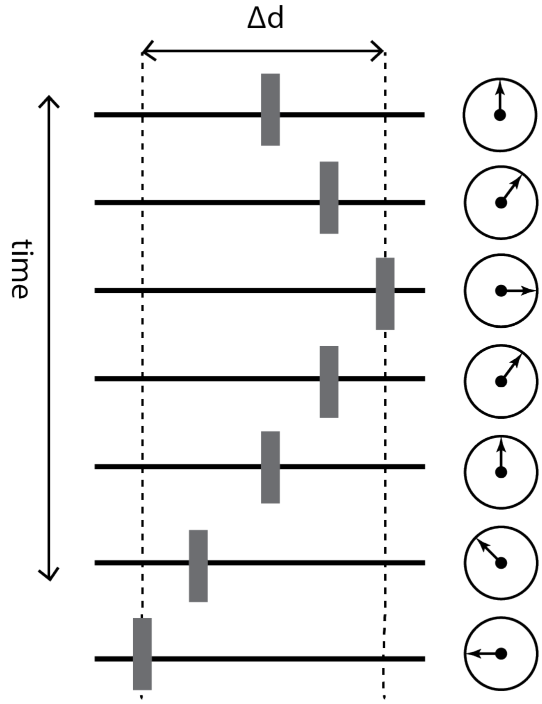



*Figure 2.8. Vibrations are measured by measuring the difference in distance over time.*

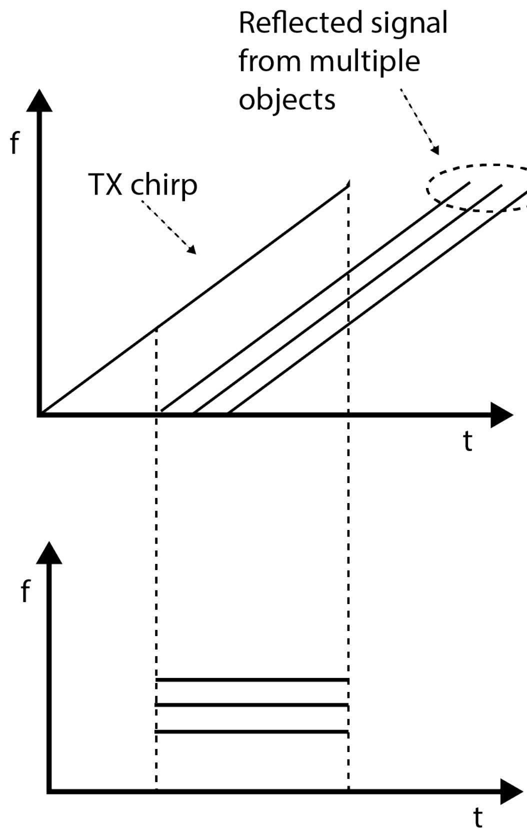



*Figure 2.9. Multiple objects in front of the radar creating multiple tones in the IF signal.*

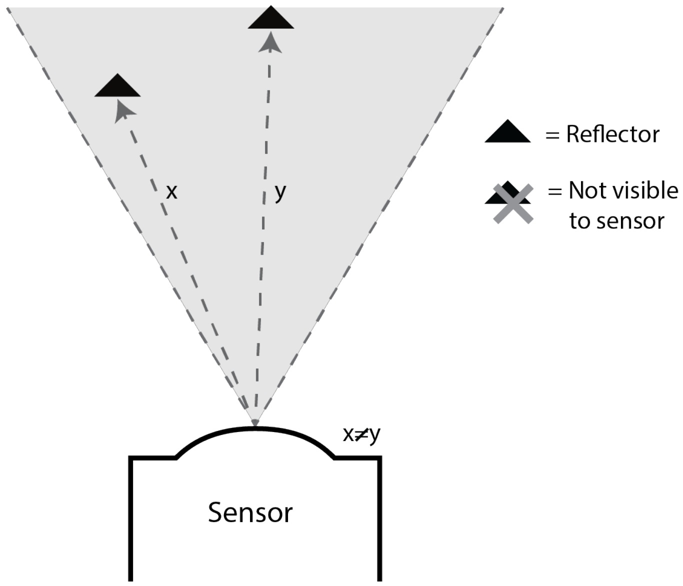



*Figure 2.10. To measure several objects at once, they need to be separated by distance to the sensor and within the radar view.*

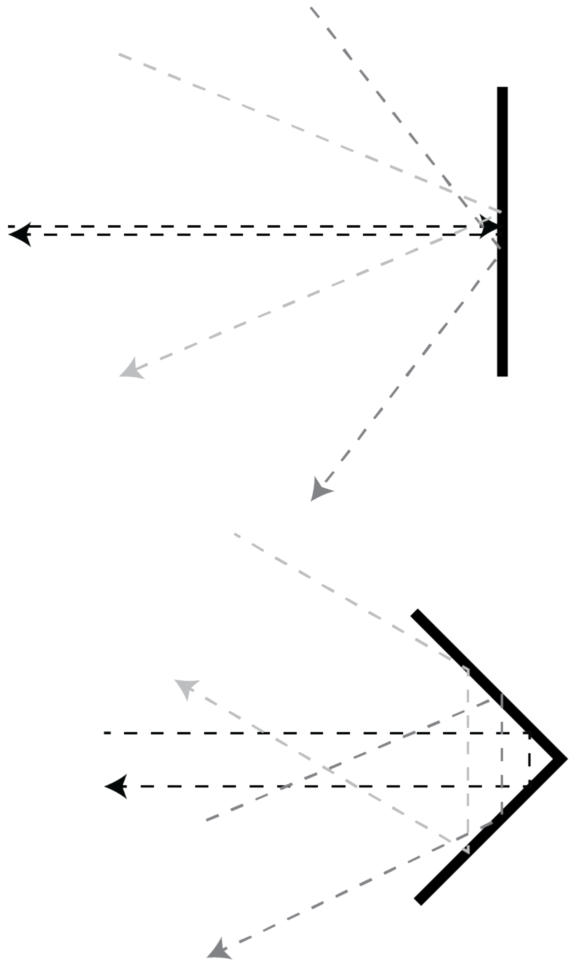


*Figure 2.11. The radar signal must hit perpendicular to the surface to return in the same direction. If a reflector is used (bottom illustration), the signal always returns in the same direction.*

be performed from any distance within the signal reach.

**Measuring of Multiple Objects**
When there are multiple objects in front of the radar, there will be multiple reflected chirps at the RX antenna (Rao, 2017), see Figure 2.9.

This means that as long as the measuring points are placed with a different distance from the antenna, it is possible to measure vibrations from several points at once, since there will be reflected signals separated by time, see Figure 2.10.

**Reflectors**
To be able to measure vibration a chirp has to be sent out and received to the same place. This means that the chirp has to be reflected perpendicular to the surface, or it will bounce off at an angle that will not be returned to the sensor, see Figure 2.11. Either the sensor can be placed in a way to make sure the signal is reflected perpendicular, for example, aimed at a water surface, or a reflector can be used. A reflector uses angled metal pieces to make sure the signal is received straight back, even though the surface might be round or difficult to aim at.

### 2.1.2 Applications of Vibration Monitoring in Literature Today

Different applications for vibration monitoring in the literature today are presented below. Both for vibration monitoring in general and radar-based vibration monitoring. The two main areas where vibrations are monitored are Structural Health Monitoring (SHM) and monitoring machine parts. Monitoring of pipelines were also researched as this was a part of Emerson's initial pre-study.

SHM is currently one of the main applications for vibration monitoring in the literature. SHM plays an important role in assuring safety and maintainability in structures such as bridges or tall buildings (Cruz et al., 2018). Vibration monitoring is an important part of enabling SHM (Piotrowsky & Pohl, 2021) as it can indicate the health status of the structure (Cruz et al., 2018). With vibration monitoring, the strength of forces to the structures can be monitored as well as sudden changes in forces due to, for example, an earthquake (Carpio et al., 2016) or mountain blasting (Ragam & Sahebraoji, 2019). Generally, structures have a low natural frequency, it is the deviation to this frequency that the monitoring needs to catch as this can affect the health (Cruz et al., 2018), therefore, continuous monitoring of vibration is of the essence. Accelerometers are most commonly used (Cruz et al., 2018; De La Torre et al., 2020; Tan et al., 2011), but non-contact options have also been explored when contact-based options are not satisfactory (Piotrowsky & Pohl, 2021; Li et al., 2015; Guan et al., 2015).

The other main area of vibration monitoring observed in the literature is machine parts, such as vibrational and rotational frequencies due to, for example, loose bolts, misalignment, or wear of the machine (Roy et al., 2018). According to Roy et al. (2020), the first sign of deterioration of a machine can be seen in changes in vibration- and rotation frequencies. To ensure preventive maintenance of machines, continuous monitoring is crucial. Accelerometers are the most used technology for this type of monitoring, as seen in (Pomorski Linessio et al., 2016; Gomathi et al., 2021), but non-contact monitoring such as laser, camera-based, and radar-based, has been researched as well, as seen in Rozic et al., 2019; Yang et al., 2017 & Rakshit et al., 2018.

Since Emerson initially did the pre-study on monitoring pipelines, this area was researched as well to gain a better understanding of pipeline monitoring as a potential application area. However, when researching vibration monitoring applications, pipelines did not appear unless specifically searched for, indicating it is not a largely researched area. However, there were some projects mentioned in the literature that are mentioned below.

There is also some research made on vibration monitoring of pipelines, mostly non-contact-based sensors (Han et al., 2013; Jin et al., 2016), but there is research on contact-based sensors as well (Ismail et al., 2015; El-Zahab et al., 2018). Li et al. (2018) researched safety in pipelines in China, as leakage can cost an immense amount of money and risk polluting the air. Causes for damage to the pipes include external factors such as drilling, heavy vehicles, or natural disasters, which can be identified in the vibrations. According to the article, optical fiber vibration sensors are the best option for monitoring pipelines, however, there are some drawbacks such as distinguishing the correct vibrations. Yang et al. (2021) studied the same technology also seeing drawbacks such as not being able to identify changes in some environments but recognizing the need for the technology as long-distance pipeline damage can jeopardize energy supply.

## 2.2 Vibration Monitoring

This chapter will present the current technology that is available for measuring vibrations today. The first subsection Existing Technology will present the existing technology that is present in the literature today and is possible to measure vibrations with. The second subsection Products on the Market will present the products that are available and common technology to buy.

### 2.2.1 Existing Technology

When existing technology used for vibration monitoring currently was researched in the literature, three main categories were found: contact-based technology, vision-based technology, and radar-based technology. Contact-based technology is mainly accelerometers of different sorts, while vision-based technology is mainly laser and camera-based technology.

There are different ways to measure vibration using accelerometers, but the most common way when monitoring machines is piezoelectric accelerometers (Randall, 2011). It gives a signal based on the acceleration it is exposed to. The acceleration is measured based on a mass that has certain properties and creates an electric charge when moved. Due to the components' properties and their assembly, this technology can measure in one or three dimensions (Rozic, 2019).

Accelerometers have an advantage on the market today due to their low cost and high reliability, measuring vibrations in all three dimensions (Cappellini et al., 2014). However, due to its contact-based technology, it can only measure one point, requiring several accelerometers to be installed to get an overall picture of the current state (Roy et al., 2020). As this can be time-consuming and difficult it can become a costly installation process (Cappellini et al., 2014).

There are two vision-based technologies mainly used in literature: camera-based technology and laser-based technology. Motion amplification uses a technology that detects small motions, such as vibrations, and amplifies them to make them visible in the video produced (Roque & Sobral, 2018). Laser-based technology instead uses a device to send out fiber-optic loops to measure distance (Rozic, 2019). A calculation is then made between the distances over time to show the vibrations in one direction.

Vision-based measurement can be very accurate (Xiong et al., 2018), however, it can be expensive and difficult to use in some environments, radar can be a well-suited alternative when a non-contact measurement is needed (Piotrowsky & Pohl, 2021). Camera-based technology requires good environmental conditions, such as good weather or no dust (Xiong et al., 2018). Laser-based technology requires good conditions as the lens cannot become dirty.

When it comes to radars, continuous wave (CW) and FMCW are technologies used to perform radar measurements (Xiong et al., 2018). The biggest disadvantage of CW is the fact that it cannot separate when the radars are being reflected on multiple targets (Piotrowsky & Pohl, 2021). However, when comparing the two, FMCW radar can be more expensive due to more complex hardware.

### 2.2.2 Products on the Market Today

As a part of the market research, the available products on the market were researched. When searching for vibration measuring products online, mainly accelerometers were the returned results. Most other technologies were offered as a service, for example, the motion amplification camera. Laser is another way to measure vibrations, however, it did not seem to be its main purpose, and the price point was considerably higher than accelerometers.

**Accelerometers –Wired**

When it comes to accelerometers, there are several different types on the market. The most common permanent wired solution is the one similar to Figure 2.12. It is screwed onto the surface of the machine where vibration is supposed to be measured and measures in that specific point in one or three directions. It is then connected via a wire to the control room where the data is collected and analyzed continuously.


*Figure 2.12. A standard permanent wired accelerometer.*

*Note. From Machinery Health Triax Accelerometers, by Emerson, n.d. (https://www.emerson.com/en-us/catalog/ams-machinery-health-triax-accelerometers). Copyright 2022 by Emerson Electric Co. Reprinted with permission.*

The price point for a sensor of this sort can range from a few hundred to a few thousand dollars, for solely the sensor. Apart from this, costs for cables and software have to be included in the total cost, making it difficult to name just one price as it depends on the application.

**Accelerometer - Handheld**

When it comes to handheld accelerometers, there are also a few options to choose from. One option is where magnets are attached to the machine with, for example, glue, and the accelerometer also has a magnetic end that attaches to the one on the machine. By using this technique, it is ensured that the measurement is taken from the same point every time.

There are also options where the handheld device is put directly on a machine. This can be done either with a sensor at the end of the device or by connecting a cord that has a sensor at the end. This can be used for troubleshooting, as it does not have the ability to measure the same point every time. The corded version has advantages as it can be attached and then the operator can read the measurement from a small distance.

The price point for a handheld accelerometer can range from 10.000 SEK to over 100.000 SEK.

**Accelerometer - Wireless**

Wireless accelerometers can be glued to a machine either temporarily or permanently. They are generally a cheaper option than the wired ones, but have some limitations. The frequency band is smaller than the wired accelerometers and the data collection rate must be weighed against the battery life. They have the option of measuring continuously but will use up the battery much faster than when measuring, for example, once per day.

**Motion Amplification**

Motion amplification cameras, such as the IRIS M™ with Motion Amplification™ distributed by MLT, is a high-resolution troubleshooting system that video tapes the problem area and uses each pixel as a measuring point. The pixels are then amplified in its software to create a visual representation of the vibrations' origin. (MLT Maskin och Laserteknik, 2022)

**Laser**

Lasers used to monitor vibrations are called Laser-Doppler Vibrometers (LDV) and are, as the name suggests, based on laser technology adopting the Doppler-effect. The measuring is contactless (SKF Evolution, 2013) and are available as either single-point or scanning laser vibrometers (OptoMET, 2022).

## 2.3 Maintenance Management

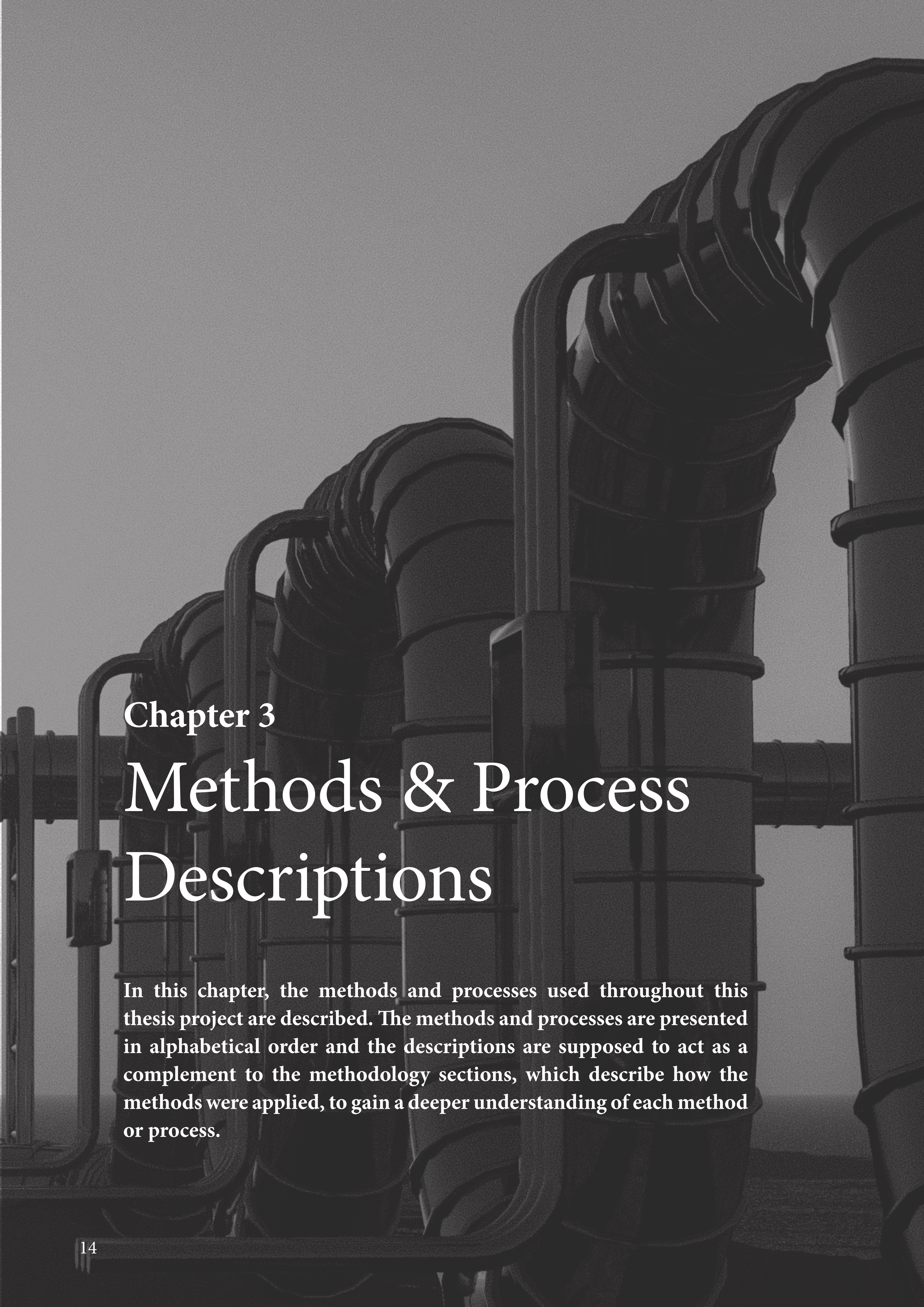
Most companies nowadays use some kind of maintenance strategy. According to Mobley (2011), maintenance costs are generally taking up the majority of a production company's total operating costs. In the year 2000, it was estimated that around a third of all maintenance costs in the US were wasted due to ineffective maintenance strategies.

An ineffective strategy can have a severe economic impact on a business due to eventual production delays, product rejects, and maintenance downtime (Mobley, 2011). In addition, there are also additional maintenance costs such as labor, overtime work, and spare repair parts. Applying an effective maintenance strategy can have a great impact on the maintenance costs due to reduction or elimination of unnecessary repairs, prevent critical machine failures, and have a positive impact on the business profitability if maintenance operations are kept strategic. The most well-known maintenance philosophies are listed below.

Reactive maintenance, also known as run-to-failure maintenance (Flores-Colen & de Brito, 2010), means that repairs take place once something breaks. The repairs are of corrective nature, meaning that they often are unpredicted emergency repairs, resulting in high maintenance costs as the repairs are more extensive compared to other maintenance strategies. Reactive maintenance also leads to unplanned, and often long, stops in production with negative economic impact as a result (Flores-Colen & de Brito, 2010; Mobley, 2011).

Peventive maintenance, also known as planned maintenance (Flores-Colen & de Brito, 2010), is time-driven, meaning that maintenance tasks are based on elapsed time or hours of operation. Therefore, repairs and rebuilds are scheduled based on predefined intervals on the basis of the mean time-to-failure statistics, often defined by the machine manufacturer (Flores-Colen & de Brito, 2010; Mobley, 2011). This strategy allows for easy estimations of maintenance costs and prevents unpredicted downtime in production due to unplanned repairs (Flores-Colen & de Brito, 2010).

Predictive maintenance, also known as condition-based maintenance (Flores-Colen & de Brito, 2010), is a maintenance strategy to detect any developing problems by regularly monitoring the machinery conditions and therefore prevent disastrous failures from happening. The main idea is to maximize the intervals between repairs, compared to preventive maintenance, where repairs are based on predefined repair intervals (Mobley, 2011).



## Chapter 3

# Methods & Process Descriptions

**In this chapter, the methods and processes used throughout this thesis project are described. The methods and processes are presented in alphabetical order and the descriptions are supposed to act as a complement to the methodology sections, which describe how the methods were applied, to gain a deeper understanding of each method or process.**

**Affinity diagram**
The affinity diagram process is used to cluster, sort, and externalize data from observations and insights in a meaningful way and is usually used once researchers have conducted several interviews (Martin & Hanington, 2019). It is an effective method to use to sort and cluster qualitative data. Quotes or observations are collected on pieces of paper, one quote or observation each, and the researchers are then supposed to cluster them with regard to their similar intent, problem, or issue sharing an affinity.

**Braindrawing**
Braindrawing is a variant of brainstorming with the same aim to produce a high quantity of ideas (Wikberg-Nilsson et al., 2015). With this method, the participants develop and present their ideas through sketching. The aim is to facilitate the creative process as other participants have the opportunity to get inspired and develop each other's ideas. The main rules are to 1) not criticize your own or anyone else's ideas, 2) aim to produce wild and crazy ideas, 3) combine and improve the produced ideas, and 4) aim for quantity and not quality.

**Brainstorming**
Brainstorming is used to and specifically produce a high number of ideas and can take place in a variety of formats (Wikberg-Nilsson et al., 2015). The ideas are presented to the group to spark creativity, inspire others with your ideas, get inspired, and develop each other's ideas. The main rules are to 1) not criticize your own or anyone else's ideas, 2) aim to produce wild and crazy ideas, 3) combine and improve the produced ideas, and 4) aim for quantity and not quality.

**Design Format Analysis**
A design format analysis is a tool to identify strong visual elements of a company's brand (Warell, 2001). Companies usually use certain style features in their products to identify their brands such as recurring elements of curvature, shape, color, material, surface finish, and composition across the brand's overall product catalog or within product families. The results of the design format analysis catch the strongest visual design elements which can be translated into the next product design, this to maintain a strong brand identity in its form language.

**Design specification**
A design specification is a document of information about the expectation of the product and could act as a mental model for the design team throughout the product development process (Wikberg-Nilsson et al, 2015). Requirements, standards, guidelines, needs, and preferences from collected data are put together and are also a way to evaluate if the product fulfills the criteria in the design specification. The criteria can either be categorized as requirements, what is expected of the product, or guidelines, what is desired but not critical for the product design.

**Image boards**
An image board, also known as mood board, inspiration board, lifestyle board, styling board, or usage board (Wikberg-Nilsson et al, 2015), is a collage of inspirational pictures, illustrations, and brand imagery to communicate aesthetics, style, audience, context, etc. The aim of the image board is to create a tangible design focus and consensus artefact used by the design team throughout the design process (Martin & Hanington, 2019; Wikberg-Nilsson et al, 2015).

**Interviews**
An interview is a way for the researcher to meet users and get an understanding of their experiences, opinions, attitudes, motivations and behaviors around topics or products and can be used during various stages in the design process (Martin & Hanington, 2019; Wikberg et al., 2015). Interviews can be structured with a strict interview script, semi-structured which allows for flexible discussions outside of the script, or unstructured which is more conversational and allows the user to speak more freely about a topic the researcher is interested in knowing more about.

**Likert scale**
A Likert scale is a kind of rating system often used in questionnaires to measure a person's opinions, attitudes, or perceptions about a topic (Jamieson, 2017). The person is often presented

with a statement that they are asked to rate on a numbered scale, often with number-coded responses ranging from "strongly agree" to "strongly disagree". The size of the scale might vary.

**Literature review**
Literature reviews are used to collect and synthesize qualitative information about specific topics and are often performed as the initial step of the exploratory phase of a paper or project (Martin & Hanington, 2019). Literature reviews are often conducted to distill information from published sources and previous research and act as the foundation to contextualize a topic.

**Morphological chart**
A morphological chart is a method with the aim to facilitate ideas for potential product solutions (Wikberg-Nilsson et al., 2015). The chart is based on identified needs and/or functions in the pre-study phase. The method is designed to generate a high number of product solutions in a relatively short amount of time.

**Observations**
Observations can be performed in a variety of ways, but what they all have in common is that they aim to let the researcher understand the user's needs by watching, listening, asking questions, and experiencing the user's situation in context (Wikberg-Nilsson et al, 2015). Observations can be semi-structured or structured (Martin & Hanington, 2019). The former is sometimes also referred to as casual observations and normally takes place at the beginning of the design process to collect baseline information important for the researcher to understand the context of territory often previously unexplored by the researcher. The latter, sometimes also referred to as systematic observations, often involve prepared material such as worksheets or checklists, among others, and derives from a restructured research session

**Personas**
Personas are a fictive description of people who are part of the target audience and is used to describe the role the user would take in a scenario or social situation (Martin & Hanington, 2019; Wikberg-Nilsson et al., 2015). Personas are based on data from research of real users and their context through data, statistics, interviews, observations, and contextual analyses used to create representative user profiles (Wikberg-Nilsson et al., 20, 2015). The reason for creating personas is to contextualize the primary user instead of only solely focusing on research and data. Creating personas might also father empathy for the user and their needs

**Prototyping**
Prototyping is a way for a designer to communicate a tangible version of a product concept. The resolution could vary from low-fidelity prototypes which are quick and rough, or high-fidelity prototypes that are more detailed and refined (Martin & Hanington, 2019). The former is usually used in the early product development process, while the latter are common in later stages.

**Pugh's evaluation matrix**
Pugh's evaluation matrix is a matrix used to evaluate a number of concepts against each other with respect to a number of criteria (Pugh, 1990). The concepts are compared to a datum which is the existing product that is to be redesigned. If there is no existing product, the concept that the design team thinks are the 'best' should act as the datum. The scores are then weighted and summarized to indicate what concept is the strongest. The results are not to be considered absolute but rather as a guideline.

**Scamper**
The scamper method can be used to support ideation by asking the questions: 1) Substitute?, 2) Combine?, 3) Adapt?, 4) Modify, 5) Eliminate?, and 6) Reverse? (Wikberg-Nilsson et al., 2015). The method is often used after a brainstorming, brainwriting, and braindrawing session to develop ideas further.

**Semantic differential scale**
A semantic differential scale is used to evaluate the meaning of a thing or concept (Baxter et al., 2015). The participants are asked to rate how they experience or feel about a product, or similar, on a 7-point scale between an adjective and its autonym. The scale could, for example, range between strong-weak or good-bad.

**SWOT analysis**

A SWOT analysis is a method to evaluate a business's strategic position in a market (Jobber & Ellis-Chadwick, 2019). This is done by identifying the business's internal strengths and weaknesses as well as their external opportunities and threats. In general, the internal factors are controllable by the business, while the external factors are out of the business's control.

**Weighted matrix**

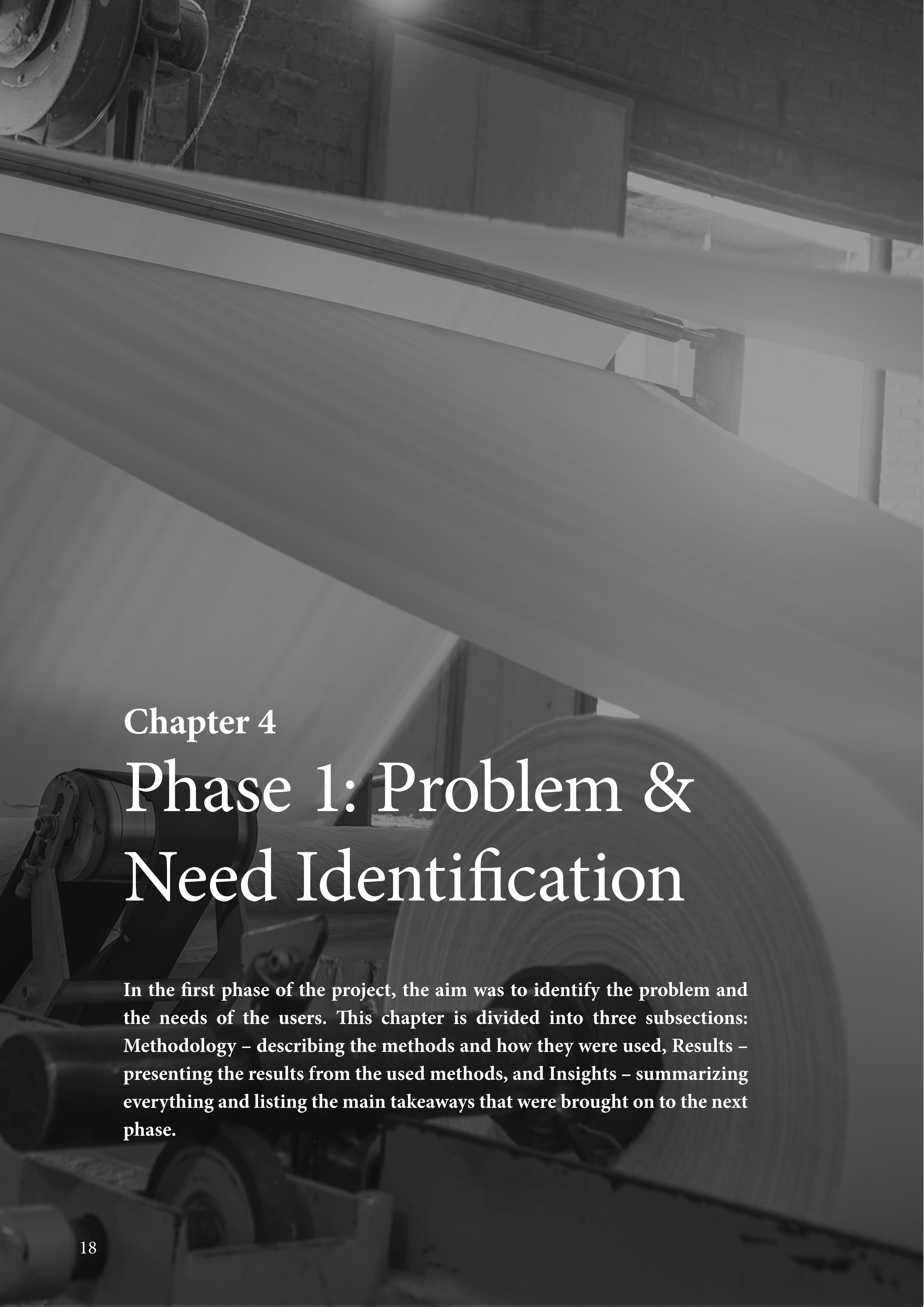
A weighted matrix is an analysis technique designed to evaluate and rank concepts with respect to a number of set criteria (Wikberg-Nilsson et al., 2015). Different criteria can be weighted if the design team finds some criteria more important than others. The method serves as a tool in the concept decision process but should be used as a guideline and not absolute.

**Word clouds**

Word clouds are colorful collages of keywords in different fonts, colors, and sizes depending on the frequency in qualitative data (Martin & Hanington, 2019). The biggest words are the ones that occur the most frequently in, for example, transcripts. The word clouds could function as a visual communicative artifact for a design team.

**Workshop**

A workshop has the aim of bringing researchers, users, or other stakeholders together to explore a problem and together through a variety of creative methods and processes come up with potential solutions (Wikberg-Nilsson et al., 2015).



**Chapter 4**

# Phase 1: Problem & Need Identification

**In the first phase of the project, the aim was to identify the problem and the needs of the users. This chapter is divided into three subsections: Methodology – describing the methods and how they were used, Results – presenting the results from the used methods, and Insights – summarizing everything and listing the main takeaways that were brought on to the next phase.**

## 4.1 Methodology

This chapter will describe the methods and how they were used. For more information on the theory behind the used methods, see chapter 3. Methods and Process Descriptions.

### 4.1.1 User Studies Round 1 & 2

The aims of the user studies were to find a potential market gap and to get an understanding of important product specifications according to the target audience's needs. The interviews were divided into two parts: 1) to understand the consequences of vibration and the need for vibration monitoring, and 2) to understand the product-specific requirements of the target audience. In addition, a total of 4 on-site visits to the companies were conducted to reach a better understanding of the problem, the production site layouts and user needs.

**Participatory sample selection**

When identifying the potential market, it was decided to keep an open mind when selecting the participatory sample. As a study on pipelines had already been performed, the project group decided to not focus on the same area. Around 60 industrial companies were contacted from a wide range of industries with their production site in Sweden. The corporations were contacted by email, phone, or through forms on their official websites. Nine companies ended up participating in the first interview round and seven companies in the second interview round. The company representatives participating in the interview were either titled maintenance engineers, measurement engineers, or operations engineers. Production managers responsible for their vibration monitoring in one way or another were also interviewed. To get an overview of the participating companies and their industry, see Table 4.1.

**Interview round 1**

In the first round of interviews, a total of nine companies participated. Due to long-distance, most interviews took place online through either Microsoft Teams or Zoom. During the on-site visits, the interviews took place in person. The interviews were conducted in a structured format with prepared questions, see Appendix I. All interviews were audio recorded with consent, which were later transcribed for further analysis.

The questions were divided into the following parts:

- Background – The interviewees position and connection to vibration monitoring in the company.
- Vibration monitoring – Where in production the vibrations occur and the consequences of vibrations.
- Maintenance strategy – If the companies

*Table 4.1. The industries who participated in the user study.*

| Industry | Interview 1 | Interview 2 | On-site visit |
|---|---|---|---|
| Medical solutions | • | | |
| Engine production | • | • | • |
| Food production | • | • | • |
| Packaging production | • | | |
| Recycling & waste management | • | | |
| Steelmaking | • | • | |
| Energy production | • | • | • |
| Pulp & paper production | • | • | |
| Chemical production | | • | • |
| Pulp & paper production | • | • | |

apply any maintenance strategies today to prevent failure in production.

- Used technology – both technologies used to monitor vibrations in-house, but also external support with measuring.
- Contactless vibration monitoring – An initial need and interest check on the possibility to measure vibrations contactless.
- Vision – What they thought would be the optimal way to measure vibrations.

**Interview round 2**

In this round, a total of 7 companies from interview round 1 participated. Two of the companies in round 1 did not have significant issues with vibrations and did therefore not participate in round 2. Most interviews took place online through either Microsoft Teams or Zoom. During the on-site visits, the interviews took place in person. The interviews were conducted in a structured format with prepared questions, see Appendix II. Like in interview round 1, all interviews were audio-recorded with consent. The interviews were then transcribed for further data analysis.

The questions were divided into the following parts:

- Purchasing process – the overall purchasing process and who decides what measurement technology to buy
- Technical specification – such as frequency range, desired number of dimensions to measure in, classifications, materials, mounting, etc.
- Hardware specification – visual appearance, size, weight, lights, buttons, etc.
- Software specification – what is desired of the digital interface and product software compatibility
- Data reading – current and desirable ways to read data from a device
- Usability – the users view on what a user-friendly is like, and how they perceive the usability of their current technology for vibration monitoring
- External factors – that might affect their measurements today and how that is dealt with
- Contactless measuring – the users' opinions on a handheld, wired and wireless vs. semi-permanent contactless product solution.
- Reflectors – users' attitudes towards attaching reflectors to equipment

**Data analysis**

After conducting the interviews in user studies 1 and 2, the qualitative data was analyzed. First, the interviews were transcribed in their entirety from the audio recordings. Thereafter, quotes that were considered interesting or important were picked from the transcripts and printed on paper. To organize the data and to find common topics and themes, the affinity diagramming method was applied where individual quotes were stacked together. The findings were then summarized and analyzed.

### 4.1.2 Study Visits

When performing the user study interviews, study visits took place at four of the companies' production sites as they invited for visits. Company representatives gave a tour around the facilities and showed the production layout, their vibration monitoring equipment in use today, and explained where in production they are in the biggest need of vibration monitoring equipment. The company representatives also demonstrated areas in production where they thought contactless vibration monitoring would be of good use.

### 4.1.3 Likert Scale

During the second interview round, interviewees were provided with Likert scales where they were asked to rate different product characteristics and factors on a scale from 1to 10 with 1 being of least importance, and 10 of highest importance. The purpose of the Likert scale was mainly to function as prompts for the interviewees to develop their thoughts and opinions, while the quantitative results' importance was secondary as the prompts could be interpreted in different ways. To see the Likert scales used in user study 2, see Appendix III.

### 4.1.4 Use Cases

Based on the examples mentioned during the interviews, three possible use cases were created to visualize for stakeholders where the product could potentially be placed, but also to help during ideation and creating the functions list. The three cases are created based on applications mentioned by two companies and are about troubleshooting a milling machine, doing regular inspections from a distance, and lastly, measuring vibrations while the production is running.

### 4.1.5 Personas

To identify the possible product users and stakeholders, three personas were created based on the results from user studies 1 and 2. The purpose of the personas was to personify the typical users, illustrate their needs, and create characters whom the design team could emphasize with and seek inspiration from further ahead in the design process.

### 4.1.6 Market Gap Identification

After the user studies had been conducted, three potential solutions were identified. The most important advantages and disadvantages of each of the possible solutions were then summarized and discussed. Based on that and the results from the user studies, one solution could be chosen to narrow down the scope for the next phase of developing the product.

### 4.1.7 SWOT Analysis

To identify internal and external factors to consider during the product development process, a SWOT analysis was conducted to identify the strengths and weaknesses of the product compared to its competitors, as well as opportunities and threats by the external environment. The SWOT was mainly created by summarizing the main points from the user studies and was a basis for creating the design specification, as well as summarizing how the product would be value-creating.

### 4.1.8 Design Specification

To summarize the results and create a base for the next phase, the development of the product, a design specification was created. Initially, it was created broad with more guidelines than requirements and very vague points. However, during the project it has been a living document, becoming more specified through iterations as more knowledge has been gathered.

The design specification was divided into different categories to get an understandable overview. Under each category, a list of criteria was compiled, with the goal of the criteria in the next column. Not every criterion was complemented with a goal as they were clear enough on their own. In the last column, an R for requirement or a G for guideline was selected.

Later in the project, the three different solutions identified, as described in section 4.2.7 Marget Gap Identification, were then evaluated against the design specification using a Pugh evaluation matrix. The purpose of using this evaluation method was to gain an indication of which solution to go further with into phase 2.

## 4.2 Results & Analysis

In this section, the results, and analysis from the first phase of the project are presented. Each section will present the results from each method used, with the user studies divided into two parts as they were conducted in two rounds. First, the results from the user studies are presented, followed by a description of the problems and opportunities found in the production sites that were visited. Further, some use cases to summarize and visualize the applications found in the user studies as well as personas, market gap, and SWOT analysis. Lastly, the design specification containing guidelines and requirements for the development phase is presented.

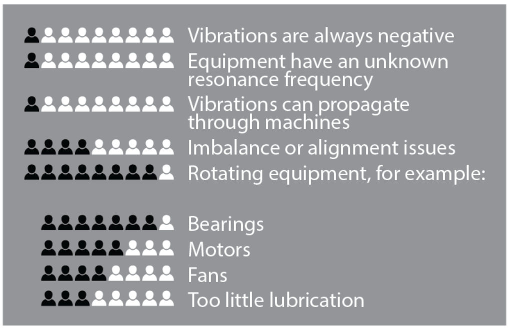
### 4.2.1 User Studies Round 1

This chapter is divided into the following sections, roughly following the structure of the interview questions:

- Current situation
- Consequences
- Maintenance
- Internal technology
- External technology
- Non-contact
- Vision

The sections are structured as follows: first, a list of the main results and how many interviewees mentioned this specific result, second, a summary of the main results as well as a short analysis is presented. The list is there to visualize how many users mentioned each problem and summarize the most important points in each section.

**Current Situation**




When asked about the current situation and how vibrations affect the companies today, vibrations were most often mentioned as something negative and unwanted in production. The main causes of vibrations were rotating equipment, mentioned by almost all companies, and imbalance or alignment issues.

> ***"Everything vibrates! Everything that rotates vibrates."***
>
> - Food company about the current situation

As mentioned by the interviewees, alignment issues can cause vibrations in machines. Wear on the machines can also create imbalances that lead to the same consequences. Rotating equipment, on the other hand, always vibrates. Rotating equipment can be, for example, bearings, mentioned by a majority of companies as something causing vibrations, shafts, turbines, fans, engines, or pumps. Apart from the rotations in themselves creating vibrations, the amount of lubrication was mentioned by several companies as something creating vibrations, especially too little lubrication.

The results from the user studies aligned with the background information received from Emerson to a certain degree. Alignment issues and imbalances were something mentioned both in the background information and the interviews, however, rotating equipment was not mentioned in the background information. The reason is that rotating equipment operates at very high frequencies, which the early technology could not measure. However, with some more iterations, it is now possible to measure high enough frequencies, meaning the possibility for measuring rotating equipment was opened again.

An interesting aspect of the results is that no one mentioned pipes as an issue. This was the main potential application area Emerson had in mind at the beginning of the project, however, during the user studies, Emerson's current customers were not interviewed, which could be why the vibration issues differ as Emerson's main customers are oil and gas industry, among others. In those industries, piping is a critical part of their production.

**Consequences**

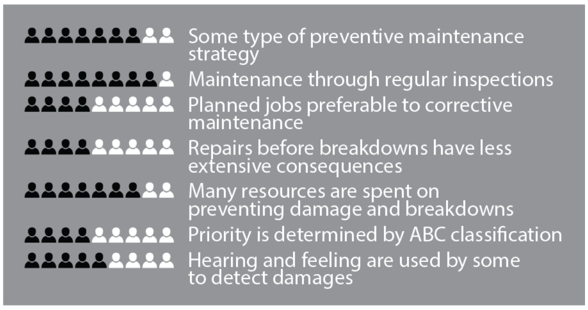

What was found in the user studies is that the consequences due to unwanted vibrations in the production site can vary greatly. A majority of the companies interviewed answered that the direct consequence will be a stop in production, which, if they become lengthy, can lead to dramatic economic consequences up to millions of SEK. The economic loss can be due to, for example, loss of product or reduced number of sales.

Apart from a stop in production, it was also mentioned that vibrations can lead to lower product quality. In industries where the surface finish is vital, an increase in vibration can lead to a larger number of products being outside the approved limits.

A third consequence mentioned by several companies was worse machine health. As mentioned in the previous section, bearings are one example of equipment that is often affected negatively by vibrations. Increasing vibrations in machines can also lead to vibrations propagating through the machine leading to secondary damage.

As money is often a driving factor, a valuable product was often mentioned in terms of how many stops it can prevent. This could be a considerable selling point for the product that is to be developed in this thesis project, for example, in terms of preventing stops and increasing the machine life span.

**Maintenance Strategies**




Most companies did seem to have some sort of preventive maintenance strategy, either preventive maintenance meaning components are replaced at a certain time interval, or condition-based maintenance meaning components are monitored and replaced based on the condition. There was one company only using their senses to inspect machines, having a run-to-failure maintenance strategy, but all other companies were monitoring or inspecting with some measuring technology, see more in the next section about internal technology. This indicates that there is a great market for vibration measuring technology in general, as they want to monitor machines and prevent damage to save money and resources.

Most companies used regular inspections as a part of their maintenance strategy. This meant they used measuring technology, most commonly handheld accelerometers, to point measure their machines at a regular interval. This interval varied greatly, some only measured once per year while some measured every week. However, even when no measuring devices are used, it is common for operators to use their senses to inspect machines. Through sounds and touch the operators will notice when there is an increase in vibrations, and they can schedule a maintenance stop to replace affected components. Some companies rely on only their senses to detect changes, while others believe it is already too late when it can be detected without a measuring device.

The number of resources spent on monitoring an object depends on its criticality. A few companies used ABC classification to prioritize their machines where A is the most critical, usually monitored continuously, and would lead to a costly stop in production if it failed. C is the least critical and sometimes not monitored at all, where there might be redundancy and failure does not affect production much or at all.

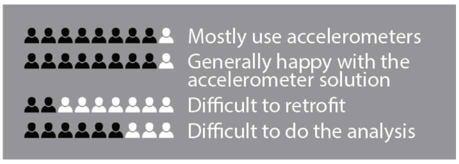
Two potential markets were identified here. Either a product that can be used to continuously monitor A-classified machines or a product that can compete price-wise with today's solutions by measuring several points at once, making it worth it to measure C-classified areas or machines.

Generally, the companies made it clear that planned stops, as well as repairs before the breakdowns happen, are desired. This was done either by detecting vibrations early in the monitoring equipment when a breakdown was about to happen, this could sometimes be done several months in advance, or by stocking spare parts to be able to plan a repair fast. Several companies mentioned that spending money on measuring equipment can be repaid quickly just by being able to plan one repair instead of getting an unplanned stop and having to wait for components to be ordered.

**Internal technology**

This section is divided into smaller sections. Accelerometers were found to be the dominating internal technology among the companies interviewed. Therefore, the section will start with the general results on accelerometers and will then be split into continuous online measurements with accelerometers, handheld accelerometers, wireless accelerometers, and lastly, other technologies used internally at the company.

*Accelerometers in general*




When interviewing the users, it was found that there was a clear dominance in using accelerometers of different sorts. They were generally happy with the technology as it is cheap and reliable. However, some drawbacks included retrofitting the sensors, which would mean production had to be stopped, which as mentioned in the consequences section, is something that wants to be avoided at all costs. Difficulties analyzing the data were also mentioned as a drawback of the technology.

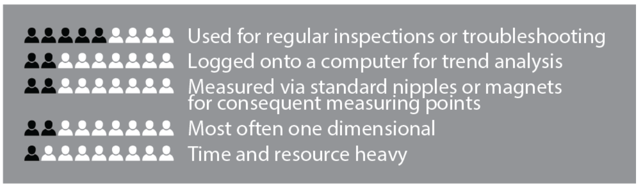
As accelerometers are such a widely used and accepted technology, one reflection is that they will be difficult to compete with on the market. Instead, designing a product that can complement the accelerometer where they are not optimal will more likely be accepted by the market. This can, for example, be areas where it is very hot, and it is not possible to attach an accelerometer.

*Continuous online measurement*


When it comes to the permanently installed wired accelerometer, they are mostly used for A-classified objects, as mentioned before in the section on maintenance. Wired accelerometers are widely used among the companies interviewed and seem to be the most popular way to measure vibrations today. Some machines today even come with preinstalled accelerometers by the manufacturers. They can measure continuously, and all data can be live monitored on a computer in, for example, a control room. Even though they measure continuously, the data collection interval is chosen, depending on the machine, and can be, for example, per minute or per hour depending on the user's need. Based on the trends that are created, limits can be chosen to set off alarms if they are outside, or even to stop the machine if it goes over critical values.

However, continuous measurement can be very expensive. The technology is relatively cheap but can easily get very expensive if many sensors are needed. The installation can also get very expensive, as installing cables is expensive and can be very time- and resource-demanding. However, for critical objects, it can be a great tool as it is more reliable than wireless, or interval measuring and enables a better trend analysis according to the interviewed companies' experiences.

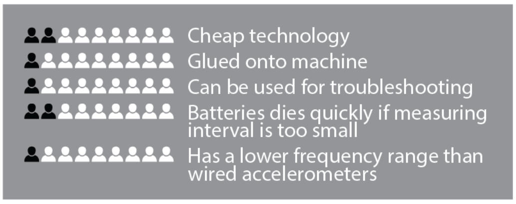
*Handheld accelerometers*




Handheld accelerometers were also widely used by the companies interviewed. Mostly, it was used to do regular inspections, as mentioned before in the section on maintenance, the time intervals depended on the classification of the machine, everything between weekly, monthly, and yearly, but it could also be used for troubleshooting. When used for doing regular inspections, the data is logged on to a computer program where the trends can be monitored. It is common to have permanently placed magnets or nipples on the machine, where the accelerometer is placed, to ensure the measurement is at the same point every time. This is important as measuring different points will give inconsequent measuring data.

It varied between the companies if the brands they used measured in one or three directions. It was mentioned by a company that their accelerometers only measure in one direction, but this was solved by placing them in three different spots to get a triaxial measurement. A general disadvantage with doing inspections with a handheld accelerometer is that measurements usually are not done at high enough intervals, as it takes a lot of time and resources.

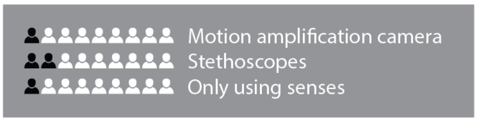
*Wireless accelerometers*




Some companies used wireless accelerometers; however, the general tone was very negative about current solutions. Advantages that were mentioned were that it was possible to attach it to a machine semi-permanently when an increasing trend has been noticed with handheld accelerometers. It can also be a cheaper option, as there is no need to install cables, which requires a lot of resources.

However, the wireless sensors collect data at a lower interval to save battery. It is possible to measure continuously but it will run out of battery faster, and the batteries are generally not possible to replace, according to one of the interviewees. In that case, the whole sensor needs to be replaced. With this lower measuring interval, it can be difficult to match when to measure if the machine is not running continuously. Another disadvantage mentioned is that the wireless sensors measure at a smaller frequency band than the wired accelerometers, meaning some vibrations could be missed if they are too high or too low.

*Other vibration monitoring technology*




For the companies using other technologies, some pros and cons were mentioned. One company had bought a motion amplification camera system since they saw value in being able to troubleshoot when it is unclear where vibrations are coming from. It is also good for visualizing movements and is a good complement to the other vibration measurement instruments. However, it is expensive, a few hundred thousand SEK, as stated by the company interviewed, and requires a lot of training to use.

Two companies used stethoscopes which was a cheap solution to bring on regular inspections to detect bearing damage early on. When it is possible to hear bearing damage, they said it is already too late and does not allow for the same amount of planning for the repairs.

**External technology**


This section will describe the results of the external technologies used at the company. External technology in this report is referred to when vibration measuring is bought as a service by an external company instead of doing it with internal resources.
Between the companies, it varied whether they did all data collection and analysis internally or if they brought in help with, for example, analysis, or if everything was done by an external company. This depended on factors such as the internal resources that existed and the budget.

Two companies outsourced all their vibration measurement needs. The most critical sensors were connected online to the external company, and for the less critical areas, external staff did regular inspections. This was positive as the resources and knowledge did not exist within the company, however, it meant having to rely on an external part and their knowledge and service.

Several companies mentioned that external companies are brought in when there are more complicated cases, for example, with complicated data analysis or to help with alignment or imbalances. One company mentioned using motion amplification technology, as it is good for troubleshooting and visualizing vibrations that otherwise might not seem problematic.

As it was common to bring in external technology or companies for complicated cases, it is not impossible to think that there is a willingness to spend more money on a troubleshooting device or a product with software that helps with the analysis.

**Non-contact**

Low or no interest
Interested in the solution:
Application: dangerous environments
Application: hard to reach areas
Application: C-classified areas

> ***"Yes, of course. That would be [of interest]. Then I would actually like to change my mind. Now, if this company is actually able to accomplish this, you could ask them to call me up."***
>
> \- Food company on contactless measuring up to 30 meters.

When the companies were asked about their interest in non-contact measuring of vibrations, it varied from no interest at all to very high interest. Three examples were mainly mentioned as potential applications for this product: areas that are hard to reach, dangerous environments, and areas with a lower criticality. Areas that are hard to reach can be machines or components located 10-15 meters up in the ceiling, where measuring from a distance would be of value to avoid using lifts. Dangerous environments, on the other hand, can be machines built into robot cells, wanting to measure while the machine is running, or extreme temperatures, pressure, or chemicals. Areas with lower criticality, such as C-classified areas, were also mentioned as an application where a non-contact product that can measure several points could be of value as a smaller number of devices are required. In this case, this would be of interest if it was cheaper than today's solutions, as it would need to be worth it economically.

Some advantages mentioned during the interviews were the possibility to measure during operation and mount the sensor during operation since a stop in production is very expensive. This is not possible with most accelerometers as an intervention in the machine is required. Measuring up to 30 meters was seen as an advantage to accessing previously mentioned hard-to-reach areas. If non-contact measurement would mean fewer cables, this was also seen as an advantage as installing cables can be very expensive. This could be, for example, if one product could replace several accelerometers or if it was wireless.

However, some companies were a bit more uncertain about how much value it would create with a contactless vibration monitoring product solution. For example, some mentioned they had built their production sites to be able to access measuring everywhere. It was mentioned one company had the budget to just buy more accelerometers or thought it was better to measure by hand. One company had not had a reason to investigate it but might have been interested if they knew more about the product.

A reflection after the interviews was that the interest in a non-contact solution was likely not dependent on what industry the company was active in, but rather on who was interviewed. Three different attitudes among the interviewees:

- The technical enthusiast – always looking for new technology to improve and move more towards an automated industry.
- The maybe person – could potentially be interested but was not actively looking for new products.
- The skeptic person – is happy with the technology today and did not see any reason to change a system that works.

The level of enthusiasm could also be based on how involved they were in the technology, for example, if they were operators working directly with collecting vibration data or if they were managers in charge of all maintenance.

There is a possibility that the solution could be too early for the market as well. It was difficult for some of the interviewees to visualize what this product could do, as it does not exist today. This could have also affected how interested they seemed in the product.

**Vision**


When the companies were asked about how they would measure vibrations in an ideal world, three things were mainly mentioned: online measuring, AI, and alarms. The majority of the companies answered they want some type of continuous online measurement, with an emphasis on being able to see trend changes easily. As mentioned earlier in the section on internal technology, some companies are already moving towards more online measurement and more automated industries today.

The development of the software lies outside the scope of the project but was still considered valuable data for future development of the product concept. Artificial Intelligence, AI, was mentioned as something to strive for, where the computer does the analysis, suggests what the problem could be, and makes suggestions for action. Lastly, alarms were mentioned, where it is shown, for example, green, yellow, and red levels to save time analyzing. If everything is ok, they can move on and only need to analyze further and/or act if it is on a yellow or red level.

The main driver always seems to be money when it comes to monitoring equipment. Many companies mentioned that they want continuous online measurement everywhere, however, it is hardly possible as it is too expensive today. Wireless monitoring, therefore, seemed interesting to the companies as they potentially could save money on expensive installation, as it is both resource-intensive, often requires a stop in production, and because it is expensive with cables. This is the reason why AI is attractive as well, as there is no need to have one person sitting and doing all the analysis.

The fact that there is motivation and ideas to improve the measuring system in many companies today could be very positive for a radar-based measuring product. This could mean companies looking for new solutions to measuring in new ways where they cannot measure today.

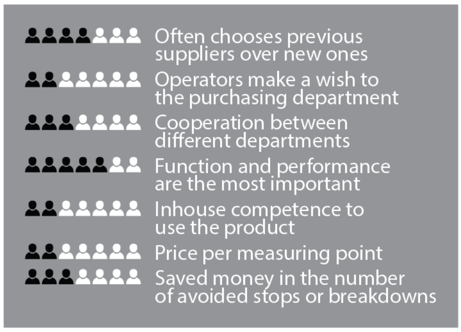
### 4.2.2 User Studies Round 2

This chapter is divided into the following sections based on the user interviews, grouped together into these categories during the KJ analysis:

- Purchasing process
- Non-contact
- Design
- Classifications
- Installation
- Software
- Hardware
- External factors

The sections are structured as follows: first, a list of the main results and how many interviewees mentioned this specific result, second, a summary of the main results as well as a short analysis is presented. The list is there to visualize how many users mentioned each problem and summarize the most important points in each section.

**Purchasing process**



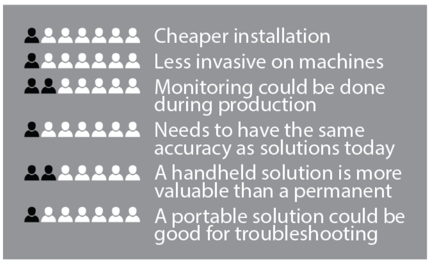

When asked how the companies' purchasing process went about, it varied a lot, but a common factor was that several people and departments were involved, but that the wish came from the operators or the people in charge of vibration monitoring. As there are many stakeholders involved in the purchasing process, it is important to take everyone's interest into consideration when designing and marketing the final product concept. This will be further exemplified and discussed below.

When a supplier has been chosen, four companies said they prefer to stick with the same supplier unless they have reason to be dissatisfied. This is partly due to vibration measuring being heavily reliant on historic data, and switching companies means switching computer software and therefore requiring data collection to start from scratch. It can also be difficult to have several different brands of products as this means different programs and interfaces.

The fact that companies are generally very loyal to the brands that they use can be a challenge for a new product on the market due to supplier contracts, compatibility with their existing technical systems, also out of convenience if they are generally happy with the brand. However, this could also be seen as an opportunity if a company would buy the radar measuring product as a complement to their current solutions where they do not work. There is a potential opportunity to convince them to change to only Emerson products for vibration monitoring if they are happy with the overall service and products provided by Emerson.

When asked what the most important factor is when buying a new product, performance was mentioned. The interviewees mentioned that it should at least have the same functions, performance, and similar price points in order to compete with existing product solutions. Competence was also mentioned, as it can be problematic if the company needs specific knowledge or competence to use the product. It is therefore important that the product is easy to use for anyone, that training is provided, or that external help with measuring is provided as a service when purchasing the product.

**Non-contact**




The questions on this section were split into two parts to investigate the value seen in a permanent and a portable solution. However, a portable solution seemed to be more valuable than a permanent solution. As mentioned earlier in the section on the purchasing process, if the product is going to compete with current solutions it needs to have the same functionality and be cheaper. However, the companies saw value in a portable solution that would complement current solutions rather than compete with them.

Some general applications that were mentioned were automated machines that had the risk to start during measuring with a handheld unit, a non-contact sensor would mean the machine could be running while measuring. Another application is dangerous machines where one does not want to put one's hands when measuring with a handheld accelerometer. It was also mentioned non-contact measuring could possibly avoid external factors that affect the measuring data otherwise, such as when several pumps are located next to each other.

The companies wished for easy and fast installation, some without the need for wiring. This is true if it is a battery-driven portable solution, however, a permanent solution measuring continuously would still need cables. A permanent product measuring several points would probably minimize cable installation since one could replace several accelerometers. When designing the product, this is an important factor to keep in mind since, in some factories, wiring can be the biggest cost of vibration monitoring products.

Several companies seemed to see the most value in a semi-permanent solution as it would offer the most flexibility and cover most user needs. Many advantages were mentioned with a semi-permanent solution, troubleshooting being one of them. When an indication of an increasing vibration trend is seen in the inspections, it is possible to leave the product for a longer time to monitor that specific area. One example mentioned is when a machine has a failure only occasionally, and to troubleshoot, a measurement device would need to be placed there for longer than is possible with today's handheld solutions. The possibility with radar technology to measure several points at once was also mentioned as an advantage as it could help with troubleshooting. For example, when it is unclear where the vibrations are originating from, several points could be monitored to find the root cause.

**Design**


When it came to the product's visual design, most companies mentioned that aesthetics does not matter at all when picking a product. However, one company mentioned that it could give a product an advantage if it catches the eye whilst looking through a product catalog. This is an important factor to take into consideration when designing the product as the visual design might affect the product choosing process on a subconscious level. Apart from this, the companies' opinions on design were mostly based on size and weight.

Mentioned by all companies was that it seemed that functionality is the most important aspect, as mentioned in the section on the purchasing process. It is also important that the design does not affect usability, ergonomics, or similar. One company mentioned that it could be an issue with portable products that they can get lost easily and suggested that a striking color could solve that issue.

When it comes to size, the production site must not require reconstruction to fit the device. As for a portable solution, it should not be too big and clumsy to carry around, however, it should also not be too small as it can easily get lost in pockets or production. In the same way, color is important so that the product is easy to identify, especially if it is smaller.

The opinion about weight was that it should not be too heavy. A heavy product could mean it becomes a work environment issue and in the worst-case cause injuries to the employees. This is in situations and companies where operators are working solely on collecting vibration data, which could mean carrying this product all day. In a company where measurements are collected on more scattered occasions weight does not play as big of a role, as long as the operators have the strength to carry it.

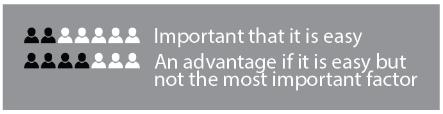
**Classifications**


As seen in the list above, the companies had varying requirements for their products. Even though they had areas where products with classifications, for example the explosion classification, were necessary, the conclusion was drawn that this product does not need to be designed with any classifications in mind apart from being waterproof. This is since most of them mentioned they do not measure vibrations in their classified areas. The need for the product to be waterproof is to fit as many applications as possible, as some potential applications that were mentioned would require a waterproofed product.

**Installation**

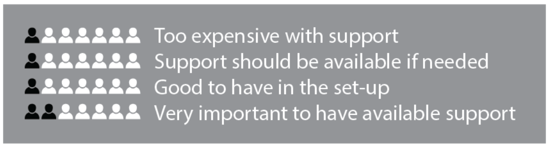
This section includes the results of the questions regarding self-assembly, support during installation, wired vs wireless products, and the need for continuous online measurement.

*Self-assembly*



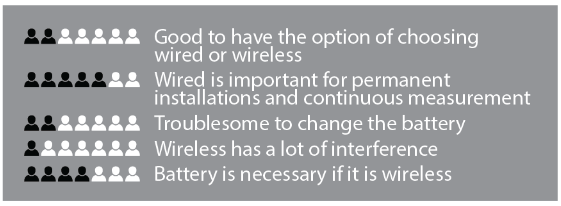

When asked about the option to install the product easily with in-house resources, most companies answered that it is an advantage if that is possible, but it is not the most important factor when choosing which product to buy. It was mentioned that it can be good to think a little about the placement, that the installation is such a small part of the lifecycle, and lastly, that it is more important with available support if needed. Two companies, however, said it was important that it was easy to install by themselves. The conclusion was made that a permanent installation could be designed to take time, but a semi-permanent installation should go fast. For example, it was suggested by the users that a semi-permanent solution could have attachments placed on beams or walls where inspections want to be made, to easily and quickly mount the sensor. In this case, the attachment on the beam could take time, but the mounting of the radar to the attachment had to be fast.

*Installation Support*




Support was mentioned as something good to have in the installation process, to make sure everything is right from the start, or just be available if needed. More companies mentioned support was important with calibration and analysis. This was mentioned as an important factor when buying a new product. Support should be available, for example, when there are issues or ambiguous results. An example of good support was one company that hired an external company for complete service and support, such as installation, measuring, and data analysis. They also had a check-in every 3-4 months to make sure everything worked well with the products as well as stayed in contact about product upgrades. A big emphasis was put on follow-up. Although this information is outside the project scope, this might be valuable information for Emerson in the future and will therefore be summarized as guidelines for Emerson in section 4.2.9 Design specification.

*Wired vs wireless*



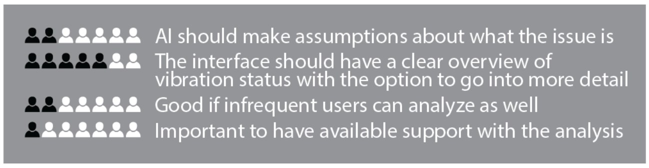

When asked about the need for wired or wireless products, the results were clear that permanent continuous measuring products need to be wired while handheld products need to be wireless. This is since permanent installations would need to eventually change batteries. Furthermore, the product could also lose connection. When it comes to a handheld product, it would be very cumbersome to carry around a product with wire.

However, when discussing a semi-permanent product, it was mentioned that it would be good to have the option of choosing wired or wireless, depending on the applications that it would be in. Some did not have an issue with having some wired points of measurement in the production, while others wanted the option of carrying it around like a hand-held product as well. As previously mentioned, wiring is an expensive part of the installation process and it was seen as an advantage if it could be avoided, especially in far-off areas. Therefore, flexibility was seen as an important factor, to be able to, for example, troubleshoot both in areas where wires are possible and vice versa.

**Software**

The section has been divided into the following sub-sections: usability, frequency range, units, values, and read data. This section will not affect the design of the product, as the digital interface has been delimited from the project scope. However, the results will be presented and summarized in a guidelines list in section 4.2.9 Design Specification, for use in future interface development by Emerson.

*Usability*




The usability of the software was an issue the companies had many opinions about. The usability of software in this sub-section refers to the digital interface only, in other words, what is shown on the computer screen and not on the physical product.

Generally, it was important to get a good overview of the status of the machines on the production site, with the option to go into more detail. For example, this could be a graphical view of the production with alarms or colors to show the status, in other words, a clear indication of if the levels are acceptable or not. Symbols or graphics seemed to be an appreciated way to show vibrations, for example, thumbs up or down.

Artificial intelligence, AI, was also

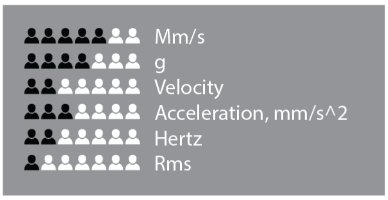
mentioned as something to strive for. Optimally, the software would give suggestions on what could be wrong and suggestions on actions, this is possible as the vibrations can be traced based on frequency and directions. Generally, an AI that can make that first analysis of an acceptable vibration level or deviating the trend, is desirable to save resources and time.

A huge area of improvement for today's usability is for infrequent users in existing software for vibration monitoring. It was explained by the companies that it can be very difficult for someone who is not familiar with the program to use today. As resources are generally limited, more people having the opportunity to use the program is of great value. As an example, summer workers were mentioned, as they should be able to do vibration measurements without extensive education.

*Frequency range*

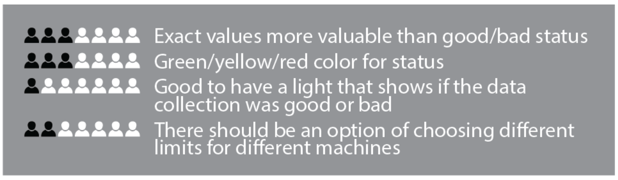
The frequency range required varied between companies and their applications. The possibility of getting different ranges at different price points was seen as something of value. Generally, there was a need to measure above 20kHz, with the highest mentioned need of 40kHz. But also measuring the lower frequencies below 500Hz was seen as something of value, as it can sometimes be difficult with the solutions available today. Based on this, the product should be able to measure between 0-40kHz of vibrations. When speaking to the developers at Emerson, the radar should be able to catch vibrations in the lower frequency range under 500Hz.

*Units*




The most common unit the companies get their vibration data displayed in is mm/s or acceleration in the unit "g", which is 9,82mm/s^2. Velocity, Hertz, and RMS-value were also mentioned. The possibility to choose which units to present the vibration data in should be available for the user on the display of the product as well as on the computer screen.

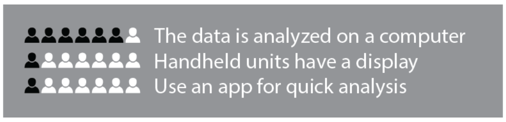
*Values*



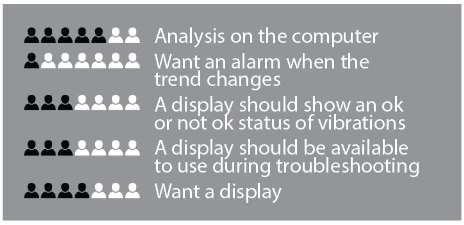

When it comes to the values the companies want to see, a good or bad status can be good to show the status with predefined values defined by the company or manufacturer. It could also be good to show if the measurement was accurate enough. However, the exact values are more important. To have the option to analyze further and make one's judgment of values is crucial. The digital interface on the display should therefore be developed with the flexibility to choose both exact values as well as a status.

*Data reading*

How it is done today:




How they want it:



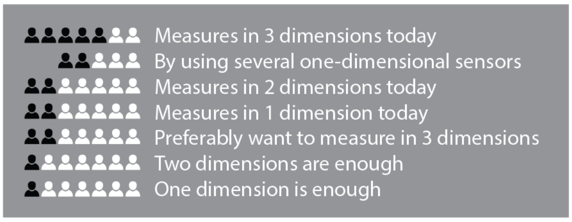

The most common way to read data today is on a computer, where the analysis is also made. This is due to the opportunity to get a good overview of all the data on a computer screen. One company also had an app connected to handheld devices, which showed a green, yellow or red status and suggested actions based on the status, however, the limits were manually predefined. Some companies had a display on their handheld devices, which was looked at to make sure the vibration levels were acceptable.

When asked how the companies would prefer to read their vibration measurement data today, it was clear that they want it displayed on a computer. A display on the product is important to show that the collected data is of good enough quality, but for the analysis, they prefer to use the computer. The most important thing they mentioned they want to be able to see is if the trend of the vibration levels changes through, for example, alarms based on predefined limits. Based on this, even though the companies mainly analyze their data on a computer, the conclusion was drawn that a display on the product is needed.

**Hardware**

Hardware is here referring to the tangible part of the product. This section is divided into the following subsections: dimensions, distance, reflectors, and usability.

*Dimensions*




As explained in user study 1, most of the companies mentioned they measure in three dimensions today. Some achieved it by attaching three accelerometers in different directions and some achieved it through three-dimensional accelerometers. It was mentioned it was optimal to measure in three directions, but in some cases, one or two directions are enough. It also seemed as if most handheld accelerometers measure in only one direction. If needed, the companies measured in multiple directions by placing the accelerometer at different points.

Even though the general wish is to have products that measure in all three directions, most companies had products measuring only in one direction, especially the handheld accelerometers. Therefore, the conclusion was that one dimension should be enough. It should also be possible to mount three sensors to get three dimensions. However, this could potentially be a costly and unpopular solution. It also requires that a specific point is reachable for the radar signal in all directions.

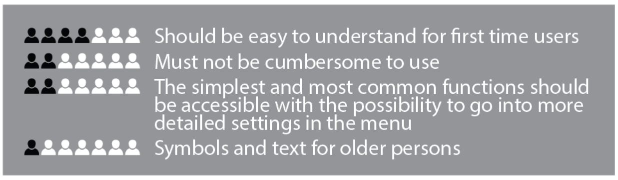
*Distance*

It was difficult for some companies to visualize the application of a contactless vibration monitoring product in their production, but for the ones who saw a need, a measuring distance of a maximum of 5 meters was seen as enough. However, it was mentioned that measuring up to 30 meters was interesting. It will likely be enough to measure up to around 20 meters, based on the input from the interviewed companies.

*Reflectors*

When talking to the software engineer, currently developing the software for radar vibration measurement at Emerson, it was made clear that a reflector is more or less required to get a strong signal. It is possible to direct the sensor in a way for the signal to be aimed perpendicular towards an object, however, this is time-consuming and difficult. The companies, however, did not seem to have an issue with placing reflectors on their machines. Today, magnets are placed on machines as measuring points for handheld accelerometers, either through drilling or gluing them on, so the companies did not see an issue with attaching reflectors in similar ways, see more in chapter 4.2.1 User Studies Round 1, in the subsection on internal technology. Based on this, the decision was to take reflectors into consideration when designing the product.

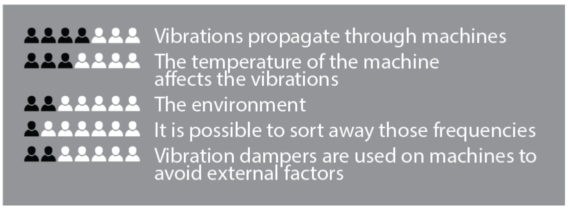
*Usability*




Usability in this section refers to the usability of the physical product interface and how to interact with it. Generally, it was important for the product to have a simple physical user interface according to the users. The wish was that it should not be difficult to use, and a first-time user should be able to understand it easily. In other words, a first-time user should be able to understand the product enough to collect the vibration data, and then a vibration specialist or AI will do the actual analysis.

To make the product easy to understand, a few things were mentioned during interviews. Only having a few buttons and the possibility to start measuring right away, but with the opportunity to change settings if desired. It should be easy to use, quick to set up and minimize misinterpretations.

**External Factors**




The main factor affecting the measuring data was vibrations propagating between machines. One example mentioned was when there were several pumps located next to each other, the vibrations of one could increase even though it was turned off. Another big factor was temperature, where lower temperatures – at the startup of the process – would mean higher vibrations, and higher temperatures meant it went more smoothly and therefore lower vibrations.

To avoid these factors, the companies have some measures they take. Some mentioned vibration dampers to avoid vibrations propagating through the building to other machines. One mentioned it is enough to sort out the frequencies, as the frequencies the machines have, and the external factors are different. One company also attached weights to their components to avoid or change the self-oscillation points.

It could be a challenge to make the sensor completely stable when there are so many external factors to consider. However, it did not seem to be a big issue among the companies interviewed, as they could filter away disturbing frequencies. Therefore, the conclusion was drawn that external factors do not need to be considered more than making sure frequencies can be filtered and that the attachment is stable. In addition, when speaking to the software engineer at Emerson, a solution for the product would be to include an accelerometer in the design to cancel out the external disturbances. However, including an accelerometer would make the product more expensive and therefore, the best option is to find a solution for the root of the external vibrations. This is an area that in the future should be studied further.

### 4.2.3 Study Visits

A big part of the project was spent on user studies and company visits whenever it was possible. As described in Table 4.1, four on-site visits were made. The general takeaway was that the preconditions were very different. Even though the interviews showed quite a similar result, with all of them having problems with rotating equipment, the potential applications varied. This section will describe the four different production sites that were visited. Thereafter, the possibilities and challenges that were identified will be presented. All the pictures in this section are examples of what the production sites could look like, as it was not permitted to take pictures at the facilities visited.

**Food Production**

In the food production, assembly lines filled up the factory as a finished product was ready to get packed every second. The production was planned to place the raw material at the start of the line and get a finished product at the end, similar to Figure 4.1.

Cleanliness was crucial and most equipment was made of steel to be easy to clean. With many people working and one line for every product, it was quite crowded. However, the production was planned in such a way that installing cables or attaching products to beams or similar would be no issue. Products that were not in contact with food did not have to be steel, as long as they were easy to clean and did not have any loose parts that could fall into the products.

**Engine Production**

The engine production site, see Figure 4.2, had, in contrast to the food production, an airy and open layout. Everything was automated and had big robot cells that moved parts from one machine to another. The operators that worked at the site mostly worked with taking care of alarms from the monitoring equipment, doing maintenance, and making inspections, among other tasks. It was quite a spacious and clean site, having much space to attach monitoring equipment. Since there was not an operator overlooking the machines to make sure everything runs smoothly, the monitoring equipment is crucial, as there might not be anyone noticing issues.

**Energy Production**

*Figure 4.1. Example picture of a company within the food industry.*

*Note. From Inside an apple processing company in northern Italy, by A. Senoner, 2022 (https://unsplash.com/photos/8V56CnwVJRE).*

*Note. From Inside an apple processing company in northern Italy, by A. Senoner, 2022 (https://unsplash.com/photos/bCgsKqFzUcg).*

The energy production site, see Figure 4.3, had quite a crowded layout. There were many machines and equipment fit in a small area, making it a challenge to find space for attaching a radar. Many stairs and ladders led to the warm furnaces. This production site did not have a lot of monitoring equipment, mostly, operators would feel and hear what and if something was wrong.

**Chemical Production**

The chemical production was mostly located outdoors in an explosion classified area, similar to Figure 4.4. There were many big machines and silos, pipes going from one building to the other. It was quite a harsh environment since most of it was outdoors. Mostly it was a very spacious area, but around the machines, it could

*Figure 4.2. Example picture of what the layout of a company within the engine industry could look like.*

*Note. From Textile Finishing unit setup, by L. Kumar, 2021 (https://unsplash.com/photos/HpPmiduL-DC0).*

*Figure 4.3. Example picture of a company withing the energy industry. (Kowalik, 2019)*

*Note. From The zinc rolling mill, by K. Kowalik, 2019 (https://unsplash.com/photos/djdoRnnKL-yo).*

be very crowded with monitoring equipment. There were also machines obstructing the view of vibrating components, making it difficult to find possible attachment placements as the radar needs to have the measuring point viewable. It was explained that machines and equipment had been positioned around the space as production grew, meaning that their placements were not planned when the facility was built.

**Summary**

In common for all the production sites visited is that they had a lot of rotating equipment and a lot of vibrating equipment. However, the preconditions varied a lot between the different sites. There were spacious areas, like the engine production and the chemical production as well as very narrow and crowded areas such as the food production and the energy production. However, spacious areas did not equal the possibilities of attaching monitoring equipment, as it could mean fewer beams and walls to attach something to.

Similarly, the possibility to install cables to wire a product varied. On the one hand, a more spacious production area would mean more space to install cables. On the other hand, it would also mean more cables would need to be installed, suddenly becoming a very expensive procedure both in time resources and material costs. The flexibility for a company to choose based on how much space and flexibility they have for cables would be very valuable.

The number of people on the site could

*Figure 4.4. Example picture of a company within the chemical industry.*

*Note. From Liquid washing equipment, by C. Kwok, 2017 (https://unsplash.com/photos/xD5SWy7hMbw).*

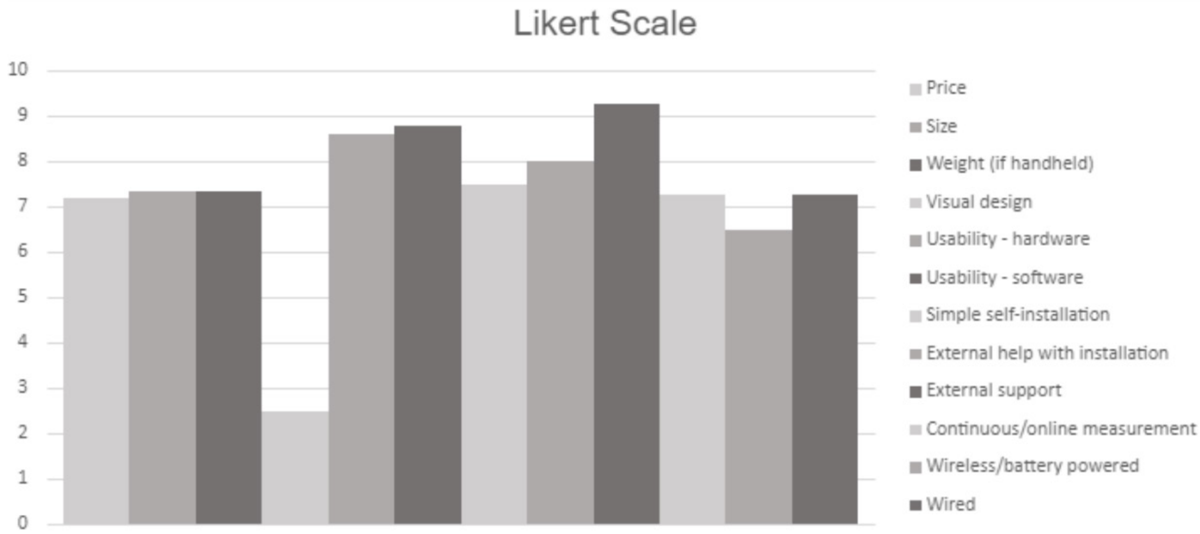



*Figure 4.5. The results from the Likert Scale presented in a column diagram.*

also affect the possibility of attaching a radar as people walking by can disturb the radar. In a production site with many people, the radar would need to be placed where it is not disturbed by them. On the contrary, on a production site with fewer people, the radar could be placed at walking height as it would likely not be disturbed as much. When talking to experts at Emerson, it would be possible to filter out those kinds of disturbances.

The main conclusion drawn from the company visits is that flexibility is very important to have in mind when designing the product. There needs to be flexibility regarding potential attachment solutions if the product is to be mounted to be able to fit in narrow areas, as well as be able to direct in spacious areas where there might not be a place to attach it nearby. The product should either be able to have the flexibility to choose materials or have a material that can handle both harsh environments as well as be hygienic enough to use in food production.

Even though it would be a possibility to choose solely one industry and focus on designing a product perfect for that specific application, the issues were still the same between the industries as no correlations between the type of industry and the layout of the production facilities could be identified. In the same way that the production sites varied between industries, they could vary within the same industry as well. Therefore, it could be of great value to design a product that could be used to solve the same problem, in many different types of industries as well as different production sites.

### 4.2.4 Likert Scale

During the second interview round, the interviewees were asked to fill out a Likert scale. The results from the Likert Scale are presented in Figure 4.5. As seen, each color represents one factor that was filled in from one to ten. On the chart, each column represents the average value of all the companies' results. Most factors were rated quite highly except for visual design which had an average value of approximately 2,5. Weight, if it is a handheld product as well as usability was also rated high.

### 4.2.5 Use Cases

Below three use cases where the radar could be used are presented.

**Case 1: Troubleshooting – Milling Machine**

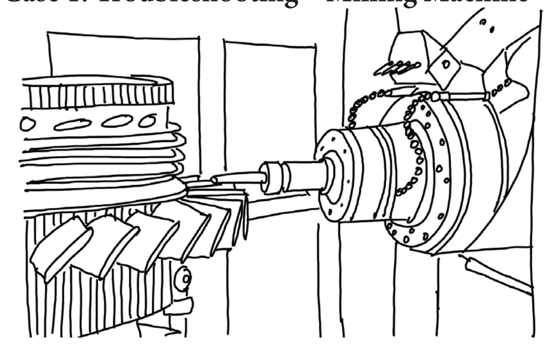


*Figure 4.6. An illustration of a milling machine.*

The first case is about troubleshooting in a milling machine, illustrated in Figure 4.6. The company described their current situation where they have one permanent wired accelerometer installed to monitor the spindle in every milling machine. The spindle is very expensive to replace, both the price of the components and the stop in production that would follow. However, when the trends change and the vibrations increase, it is not always obvious where the vibrations are coming from. It was mentioned that due to the shape of the products that they put in the machine, they can sometimes go into a self-oscillation which will show on the accelerometer's values, even though it is not the spindle.

Based on this issue, they were very interested in a non-contact vibration measuring product that can measure several points at the same time, for troubleshooting. It was mentioned that there could be, for example, a sturdy magnet inside the machine where the sensor is attached, then a few reflectors are attached to the points that are desirable to measure. The sensor would then be left there measuring for a while, while the machine is running.

There are some challenges with this case, one being that the product would have to be waterproof since this case requires the product to measure while the machine is running. All the fluids used in the milling process could disturb the radar signal as well, and lastly, it will be a challenge to make sure the product stays stable the whole time to get a reliable measuring value. However, when discussing the issues with the software engineer, the fluids would likely not be an issue.

**Case 2: Inspections at a Distance**

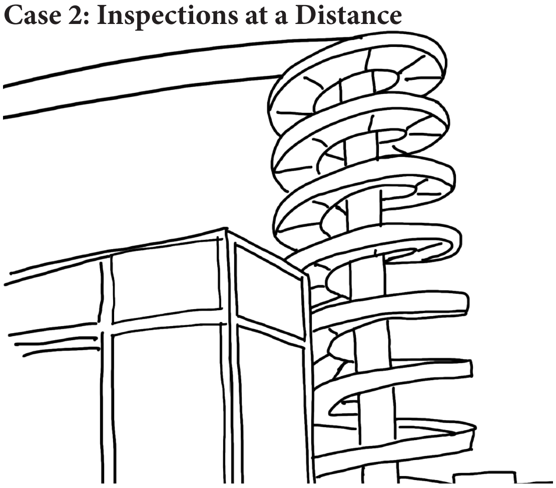


*Figure 4.7. An illustration of a conveyor belt where a motor could be placed high up.*

The second case was described by a company in the food industry that saw value in using non-contact vibration measurement for inspections at a distance in their production, where they cannot use current solutions on the market today. One example that described their current situation is an elevator, as they called it, that was used to transport the products. In this case, the motor was placed at the top of the elevators, a few meters up in the air, as illustrated in Figure 4.7.

They described that it was not worth the money to install a permanent wired accelerometer, as the motor did not have enough disturbances. But due to its placement, it was very difficult to do regular inspections with a handheld accelerometer, which they would normally use for a machine that is not critical enough to install a wired one. To do inspections with a handheld accelerometer, a lift would be needed, which consequently meant several safety issues for the operator. As a solution the company had also tried wireless accelerometers, however, they only measured once an hour. The motor in this case was only running for 20 seconds each time, a few times per hour, which meant if the accelerometer measured once an hour, it could miss every run, only measuring when the motor was turned off.

In this application, the company saw great value in a semi-permanent non-contact measurement solution where they could attach the sensor to a wall or a beam near the motor with, for example, a clamping bracket. Then they could leave the product measuring for a while to measure a few runs thereby avoiding the issues of the wireless sensors. By being able to measure from the ground, the safety issues with the lift would consequently be avoided.

**Case 3: Measuring During Production**

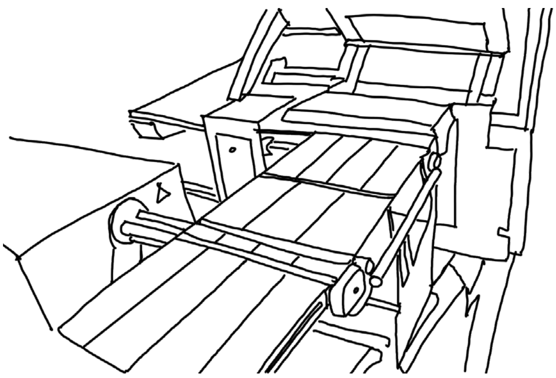


*Figure 4.8. An illustration of a slicing machine.*

The third case was described by the same food company as in the second case, where great value was seen in being able to measure vibrations while the machine was running, but where they could not install wired accelerometers. Today, when they are doing inspections, they would need to stop the machines to be able to measure by hand. A specific example that was mentioned was a slicing machine as illustrated in Figure 4.8, which is very dangerous to measure by hand and similar to most machines in their production, they never want to stop it if it can be avoided.

By doing inspections with a non-contact radar sensor, the machines can be measured while running. They would only need to be stopped to attach reflectors, which have to be done only once and can be done while there is a cleaning stop or similar.

### 4.2.6 Personas

Based on the interviews, three personas were created to represent three different stakeholders when it comes to the usage and purchase of the product. The identified personas were the experienced machine operator, the novice summer intern, and the selective procurement engineer.

*Figure 4.9. The persona Claes.*

**Claes, 62**
Maintenance engineer

Claes, Figure 4.9, has long experience in production and has worked as a maintenance engineer for a pulp and paper factory for the last 8 years. His main responsibility is to make sure all the machines are healthy and running. Especially rotating equipment such bearings in engines, pumps, and turbines are prone to wear out over time and therefore it is important to identify any trend changes in vibration levels over time. A potential failure may have serious economic consequences if the production is interrupted for repair. For the most critical machines, they use accelerometers that measure continuously, and Claes can monitor the vibrations in real-time from the control room. For the less critical machines, he takes rounds every two weeks with a handheld accelerometer. Over the years, he has gone through many different types and brands of equipment, and he knows exactly what he prefers in a product and is often involved when it is time to purchase new vibration measurement equipment.

*Figure 4.10. The persona Robin.*

**Robin, 21**
Summer worker

Robin, Figure 4.10, is a teacher-student, and this is his second year as a summer worker at a metal factory. This year, one of the measurement engineers has asked him to step in for her while she is on vacation. Robin considers himself a fast learner but knows that the devices and computer systems can be very technical and tricky to understand, so he is a bit worried he will mess something up. He wonders to himself why all industrial systems and devices look like they are all from the 90s - complicated menu structures, dull colors, and it is hard to get an easy overview of the vibration levels for the different machines. If the interfaces were more user-friendly, he would probably feel less overwhelmed and confused.

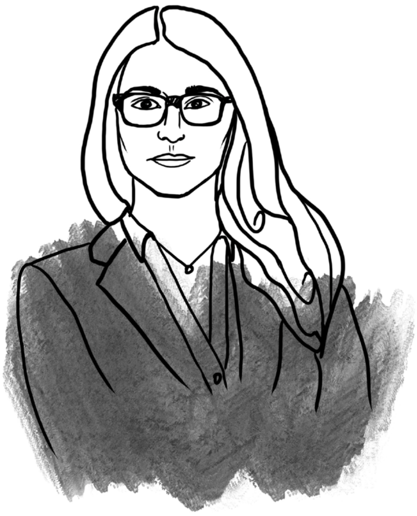


*Figure 4.11. The persona Helena.*

**Helena, 36**
Procurement engineer

Helena, Figure 4.11, works in the office at an energy production facility as a procurement engineer. Her position involves mapping what products and technologies that are available on the market. Price and supplier agreements are what mainly steer her decision-making when it comes to purchasing new equipment, but she must also make sure that the product fulfills the technical requirements. Occasionally she purchases new vibration monitoring equipment, and she often has a close dialogue with the maintenance engineers as they often know what is required of the product. However, the suppliers and products are many and equivalent to each other, so the decision-making process can often be hard as nothing really sticks out.

### 4.2.7 Market Gap Identification

After the user studies three potential solutions were seen as feasible: a permanent solution, a handheld solution, or a semi-permanent solution. In this section the most important advantages and disadvantages of each of the possible solutions are discussed. Lastly, a conclusion on which solution is the most feasible and valuable on the market is presented.

A permanent solution has the advantage of measuring vibrations continuously, which can be challenging for a product with a battery as it would run out faster. Another big advantage is that a permanent solution would mean more sales in the sense that a company would need to purchase more products, compared with a handheld unit where only one per company is needed. However, as the radar can only measure vibrations in one direction, three products would be needed in order to achieve a triaxial measurement. This would mean a larger expense for the customers as well as a challenge to place the sensors in a way that all measuring points are visible.

A big advantage of a handheld unit is the fact that it is portable, and therefore offers greater flexibility in choosing where to measure vibrations. This also means it is a cheaper solution since a company would only need to buy one or a few. However, this consequently means fewer sales. A disadvantage is that it is not optimal to measure continuously as the battery will run out fast. It would also be challenging to direct it and keep it still in the hand long enough to get a good measurement, especially from a longer distance.

A semi-permanent solution would mean the greatest flexibility as it can operate both as a permanent solution as well as be portable and handheld. This flexibility offers many application areas as it can be used for continuous measurement, troubleshooting, or as an inspection device. This flexibility, however, will likely be a more expensive solution for the customer and less sales as a company would only need one or few.

**Conclusion**

The conclusion was made that the semi-permanent solution would create the most value for the customers. This is due to the flexibility that it offers in being able to be used for troubleshooting, inspections and to be left to monitor continuously in between. In other words, the semi-permanent solution can be used as both the other products. However, a handheld unit would mean many challenges with, for example, keeping it stable enough to direct, which a permanent solution does not require. Therefore, a semi-permanent solution that can be attached to an attachment for a short amount of time while doing inspections or a longer period to troubleshoot, is perhaps more feasible.

As mentioned in the user study results, the companies are generally satisfied with the solutions that are used today, permanent and handheld. After discussions with Emerson vibration engineers, it would be difficult to compete price-wise and it would be the most realistic to not aim to compete with them, but rather aim to complement them with a premium troubleshooting product. This was mentioned, by Emerson solutions engineer, to be on-brand for the company to offer premium products when other solutions are not good enough. A comparison was made to the motion amplification technology, being a very expensive technology, but still a very popular solution for troubleshooting. If the product to be developed can solve issues that are not currently possible to solve, it will likely be very valuable on the market.

### 4.2.8 SWOT Analysis

Below the results from the SWOT are presented. It is divided into four subsections: Strengths, Weaknesses, Opportunities & Threats.

**Strengths**

With Emerson's current technology, it is thought that the product will be able to measure from 30-50 meters and at a frequency of up to 20kHz. In addition, radar technology offers the opportunity to measure multiple points at once as long as there is a difference in distance between the measuring points.

Today, there are areas that are not accessible to measure due to dangerous environments or other hard-to-reach environments. Some accelerometers are unable to operate in extreme temperatures, where a contactless vibration monitoring solution could come in handy. Another example is corrosive environments where a contact-based solution might be destroyed. In addition, a contactless solution would also be suitable for hard-to-reach environments such as in robot cells or machines positioned high up in the air. As mentioned by the companies in the user study, another application area is low-prioritized C-classified equipment that is typically not monitored today.

A vibration monitoring device using radar technology offers flexibility in a variety of ways. First off, it could potentially be used as a troubleshooting device as suggested in the results of the user studies. In that case, the device could be placed by a machine for troubleshooting and left there over a period of time. Secondly, an advantage of radar technology is its ability to measure multiple measuring points at the same time on the condition they are distributed at different distances from the sensor. In theory, fewer measuring devices are needed per measuring point.

The technology of the product is based on Emerson's non-contact radar Rosemount™ 1408 Level Transmitter which roughly costs around 10.000 SEK today. With this in mind, it could be assumed that the price for the product concept developed in this project will be around the same price point, if the same components and materials are used. This can be compared to motion amplification camera systems which may cost a few hundred thousand SEK to buy new. The price of accelerometers varies a lot depending on its application and specifications. However, the goal is not to compete with accelerometers as they are well-established on the market. Instead, the product is meant to act as a compliment. As previously stated, the radar technology has the potential to measure multiple measuring points at the same time, meaning that there might be greater value per measuring point. Also, if the product is handheld or semi-permanent, it is also possible to measure multiple measuring points with the same device.

As mentioned, the technology is in theory a good tool for predictive maintenance as it helps to detect deviating trends in vibrations. By preventing interruptions in production due to failure, the device could have great economic benefits. In addition, by applying predictive maintenance, there might be an increase in machine health and lifespan of machines and tools, and also maintain good product quality.

**Weaknesses**

What was found during the user studies was that the current technology more or less requires reflectors for the receiver to detect a strong signal. This means that the product is dependent on reflectors mounted on the machines, which creates an extra step for installation and provides less flexibility.

Some companies wish to be able to measure in multiple directions, something some accelerometers can today. The reason being is that measuring in multiple directions provide more detailed data for the user to analyze which is helpful when identifying deviating trends and their causes. A radar-based contactless vibration monitoring product is only able to measure in one direction at a time. If the user wishes to measure in multiple directions, multiple devices have to be used which could potentially be costly.

A contactless radar solution is supposed to be positioned at a distance from the measuring point(s), it must be positioned in such a way that the radar signal is not disturbed. This means that the radar signal cannot be blocked by other machines or equipment, something that might be a challenge in crowded areas. In addition, the desired point to measure might be placed in such a way that it is hard or impossible for the signal to reach.

According to the user studies performed in the project, users stated that the user experience of the digital interface and compatibility with other products are equally or more important than the physical product. Furthermore, they also stated that the amount of support provided by the supplier is also highly considered during the purchase decision process. In other words, the product's business performance might be very dependent on its software and support provided rather than the physical product's qualities.

One advantage with a radar-based vibration monitoring device is that it is able to measure several measuring points at the same time. However, multiple points generate lots of data which is a challenge for the software. This is an issue that needs to be solved before entering the market.

**Opportunities**

Today, there are no radar-based vibration monitoring devices found on the market. There are, however, contactless options such as motion amplification cameras and lasers. Motion amplification cameras are used for troubleshooting, and due to their high price, it is rare that companies have one of their own. Lasers are also uncommon, supposedly due to the expensive price, and rays being harmful to the eyes, but also because it being sensitive to dirt on the lens.

Automated industries are on the rise, which paves the way for more efficient and intelligent production sites. This is an opportunity for the product if it in the future is able to adapt software technologies such as AI and continuous online measuring.

As mentioned, since accelerometers are widely popular on the market, they would most likely be difficult to compete with. Instead, the product solution should be seen as a complement to accelerometers where they are not suitable, such as inaccessible areas, and dangerous or extreme environments.

An advantage of radar technology is that it would be able to detect deformations over time, which could be an indication of potential future fatigue failure. This is since the radar could measure both distance and vibrations, and therefore detect if the monitored object moves over time. If the customers find value in deformation measuring, this could be another selling point for the product.

**Threats**

Although contactless vibration monitoring is an unclaimed market gap, this also means that the market is new and unexplored which makes the market entry challenging. Companies seem happy overall with current product solutions and therefore it might be a challenge to convince them to try this product.

Today, accelerometers are dominating the vibration monitoring market and users seem to be generally happy with the product solution. This means that the product concept should not be designed to compete with accelerometers, but instead act as a complement where accelerometers are weak such as in inaccessible locations, and dangerous or extreme environments.

The goal is to make the product semi-permanent, which means that the user is able to move a device around their facility and place it where vibration monitoring is needed, e.g., for troubleshooting. The goal is also to make the product measure multiple points with the same device. However, this would also result in less sales as the user might only need a few or a single device.

During the user studies, companies said that they often prefer to buy products from the same supplier they already use out of convenience. It is of inconvenience to have multiple suppliers as it may result in software incompatibilities, multiple systems to monitor, and different channels for support. If the customer does not currently use technology by Emerson, it might be hard convincing them to add another supplier.

There are constantly new technical developments and there is always the threat of new and improved technologies entering the market or pushing down prices.

### 4.2.9 Design Specification

The results from the user studies were compiled into a functions list. It has been divided into two sections, table 4.2 contains everything that will have an impact on the design of the product. Table 4.3 instead contains the guidelines that will not have an impact on this design concept but contain the functions that the users want

*Table 4.2. Design specification containing criteria affecting the physical design of the product.*

| | Function criteria | Goal | R/G |
|---|---|---|---|
| **1.** | **Classifications** | | |
| 1.1 | Be waterproof | IP67 | R |
| **2.** | **Product hardware** | | |
| 2.1 | Have an eye-catching color | To find it from a distance | G |
| 2.2 | Have an eye-catching overall design | To stand out in a product catalogue | G |
| 2.3 | Not be too big | Should not require reconstruction | R |
| | | Should not be too bulky to carry around or mount | G |
| 2.4 | Offer stable attachment solution | Should not influence vibration measuring | R |
| 2.5 | Not too small | Should not be easy to lose | G |
| 2.6 | Not too heavy | Should not tire arm or hand | R |
| 2.7 | Be corrosion resistant | Acidic and saline environments | R |
| 2.8 | Be impact resistant | Should be able to handle a drop from 1.5 meters | R |
| 2.9 | Enable wireless (continuous) data transfer | | R |
| 2.10 | Enable wired continuous data transfer | | R |
| 2.11 | Enable battery power source | | R |
| 2.12 | Show battery status | Show on display and/or hardware | R |
| 2.13 | Show connection failure | | R |
| 2.14 | Offer separate reflectors | Glued, magnetized or welded | R |
| 2.15 | Be easy to direct to a measuring point | From < 20m distance | R |

| | Function criteria | Goal | R/G |
|---|---|---|---|
| 2.16 | Be able to measure in 1D | | R |
| 2.17 | Be temperature resistant | Should be able to handle low to high production site temperatures | R |
| 2.18 | Have a consistent design | With other Emerson products | G |
| 2.19 | Be able to measure from a distance | < 20m | R |
| **3.** | **Installation** | | |
| 3.1 | Enable permanent self-installation | Should be fast and simple to install | G |
| | | Installable during running production | G |
| 3.2 | Semi-permanent self-installation | < 1 min to install after attachment has been permanently installed | G |
| | | Installable during running production | G |
| **4.** | **Usability (product hardware)** | | |
| 4.1 | Be portable | Carry around with ease by hand | R |
| 4.2 | Easy to operate | For a first-time user | R |
| 4.3 | Prevent slip mistakes | | G |
| 4.4 | Be consistent | With other Emerson products | G |
| 4.5 | Show operation status | With symbols or colored lights | R |
| **5.** | **Display** | | |
| 5.1 | Provide clear font and font size | | R |
| 5.2 | Provide clear colors | For color blind to differentiate | G |
| 5.3 | Provide commonly used colors and symbols | | G |
| 5.4 | Indicate a good/bad measurement | In a clear way, for example graph, symbols or colors | R |
| 5.5 | Show battery status | Show on display and/or hardware | R |
| 5.6 | Offer detailed data on display | | R |

*Table 4.3. Guideline function list, containing criteria that will affect the software development.*

| | Function criteria | Goal | R/G |
|---|---|---|---|
| **6.** | **Software** | | |
| 6.1 | Provide accuracy | Should have the same accuracy as a standard accelerometer | R |
| 6.2 | Offer filtering of noise frequencies | To sort away external factors | R |
| 6.3 | Enable fast single-point measuring | | R |
| 6.4 | Measure multiple measuring points | ≥ 3 measuring points | R |
| **7.** | **Compatibility** | | |
| 7.1 | Be compatible with Emerson software | | R |

| | Function criteria | Goal | R/G |
|---|---|---|---|
| 7.2 | Be able to connect meters placed in different directions | Up to direction XYZ | R |
| **8.** | **Usability (computer software)** | | |
| 8.1 | Be easy to operate | For a first-time user | R |
| 8.2 | Be consistent | With other Emerson products within the digital interface | G |
| 8.3 | Offer reminder notifications | To not miss rounds or measuring points | G |
| 8.4 | Prevent slip mistakes | | G |
| 8.5 | Provide simple start-up menu | Few buttons and/or symbols | G |
| 8.6 | Enable detailed overview for analysis | For example, tree diagram structure | R |
| 8.7 | Enable AI | To suggest cause of vibrations | G |
| | | To identify and suggest vibration thresholds | G |
| 8.8 | Show operation status | In a clear way, for example symbols, text or colors | R |
| 8.9 | Show simple graphic system or machine overview | To illustrate positions of measuring points and problem area | G |
| 8.10 | Enable threshold customization | For each measuring point | R |
| 8.11 | Show vibration trends over time | Graphs over time | R |
| 8.12 | Warn about alarming vibration | In a clear way, for example symbols, text or colors | R |
| 8.13 | Offer ID for each point | Position and name | G |
| **9.** | **Support** | | |
| 9.1 | Provide data analysis support | By Emerson | G |
| 9.2 | Provide technical support | By Emerson | R |
| 9.3 | Provide post-purchase follow-up | By Emerson | G |
| 9.4 | Provide installation support | By Emerson | R |
| 9.5 | Provide sales support | By Emerson | R |
| **10.** | **Units** | | |
| 10.1 | Show data in speed | mm/s | R |
| 10.2 | Show data in velocity | Speed and direction | R |
| 10.3 | Show data in acceleration | m/s^2 or g (=9.8m/s^2) | R |
| 10.4 | Show data in frequency | Hz | R |

and need in, for example, the digital computer interface.

The design specification is divided into six categories: classifications, product hardware, installation, usability, and display. Product hardware contains the functions that will affect the product design, everything that one can see and touch.

The guidelines for future development by Emerson are presented below and divided into the following five sections: software, compatibility, usability, support, and units. These guidelines regard the parts that are not visible but still contain functions important for the product and the customers.

## 4.3 Insights

In this chapter, the market has been investigated to find the problems that exist today and a gap where there is a need for radar vibration monitoring. The needs and requirements for monitoring equipment in this market have been investigated as well to get a thorough foundation for the development of a physical concept, presented in the next chapter.

Some insights that had great importance and were brought on to the development phase:

- Rotating equipment needs to be monitored for vibration
- It will be difficult to compete with accelerometers
  - Develop a product that will act as a complement
- There are some areas where accelerometers are not optimal, which could be a good niche for radar-based vibration measurement
  - Dangerous environments
  - Hard to reach environments
  - Troubleshooting
- Flexibility & reliability is of great importance

## Chapter 5

# Phase 2: Product Development Process

**In the second phase of the project, the aim was to develop a concept that would fulfill the needs of the users and fit into the identified market gap. The chapter is divided into three main sections: Methodology – describing the methods and how they were used, Results –presenting the results from the used methods, and Insights – summarizing the main points from the chapter.**

## 5.1 Methodology

In this section, the product development process will be described in three different steps: the design goals, the design format analysis, and the ideation process.

### 5.1.1 Design Goals

In the initial phase of the design process, a set of common design goals were set up. The methods used were word clouds and visual board.

**Word clouds**

Four different word clouds were created: Emerson Design Guidelines, Product Design Guidelines, Customer Design Guidelines, and lastly Design Expression Guidelines.

In the first word cloud, key words from the Emerson design guidelines were picked. This is since it was important for the product to incorporate the design language, to fit into the product portfolio. There are two different types of guidelines that either apply to one of the Emerson core business platforms known as Automation Solutions or all Emerson brands in general. The Emerson Automation Solutions design guidelines are common guidelines for all products produced within Emerson's automation solutions platform, while the Emerson non-signature brand design guidelines are common for all Emerson's global brands.

In the second word cloud, key words were picked from the user study interviews and the design specification, to summarize the main points and have them in mind for ideation. The word cloud consisted of a high number of words as the focus was on listing all the different attributes that were mentioned throughout the user studies. In this stage, quantity was key.

In the third word cloud, some of the more mentioned and important words from the Product Design Guidelines word cloud were picked. The size of some words that were mentioned several times were emphasized as they were considered more important throughout the design process. The aim was to summarize and define some of the more important, and above all, mostly mentioned points from the user studies.

Lastly, a word cloud consisting of words connected to the product's design expression was created. The words were chosen with the purpose to serve as common design expression guidelines throughout the design process.

**Visual board**

As a source of inspiration, a visual board was created. The board was developed by browsing for pictures that could be used as inspiration. The pictures could be of an object, form, material, expression, or feeling. The pictures were then collected on a board. The purpose of this visual board was to form a common idea about the visual attributes and expressions of the product that was to be developed.

### 5.1.2 Design Format Analysis

Although Emerson has developed extensive design guidelines for their brand and products, it is not always enough to summarize the form elements and attributes that are typical for a brand or product family. Therefore, a design format analysis was conducted to identify specific key elements characteristic of Emerson's brand identity that are to be visually found in their products.

The products to be analyzed were chosen solely from the Rosemount brand, as the product to be developed will have the same brand. Since level measurement is what characterizes the brand the most, most products that were analyzed were chosen from this product family. Products with dissimilar housings were chosen, as well as two products that were outside the level measurement family, they were chosen to get a larger number of products to analyze. One hygienic application product was chosen to have one more product that was not blue, and one product that displayed the design language well, according to the project group.

### 5.1.3 Ideation Process

With the word clouds, visual board, and design format analysis as a foundation, the next step was to start the ideation process. The ideation process was visualized in Miro which is a visual collaboration tool that enables its users to create boards together. The ideation process was divided into three rounds, see Figure 5.1.

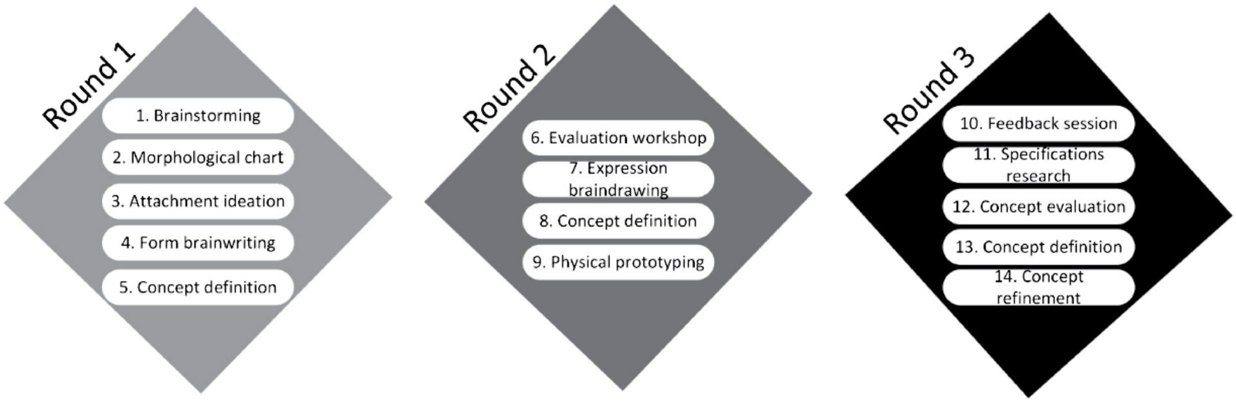



*Figure 5.1. An illustration of the different steps in the ideation process.*

**Round 1**

*Step 1: Brainstorming*
The first round started with a brainstorming session. A high quantity of initial and basic ideas was brainstormed and sketched out by hand. The purpose of this stage was to visualize any initial ideas that each team member has had on their mind throughout the project so far.

*Step 2: Morphological chart*
Next, the morphological chart method was utilized to create a high quantity of potential concepts. This was done by picking a number of criteria from the design specification that were important and had several potential design solutions. Thereafter, the project members separately listed possible solutions for each criterion. The solutions for each criterion were combined into a few different concepts each to spark creativity and ideas when presented to each other.

*Step 3: Attachment ideation*
In the third step, the project group ideated some possible attachments. This was performed by researching existing attachment solutions for other product categories such as TV screens, cameras, etc. In addition, other solutions such as strapping, screwing, etc. were researched. The different attachment solutions were then evaluated in a modified weighted matrix used as an indication for the better solutions based on a number of criteria retrieved from the design specification. The different solutions were given 1, 2, or 3 points based on how well they fulfilled each criterion, where 1 point meant it did not fulfill the criterion, 2 points meant it fulfilled the criterion ok, and 3 points meant it fulfilled the criterion well.

*Step 4: Braindrawing of the form*
In this step, braindrawing was used as the ideation method to come up with the form of the product. The project members sketched a number of form ideas each for a predefined amount of time. The sketches were then uploaded to Miro and each project member could then take inspiration or develop the other member's idea further. The braindrawing rounds were repeated until both team members were out of new ideas.

*Step 5: First concept definition*
Based on the form braindrawing in the previous step, three different form ideas were picked and refined into four base concepts. The goal was to pick forms very different from each other to use as prompts for discussion in the following concept evaluation workshop, see Step 6.

**Round 2**

*Step 6: Concept evaluation workshop*
The concepts from Step 5 were evaluated together with two mechanical engineers at Emerson. This was conducted through a workshop with elements of co-creation. Both project members participated in the workshop where one took the role as the facilitator while the other took the role of a participating designer to discuss and develop ideas with the mechanical engineers who took

the role as mechanical experts. The workshop was divided into four parts: icebreaker activity, concept presentation, concept evaluation, and scamper method.

The workshop was initiated with an icebreaker activity to get to know each other and warm up their sketching abilities in a relaxed manner. In the next step of the workshop, four base concepts with different form variations were presented to the participants. The participants were then allowed to ask questions to better understand each concept and its functionality. The participants were also asked to share spontaneous thoughts about their designs and technical functionalities to evaluate the presented concepts.

Afterward, the scamper method was utilized to develop the four concepts further and to spark new ideas. The participants were handed pieces of paper with the different concepts printed onto them. The facilitator then presented each prompt from the scamper method to the participants who then were given time to sketch or write down their thoughts and ideas. At the end of the session, each participant got to present their results from the workshop.

*Step 7: Expression braindrawing*
After the workshop, it was decided to move further with one of the presented concepts based on the workshop input. More rounds of braindrawing like the ones in step 4 were created, now with an emphasis on the product expression, as well as incorporating ideas and input that was mentioned during the workshop.

*Step 8: Second concept definition*
Once the braindrawing rounds had taken place, three designs were picked to be refined. CAD models for each concept were made in Creo to illustrate their design expressions on a detailed level. In this stage, an initial attachment idea was applied to the concepts as well.

*Step 9: Physical prototyping*
To get a better feeling for the size of the product, a physical model was created using Capa board. The model was a quick and rough low-fidelity prototype, only focusing on size. The prototype was then used in Step 10.

*Step 7: Expression braindrawing*
After the workshop, the project team decided to move further with one of the presented concepts based on the workshop input. More rounds of braindrawing like the ones in step 4 were created, now with an emphasis on the product expression, as well as incorporating ideas and input that was mentioned during the workshop.

*Step 8: Second concept definition*
Once the braindrawing rounds had taken place, the project team picked three designs to refine. CAD models for each concept were made in Creo to illustrate their design expressions on a detailed level. In this stage, an initial attachment idea was applied to the concepts as well.

*Step 9: Physical prototyping*
To get a better feeling for the size of the product, a physical model was created using capaboard. The model was a quick and rough low-fidelity prototype, only focusing on size. The prototype was then used in Step 10.

**Round 3**

*Step 10: Concept feedback session*
Once the second round of concepts had been defined, it was time for the concept feedback session with three mechanical engineers and one representative from the market department. Due to conflicting schedules, the feedback session had to be split into two with two participants attending each session.

During the sessions, the three concepts were presented to the participants who were asked to give their spontaneous thoughts about each concept and improvement areas. The initial attachment idea was also presented which the participants also were to comment on. Some discussion points were listed and presented to prompt discussion. The participants were also asked to rate their favorite concept out of the three.

*Step 11: Concept specification research*
Based on the feedback in Step 10, the project team conducted research on four different areas: IP classifications, mounting solutions, wire inputs, and rotatable screens. The research was conducted by consulting engineers at Emerson,

inspecting existing Emerson radar products, and browsing the web. Based on the research results, the project team decided on what specifications to utilize in the final product.

*Step 12: Concept evaluation*
To decide on what product concept to move further with, two evaluation methods were applied: a semantic differential scale and a weighted matrix. The project team also collected qualitative input from the workshops and evaluation sessions.

The words from the design expression word cloud, paired with their autonyms, were used for the semantic differential scale. The semantic differential scale is illustrated in Figure 5.2. Twelve engineers of varying professions and experience within the company were asked to fill out one semantic differential scale for each concept, only focusing on the design expression. The results were then collected and an average for each word was calculated for each concept. The results were used to see how well each concept fulfilled the desired expressions and used as an indicator in the concept decision process.

In parallel, a weighted matrix was conducted to evaluate each concept with respect to the criterion in the design specification. Each criterion was weighed against one another, and a score was calculated for each concept. The purpose of applying this method was to see how well each concept fulfilled the criterion in design specification, and the results were used as an indicator in the concept decision process.

*Step 13: Concept definition*
Once all the different evaluation processes had been conducted, the project team used the results together with their own intuitions to decide on a final concept.

*Step 14: Concept refinement*
The last step in the concept development process was to refine the last details such as the visual design, symbols, lights, size, and wire input, among other things. It was done mainly through uploading renders to Miro and, like in the earlier steps, commenting and sketching on each render improve the concept based on all feedback and results that had been gathered throughout the project. The design was then visualized using CAD.

## 5.2 Results & Analysis

The results in this chapter have been structured according to the ideation rounds that were made. First, the pre-work for the development phase is presented: design goals and design format analysis. Later ideation rounds one, two,

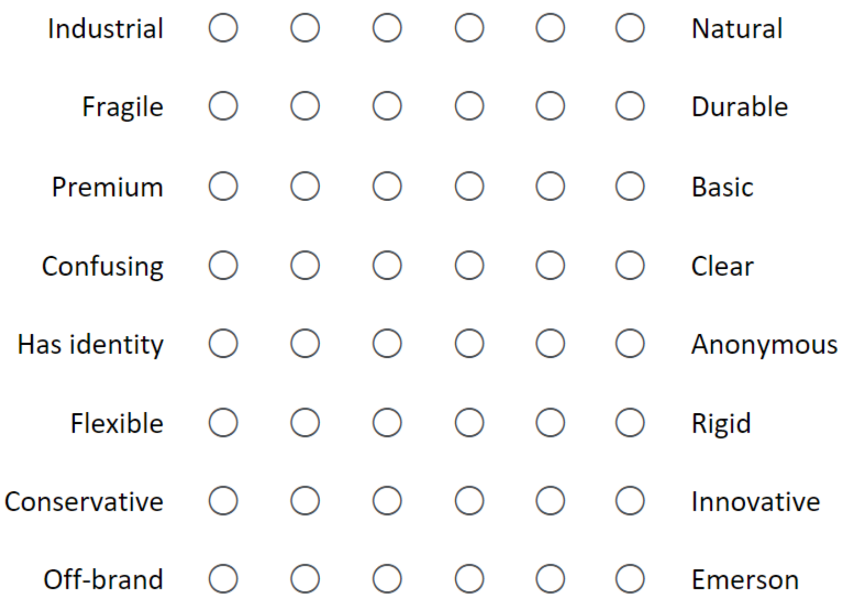



*Figure 5.2. The semantic differential scale used for concept evaluation.*

and three are presented, each round containing an ideation phase, an evaluation phase and some type of choice of concepts.

### 5.2.1 Design Goals

In this chapter, four word clouds are presented together with a visual board, that were used as inspiration throughout the ideation process:

- In Figure 5.3, the word cloud created using Emerson's design guidelines is presented.
- In Figure 5.4, the word cloud created using words from the design specifications is presented.
- In Figure 5.5 a word cloud based on the most mentioned characteristics desired by the interviewees is presented. The most important characteristics were highlighted.
- In Figure 5.6, the design expression word cloud is presented, based on previous word clouds, input from Emerson employees, and personal preferences.
- In Figure 5.7, the visual board is presented with the aim to reflect the desired keywords and expressions of the product.

The word clouds and mood board were great tools to form a common vision and idea about the product characteristics and expressions before moving on to the product design process. These tools helped visualize the user needs, Emerson's product values, as well as the desired 5.2.2 Design Format Analysis


*Figure 5.3. A word cloud created using Emerson's design guidelines.*

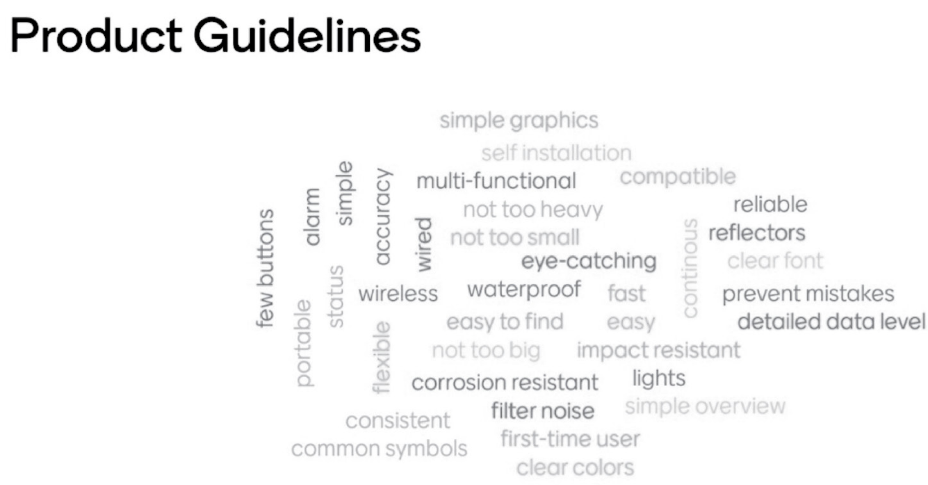



*Figure 5.4. A word cloud created based on the design specification.*

## Customer Guidelines


*Figure 5.5. A word cloud based on the most mentioned characteristics desired by the interviewees.*

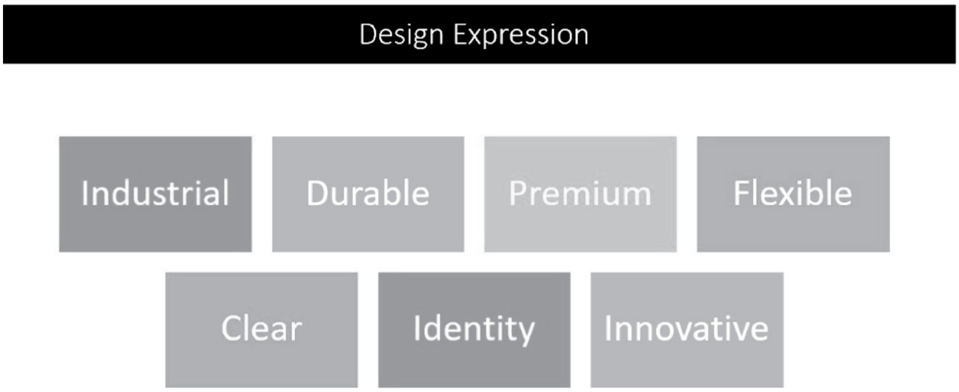



*Figure 5.6. The design expression word cloud.*

*Figure 5.7. The created visual board.*

## 5.2.2 Design Format Analysis

A design format analysis was performed to identify design elements characteristic of Emerson's Rosemount product catalogue. The result is illustrated in Figure 5.9. The vertical scores illustrate how characteristic each design attribute is for the Rosemount brand, while the horizontal scores illustrate how characteristic each product is for the Rosemount brand.

Rounded edges were found to be the most characteristic design attribute for Rosemount together with the cylindrical shape scoring nine points each. In addition, the Emerson blue color, a glossy finish, and symmetrical shape were also found to be very characteristic of the brand with seven points each. Splines and split lines also scored high in the analysis.

The results were important information in order to understand what design attributes are most characteristic of Rosemount's, and Emerson's, brand identity. It is important for the product to have a strong identity in order to stand out in a product catalogue. Emerson does not have a product family for radar-based vibration monitoring, this leaves room for creative freedom and a possibility to create a new identity for the product family, but without standing too far away from the collected brand identity.

When performing the design format analysis, the different product families were analyzed together such as their regular level measuring family and their hygiene family, which are quite different from each other in their design expressions. If a design format analysis had only been conducted on the regular product family only and not the hygiene product family, certain attributes would have been more prominent in the results such as the Rosemount blue color and splines which the hygiene products lack.

## 5.2.3 Ideation Round 1

The first ideation round results is presented in two subsections: ideation and concept choice 1. The ideation sections show sketches and ideas that came up during the fuzzy stage of the round, whereas the concept choice section presents the four concepts that were chosen to develop further in the next phase.

**Ideation 1**

In this section, the results from the ideation process of the first ideation round are presented.

*Brainstorming*

Some early concepts that were created during the first brainstorming session are presented in Figure 5.8. The brainstorming session was a good method to trigger some base ideas. It was also a good outlet for ideas that had been held onto since the start of the project.

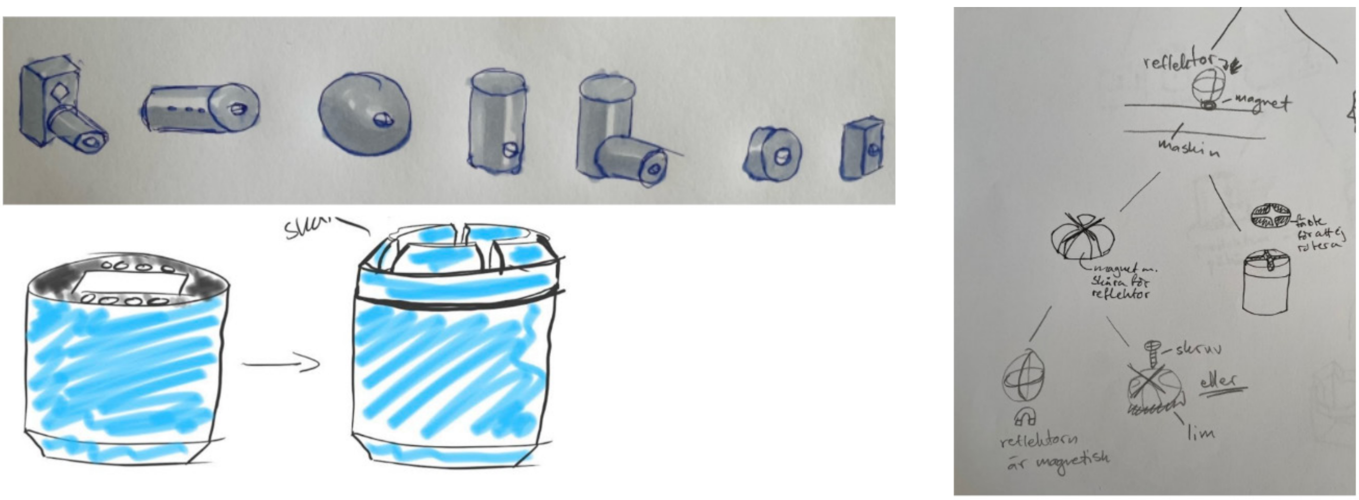



*Figure 5.8. Some initial sketches in the project.*

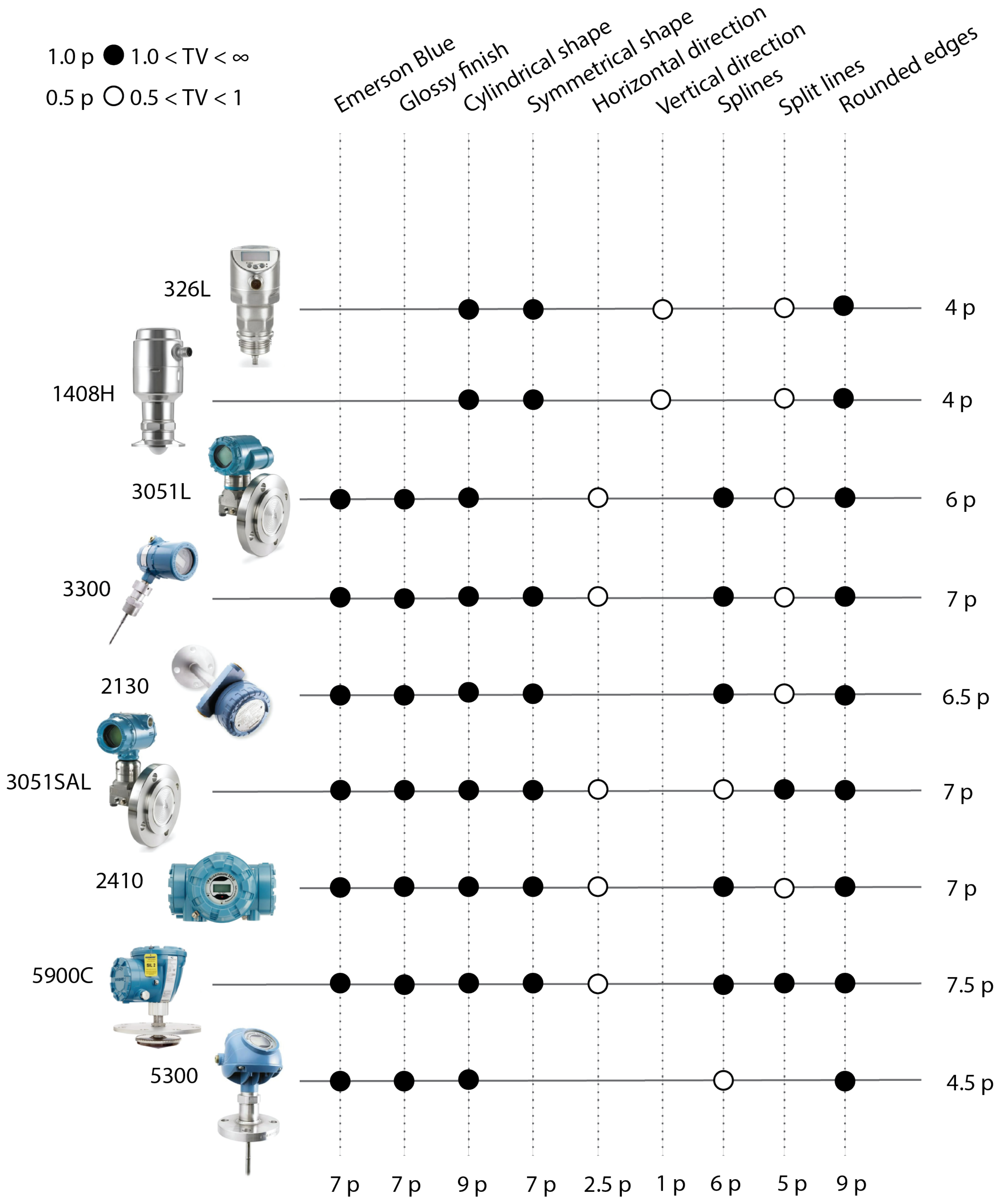



*Figure 5.9. The results from the design format analysis when analyzing nine products from Rosemount's product catalogue.*


*Figure 5.10. Two concepts created from the morphological matrix.*

*Morphological matrix*
Some ideas from the morphological matrix are presented in Figure 5.10. This method was useful to trigger new ideas by combining different features and attributes with each other, ideas that might not have come up otherwise. In that sense, new-thinking outside-the-box concepts were created.

*Braindrawing*
After ideating in a few different ways, three main body shapes were identified as commonly reoccurring in the sketches: a rectangular body, a cylinder-shaped body, and a double cylinder – one main cylinder with one cylinder in the other direction.

*Attachment ideation*
Mainly existing solutions on the market today were chosen for evaluation with a modified weighted matrix. They were evaluated based on the following factors:

- Price
- Invasiveness on machines
- Time to mount sensor
- Possibility to direct radar
- Feasibility
- Possibility to tighten

Four main ideas received high points from the matrix: camera attachment, tv attachment, grip claws, and straps, see Figure 5.11. The camera attachment had the great advantage of being able to direct the antenna easily, mount the sensor quickly through a snap-on technology, and being able to tighten as it can hold a camera without a problem. However, it would be an expensive solution. The TV attachments had similar advantages, however, not being as fast to mount, and also likely being an expensive solution. The grip claws had the advantage of being a cheap solution and having the ability to tighten. However, it did not have the same ability to easily direct the radar. Lastly, the straps also had the advantage of being cheap and quick to

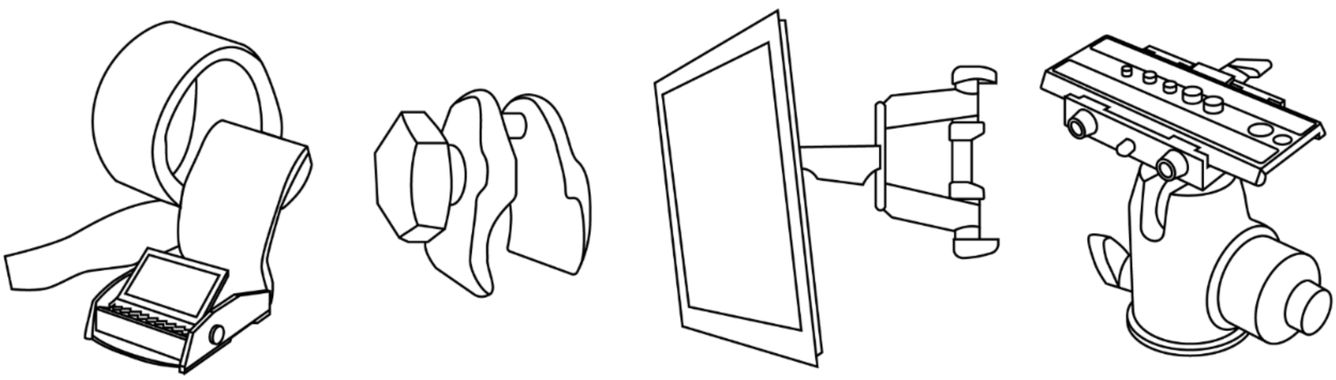


*Figure 5.11. The four attachment ideas that received the highest evaluation points.*

mount. It was also the only concept that would not be invasive on the machines or buildings. However, similar to the grip claw, the possibility of directing the radar antenna toward the measuring point is limited as well as tightening the straps.

After the attachment evaluation, it was realized that the four potential attachment solutions would not affect the main body shape of the sensor that much. Therefore, it was decided to move on with designing the attachment and the main body shape separately.

**Concept Choice 1**

After the first round of ideation, the following

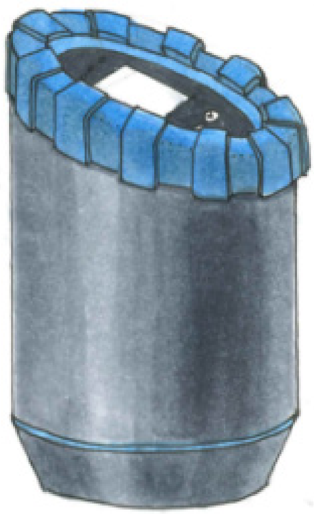


*Figure 5.12. Concept 1 - Ideation round 1.*

four concepts were chosen to bring on to the next ideation round.

The first concept is a cylinder with an angled cut, see Figure 5.12. The top part of the cylinder is a protective lid, with the display and buttons underneath. The antenna, from which the radar signal is sent out, is placed at the bottom of the cylinder. Furthermore, as a detail, it has a split line at the bottom incorporating the Rosemount blue, which is a brand characteristic color, also present in the lid. The splines in the lid are a design feature to incorporate design features found in the Emerson products today.

The second concept is a rectangular shape where the display is placed on the top and the antenna on the side, see Figure 5.13. The buttons are placed in connection to the display and can mirror depending on which

*Figure 5.13. Concept 2 - Ideation round 1.*

way the product is held. The silver line around the product is a design feature to incorporate the metal found in their hygiene radar product

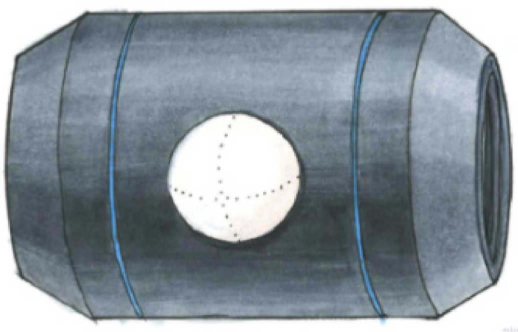


*Figure 5.14. Concept 3 - Ideation round 1.*

family. The big rounds are added as many of Emerson's products have them.

The third concept has a cylinder-shaped main body, see Figure 5.14. The antenna is placed on the front of the cylinder, with the display on one side and a logo on the other side. Two split lines are added as a design feature incorporating the Rosemount blue. The chamfers are added as a

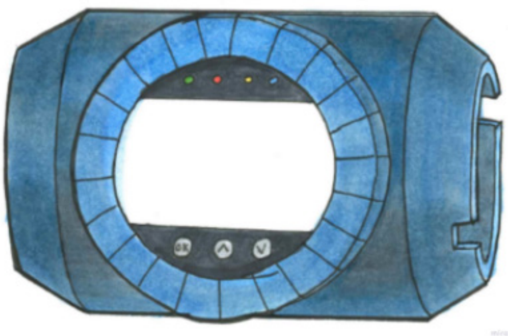


*Figure 5.15. Concept 4 Ideation round 1.*

design feature since many of Emerson's products have them.

The fourth concept is similar to the third concept with a cylinder main body as well, see Figure 5.15. The display, however, is placed on the front of the cylinder. On one side the antenna is placed and on the other side, a logo is placed. The lines around the cylinder are there to represent splines, as well as the indentations on the side. This concept is colored Rosemount blue.

### 5.2.4 Ideation Round 2

During the second ideation round, initially an evaluation was made, choosing one concept to ideate around, and lastly, choosing three new concepts to bring on to the next ideation round.

**Evaluation of Concept Choice 1**

Through a workshop with mechanical engineers at Emerson, the four concepts were evaluated. Some feedback that was given at the workshop will be presented below.

Initially, feedback on the attachments was given. The flexibility with the straps was seen as very valuable, however, not as robust as some of the other ideas that could be tightened more. An idea to create a base where several of the attachment ideas could be incorporated into one was presented by one of the participants. The suggestion would offer the flexibility for the customer to choose the attachment based on their needs and preconditions in their production.

When evaluating the concepts, a lot of emphasis was put on the splines and split lines that were incorporated into the concepts. The participants expressed that the splines suggested that those parts would be openable. For example, the lid of the first concept as seen in Figure 5.16. expressed that it was supposed to be twisted, however, it was supposed to be flipped open. This could potentially mean that users try to twist it and break the mechanisms in the product.

The issue of the splines became a bigger part of the development process than expected. As seen in the DFA, Figure 5.9, splines were seen in most of the Emerson products, making it quite characteristic of the Emerson design language. However, they were initially only incorporated into the designs by Emerson to serve a function.

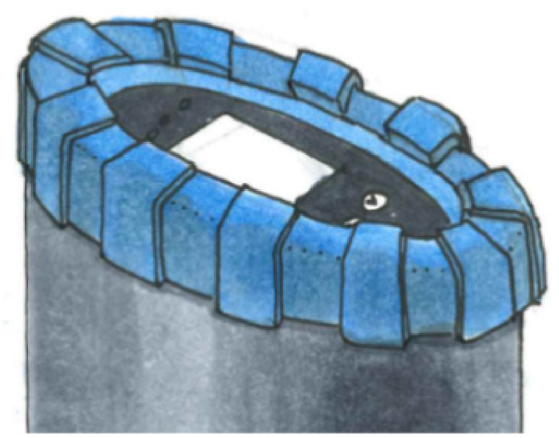


*Figure 5.16. The lid of the first concept expressed that it was openable.*

Therefore, they must only be placed on the product if it actually serves a function to not mislead the user.

The favorite concept of the participants was the double cylinder with the antenna on the front as it would likely offer the most flexibility. However, it was unclear whether it would be a feasible solution. Based on this feedback, it was decided to continue developing the double cylinder concept, with the display on the front instead, see Figure 5.15.

**Ideation 2**

In the second ideation round, the focus was put on iterating the main shape and flexible attachment solutions, as seen in Figure 5.17. Different shapes and proportions were explored to achieve the right expression based on the design goals set before the first ideation round.

**Concept Choice 2**

Based on the second ideation round, three main shapes and expressions were identified and iterated. To separate them, they were named The Cylinder, The Hub, and The Lobe, as seen in Figure 5.19-5.21.

The first concept, The Cylinder, see Figure 5.19, was based on the fourth concept in ideation round 1. It has a main cylinder with a second cylinder going through the front. In the front cylinder, a display is placed, with symbols around it to represent a logo. On the left side, the antenna is placed, and on the right side, a logo is placed. There Rosemount blue split lines were kept in the design since the product would likely

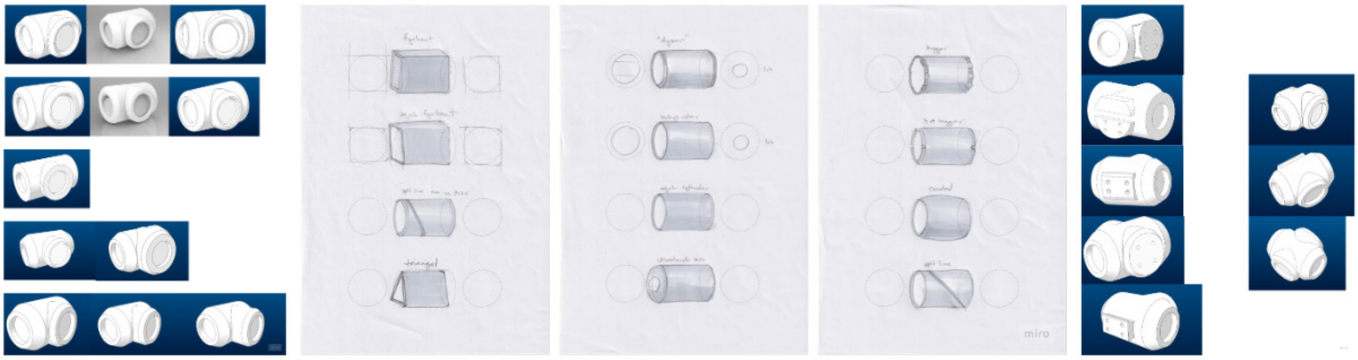


*Figure 5.17. The focus of the beginning of ideation round 2 was put on the shape & flexible attachment solutions.*

have to be openable during production.

The second concept, The Hub, see Figure 5.20, is based on the expression word Robust from one of the word clouds. It was created with a lot of heavy splines, characteristic for Emerson products to provoke ideas during the feedback session about product identity and expression. Big splines are placed on the sides and the front lid and the chamfers have a steeper angle than The Cylinder.

The third concept, The Lobe, see Figure 5.21, was based on the third concept of the first ideation round. Even though the workshop feedback included a skepticism towards this concept's feasibility, it was decided to develop it anyway to further trigger ideas and feedback during the feedback session, as well as get some input from more stakeholders than those that were present during the workshop. Based on some feedback from the workshop, protective housing was put around the antenna, in two different variants. Split lines were also added to achieve more of the Emerson design language, as well as the blue color.

In addition to the three concepts, one attachment idea was created incorporating several of the previous attachment ideas, see Figure 5.18. The idea with this attachment concept was to have a snap-on function with an angled attachment which is common for DSLR cameras. With this kind of attachment solution, it only takes a few seconds to mount the product to a wall, tripod or similar. Apart from this attachment solution, the cavities in the attachment are incorporated for the user to slide through a strap or cable tie, to be able to mount the sensor more flexibly and cheaply onto, for example, a railing. Lastly, four M6 screw holes are placed on the attachment, if the user wants to use screws to attach the sensor to, for example, a wall.

### 5.2.5 Ideation Round 3

The last ideation round contains a lot of evaluation to choose, define, and iterate the concepts into one final concept. For the final concept, see chapter 6. Final Concept.

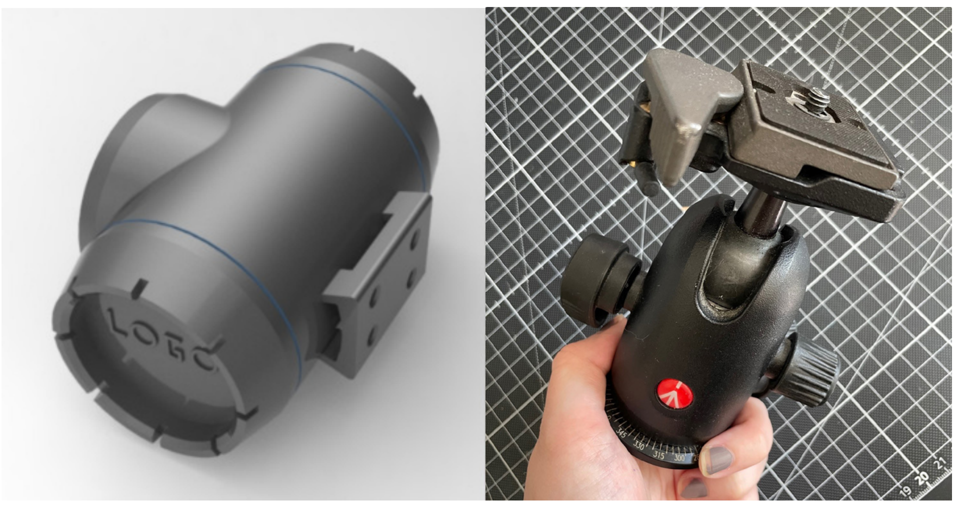


*Figure 5.18. The attachment idea developed in ideation round 3, illustrated on the first concept, The Cylinder.*

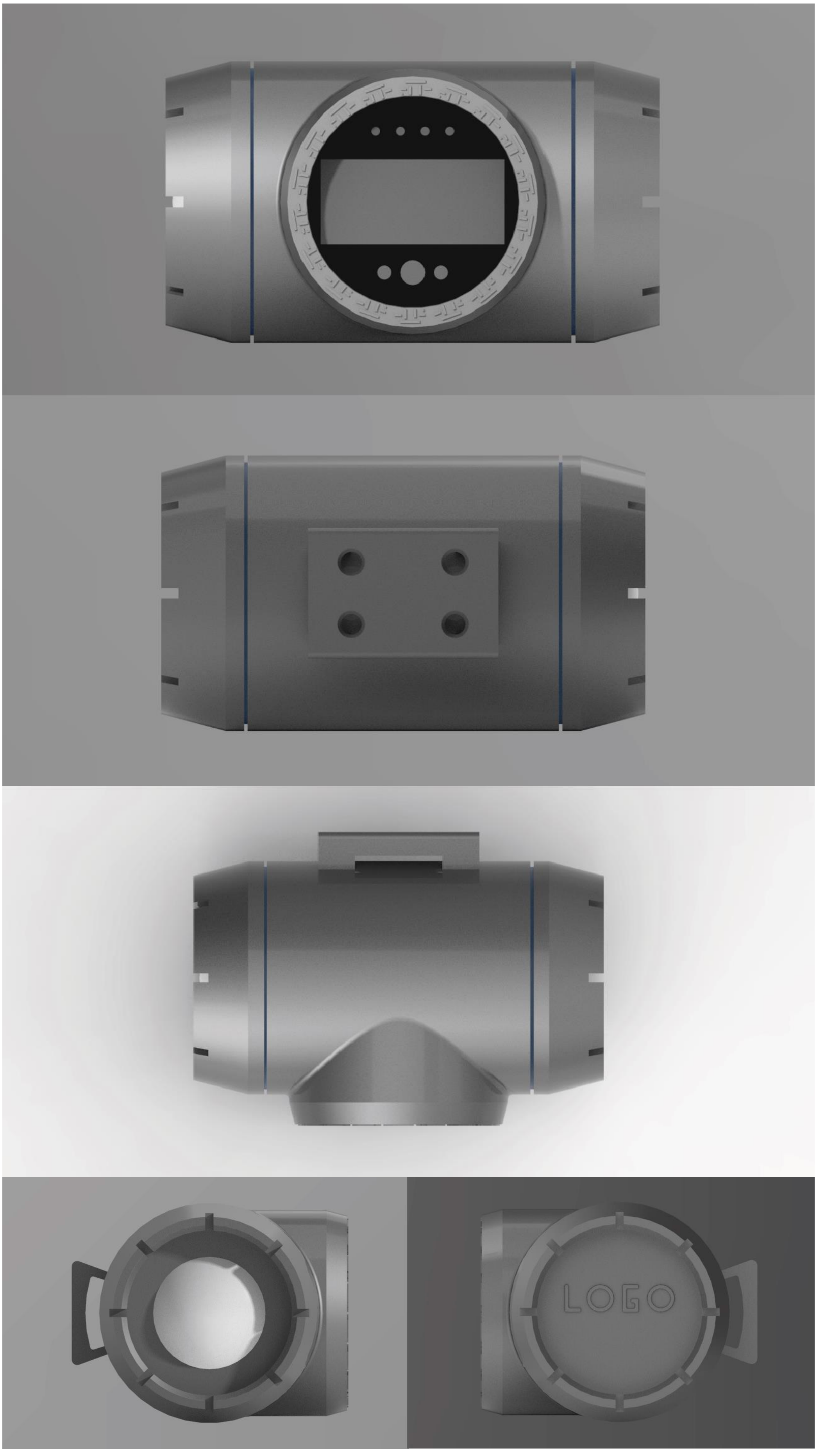



*Figure 5.19. The concept called the Cylinder developed in ideation round 2.*

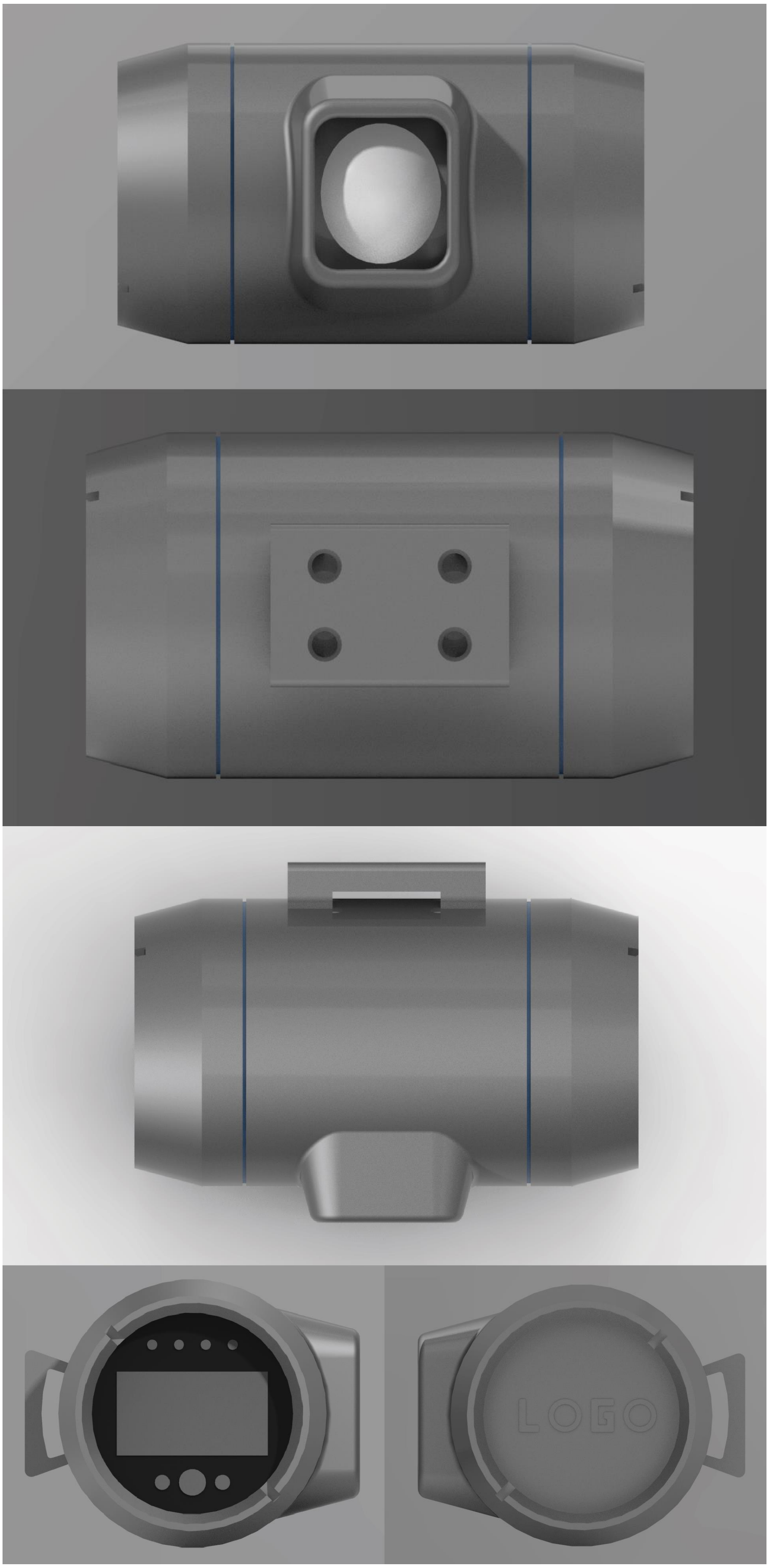



*Figure 5.20. The concept called the Lobe developed in ideation round 2.*

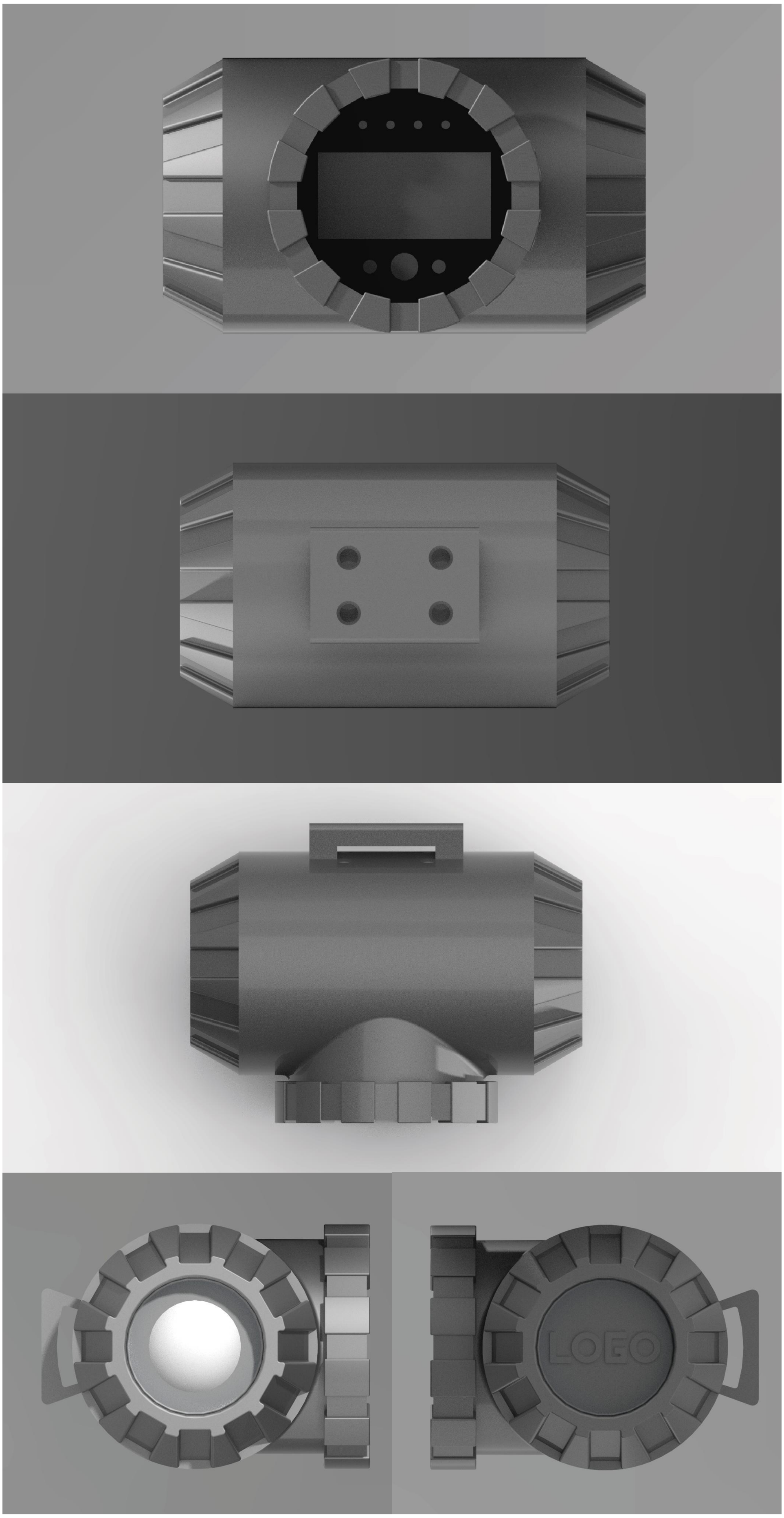



*Figure 5.21. The concept called the Hub developed in ideation round 2.*

**Feedback Session**

The third ideation round started with a feedback session, evaluating the three concepts presented in the second concept choice, as well as the attachment idea.

The attachment concept received positive feedback as it offered flexibility which the users valued high in the user studies. However, it was said that it was a very expensive solution to manufacture. If the attachment did not have cavities for straps or zip ties, the main body, without the lids, would be able to be cast in one single piece, making it much cheaper to produce. To solve the issue, an add-on piece could be created to offer the same flexibility but at a cheaper price.

The general feedback on the three concepts was positive, but most participants preferred the Cylinder. It was, according to the participants, the concept that expressed Emerson's design language the most and had the cleanest and most timeless design.

The Hub was the concept that seemed to be the most eye-catching. It was the one with the most reactions when presented, and words such as "robust", "durable", and "high-end" were used to describe the concept. However, it was also said that perhaps it reflects an application for which it is not intended to be used.

The Lobe got feedback that it looked plastic and was designed for a lower-end application than the others. A reflection was made that this could be due to the Rosemount blue color that was applied to present at least one concept in the company brand color. Other feedback mentioned was that it could be difficult to clean the area around the antenna, possibly disturbing the radar if too much dirt is gathered.

**Evaluation**

After collecting all the feedback, it was still not obvious what concept to move on with as they all had their pros and cons. Therefore, another evaluation round was applied.

The results from the semantic differential scale were compiled into a mean value and showed very similar results. The Hub got the highest rating, The Cylinder second highest, and The Lobe received the lowest rating. However, since they were so similar, it could have been difficult to differentiate the concepts. Since the participants got little to no information on the functionality of the concepts and were asked to use only their intuition when rating the design expressions, some words were a bit difficult to interpret. "Flexible" was one word that confused some participants, as the chosen antonym was "Rigid". To ensure the fairest comparison, after the feedback in the feedback session, all concepts were colored gray with blue details, see Figure 5.19-5.21.

It was decided that the results were not dissimilar enough to base a concept choice on it. In addition to the semantic differential scale, a concept evaluation matrix was also applied based on the design specification, Two different kinds of weight methods were used, but both showed the same results: The Cylinder got the highest rating, The Hub was rated second highest, and The Lobe received the lowest rating. However, much like the semantic word scale, the results were quite similar.

Based on all the feedback combined, the conclusion was that all concepts had their advantages and disadvantages, and with some refinement, either one could be chosen as the final concept. Therefore, the decision was based mainly on the favorites from the feedback session, as well as the favorite within the project group. Therefore, the Cylinder was picked as the concept to work further with in the last iteration.

**Ideation 3**

The third ideation round was based mainly on refining The Cylinder concept. Some things that needed to be addressed after the feedback session were:

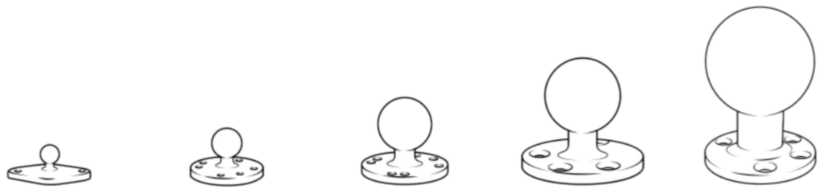
- Placement of a label
- Placement of an output connection
- Refining the attachment
- Making sure it can be waterproofed
- Defining the modularity
- Only having splines where the product is openable
- Making the display rotatable

The attachment was researched to find a standard snap-on solution as used for camera attachments. However, no standard for snap-on attachments was found. However, a tip received during the feedback session was to investigate

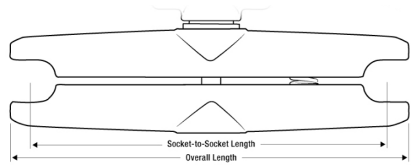
## SIZE GUIDE

Ball Sizes | Arm Sizes

The unique double ball and socket design allows you to adjust your mount to the perfect viewing or operating angle, all with the turn of a single knob. This modular design can be configured with a variety of interchangeable components to fit your specific mounting needs.



| A Size | B Size | C Size | D Size | E Size |
|---|---|---|---|---|
| **Holds .5 lbs** | **Holds 2 lbs** | **Holds 4 lbs** | **Holds 6 lbs** | **Holds 15 lbs** |
| 9/16" Ball | 1" Ball | 1.5" Ball | 2.25" Ball | 3.38" Ball |
| Trail Cameras | Phones<br>Action Cameras<br>Light Duty Tablets | Fishfinders<br>Heavy Duty Tablets | Monitors<br>Large Fishfinders | Heavy Monitors |




| Ball Sizes | | Short Arm | Medium Arm | Long Arm |
|---|---|---|---|---|
| A Size | Overall Length | N/A | 2.11" | 3.57" |
| | Socket-to-Socket Length | N/A | 1.67" | 3.12" |
| B Size | Overall Length | 2.42" | 3.73" | 6.00" |
| | Socket-to-Socket Length | 1.75" | 3.00" | 5.31" |
| C Size | Overall Length | 3.56" | 5.69" | 9.13" |
| | Socket-to-Socket Length | 2.50" | 4.66" | 8.00" |
| D Size | Overall Length | 5.10" | 8.44" | 12.98" |
| | Socket-to-Socket Length | 3.60" | 6.88" | 11.41" |
| E Size | Overall Length | 7.31" | 12.63" | N/A |
| | Socket-to-Socket Length | 4.98" | 9.88" | N/A |

*Figure 5.22. Ball adapters and arm lengths for RAM® Mount equipment.*

*Note. From RAM® Mounts equipment, National Products Inc, n.d.b. (https://www.rammount.com/). Copyright 2022 by National Products Inc. Reprinted with permission.*

a company, RAM® Mounts, that sold similar attachment products but made for industry instead of cameras. In this case, Emerson could collaborate with the company by selling the attachments together with the sensor.

On the webpage for RAM® Mounts (RAM® Mounts, n.d.a), there was a myriad of options, depending on the size and weight of the product that was to be attached, see Figure 5.22. The conclusion that was made was that the product should have a centered ¼"-20 threaded hole in the attachment on the sensor, and if the users would want a different sized product from the external company, there were adapters to be bought as well.

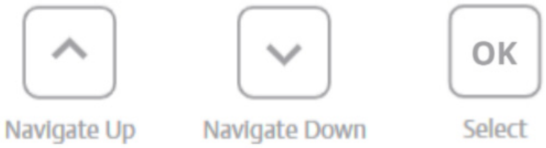



*Figure 5.23. The up and down navigation buttons, and the select button.*

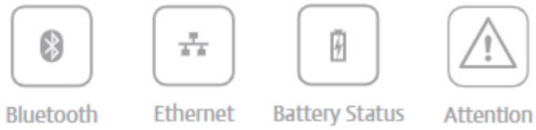



*Figure 5.24. The symbols positioned over the LED lights.*

**Lights and symbols**

As a last step, it was time to decide on the LED lights and symbols for the screen part of the product.

When deciding on the symbols for the buttons and above the LED lights, the Emerson Automation Solutions design guidelines (Emerson Automation Solutions, 2022a) were taken into high consideration to stick to company standards and provide continuity throughout the product catalog. The standard symbols used by Emerson were also considered universal enough to be used in the concept. For the chosen symbols for the buttons, see Figure 5.23. For the LED light symbols, see Figure 5.24.

When deciding on the LED light colors, the Emerson Automation Solutions design guidelines have been taken into high consideration as well to stick to company standards and provide continuity throughout the product catalog, see Figure 5.25.

One factor to take into consideration is color blindness. When evaluating the colors using the to the Adobe Color Accessibility tool (Adobe, n.d.a), the contrast between the different colors is color blind safe, see Figure 5.26.

## 5.3 Insights

In this chapter, the development of the final concept is presented. Three ideation rounds were conducted where the concept and ideas became more refined and detailed with every step. Below the main insights from this chapter are presented, that were a part of creating the final concept that will be presented in the next chapter, 6. Final Concept.

- Function & cost-driven design as stated by the users & Emerson
- Outsourced attachment options instead of Emerson producing their own
- Separate attachment for straps to offer a cheap mounting solution
- Flexibility is key for the design
- Design sticking to the Rosemount brand identity
- Accessibility through color blind safe colors & universality in symbols

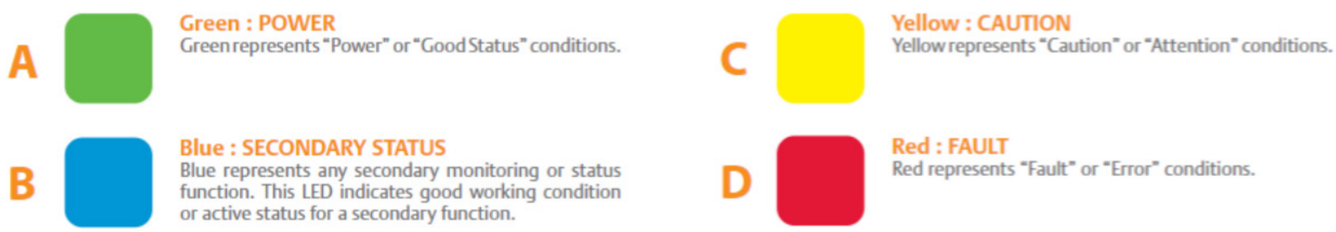



*Figure 5.25. The Emerson LED light status standards. (Emerson Automation Solutions, 2022b).*

*Note. From Emerson Automation Solutions, 2022. (https://www.rammount.com/). Copyright 2022 by Emerson Automation Solutions. Reprinted with permission.*

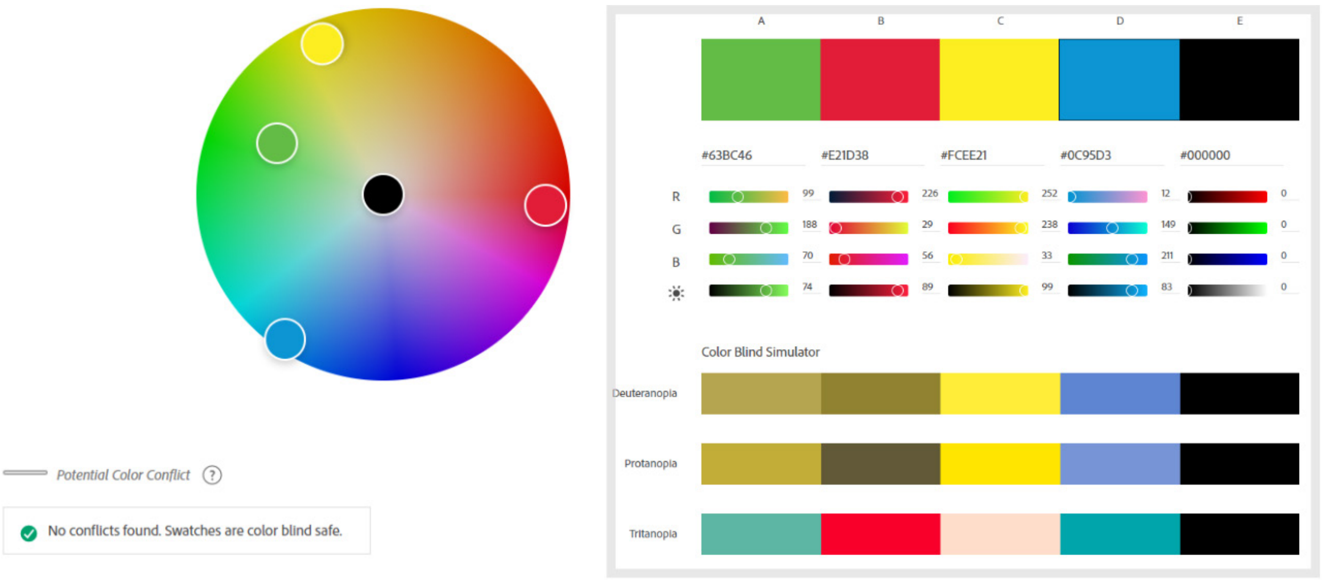



*Figure 5.26. According to the Adobe Verification Tool, the LED light colors are color blind safe (Adobe, n.d.b)*

*Note. From Adobe, n.d.b. (https://color.adobe.com/create/color-accessibility). Copyright 2022 by Adobe.*

Chapter 6

# Final Concept

**In this chapter, the final concept is presented along with its main features and product options, a review of the visual design and design language, and lastly, a case verification.**

## 6.1 Concept Overview

The final concept is a radar vibration monitoring device offering a lot of flexibility to its user. The design is compact, flexible, and durable. It has been designed to fit in the Emerson Rosemount automation solutions product catalog, but with a strong identity to differentiate itself and its own, new product family. The product is to be produced in aluminum with corrosive resistant paint in the Rosemount Blue color. In Figures 6.2 and Figure 6.3 on following pages, the main features are highlighted, in Figure 6.11 and 6.12 the concept is rendered into an industrial environment. In Figure 6.4 the main measurements are shown.

## 6.2 Features

The final concept is a radar vibration monitoring product with a flexible attachment and flexible application solutions. It can be customized depending on the need of the user. Below, the different features and functionality of the product is further explained.

**Splines**

Splines were added as a feature on the front lid over the display, as well as on the right lid to access the battery and ease putting components in during assembly, see Figure 6.5. The splines are placed to facilitate easy opening by placing a screwdriver or similar in two opposite splines and using the momentum to twist. The front lid has a glass to protect the display and is openable for the user to adjust and make settings on the display. By only putting splines where there is an openable part, mistakes are prevented.

**Display**

The display will be rotatable and have four different modes it can be put in so that the display is always in level regardless of the position of the sensor and direction of the antenna. It is connected by putting one of the four metal areas in contact with pins that are placed on the technology inside the housing, see Figure 6.1. Thereby the display can be rotated based on which angle the product is placed. To rotate it, the front lid has to be unscrewed, the display taken out, rotated, put back into contact with the pins, and lastly, screw on the lid again. The display part is also provided with three buttons to navigate the digital interface and LED lights to show operation status.

**Stability**

To make sure potential external factors do not affect the measurement, an accelerometer will be added to the sensor. This accelerometer will sense externally induced vibrations inside the radar, and then software will subtract them from the measured vibrations from the radar, only leaving the measured vibrations to be shown on the computer system.

**Status indication**

To be able to understand product status, lights have been added onto the display area, see Figure 6.6. The first symbol, attention, lights up and flashes in red whenever there is a fault in the product. The display will then show more details on what the fault is. The second light, battery status, will be green when the battery level is high. When the battery level is getting low, it will show either on the display or on the attention light. The third light, ethernet, will light up in

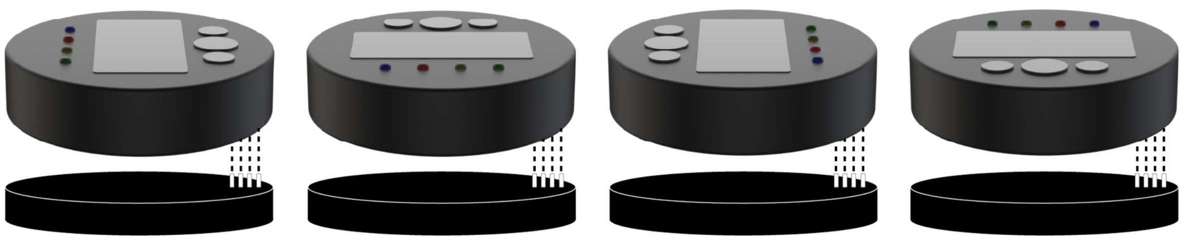


*Figure 6.1. The display can be rotated and placed in four different ways, by connecting the pins to the display (left).*

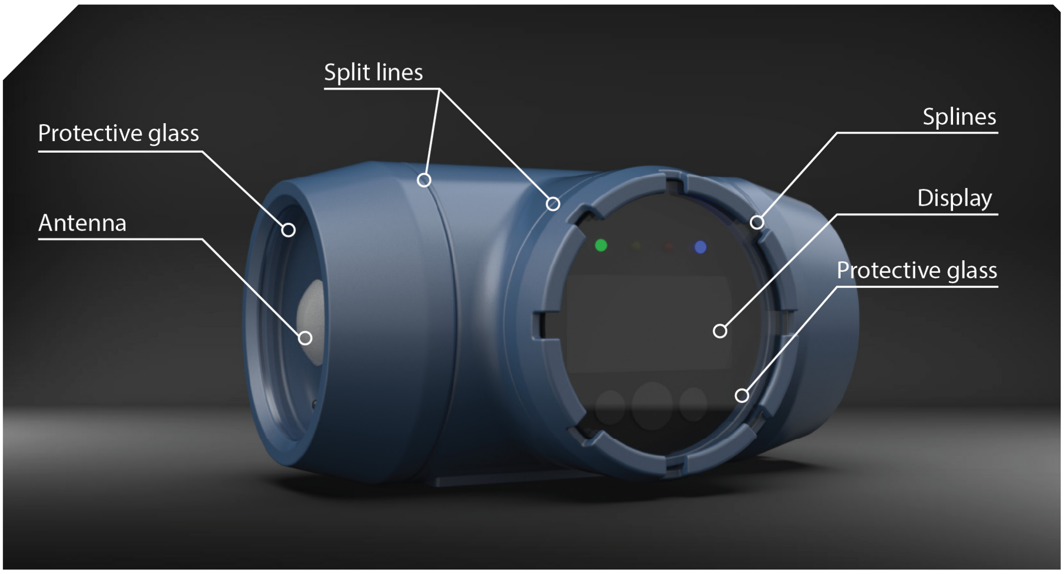



*Figure 6.2. Overview of the main features of the final concept.*

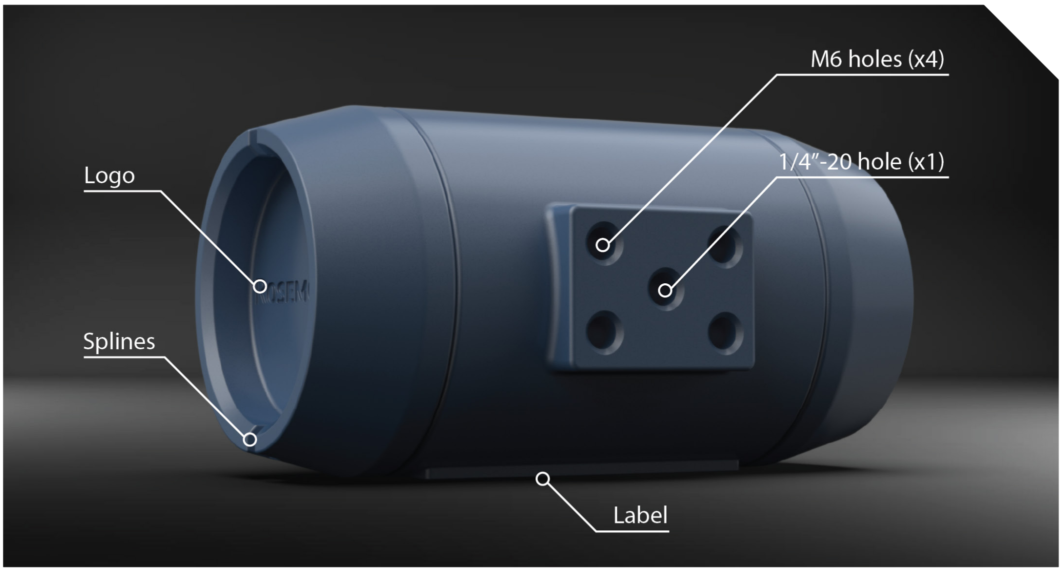



*Figure 6.3. Overview of the main features of the final concept.*


*Figure 6.4. The main measurements of the concept.*

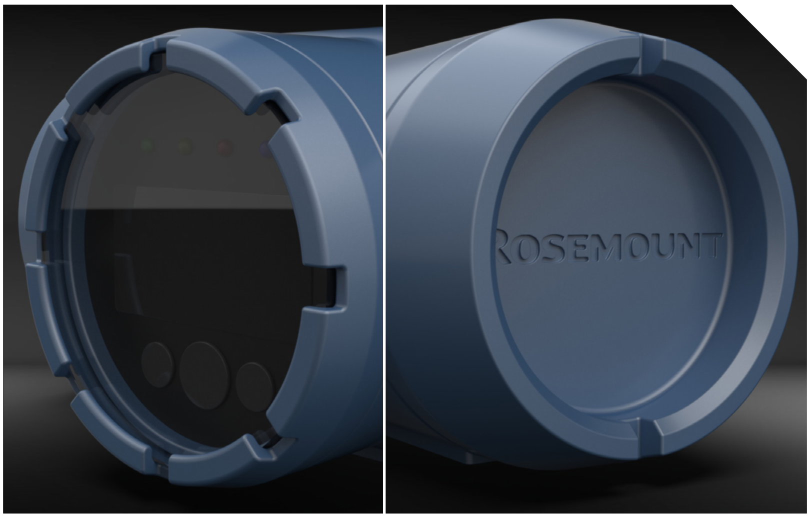



*Figure 6.5. Two splines are added to the battery lid (right) and eight splines on the display lid (left).*

*Figure 6.6. Lights are added to increase understanding of the product status. To the left all lights are turned off and to the right the battery status and Bluetooth connection are switched on.*

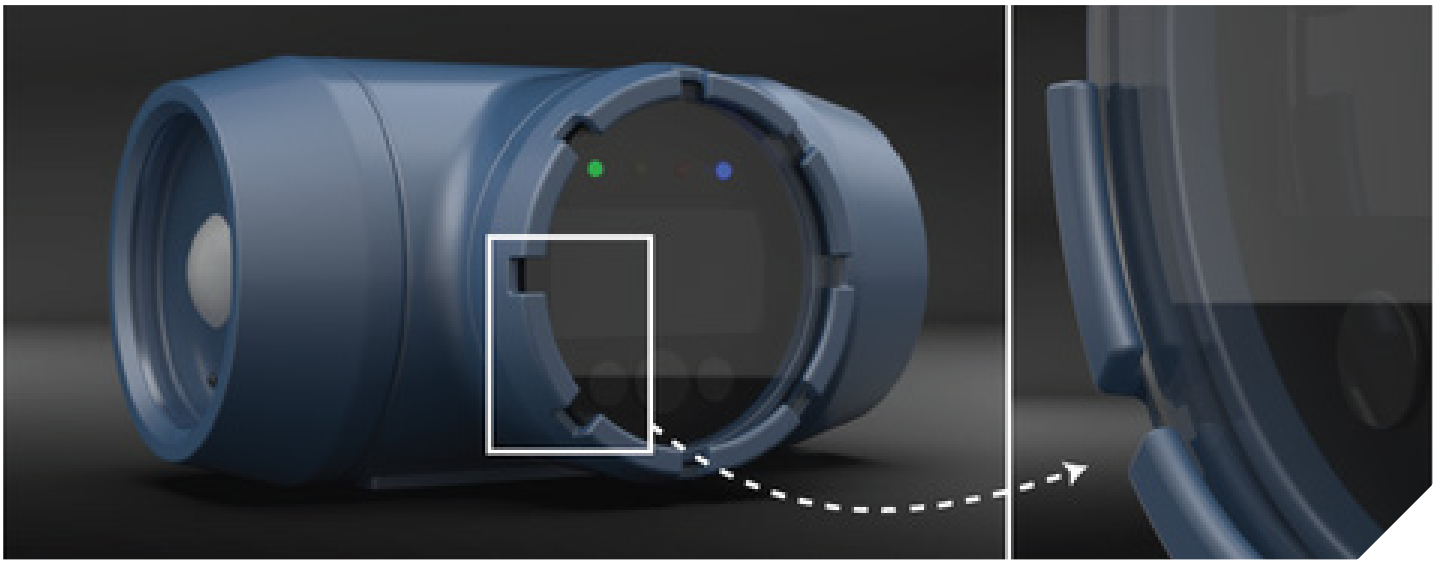


*Figure 6.7. A protective glass is put over the antenna (left) and the display (middle).*


*Figure 6.8. The wired option will have an input placed at the bottom of the product.*

*Figure 6.9. The M6 threaded holes with the ¼-20 hole for the camera attachment.*

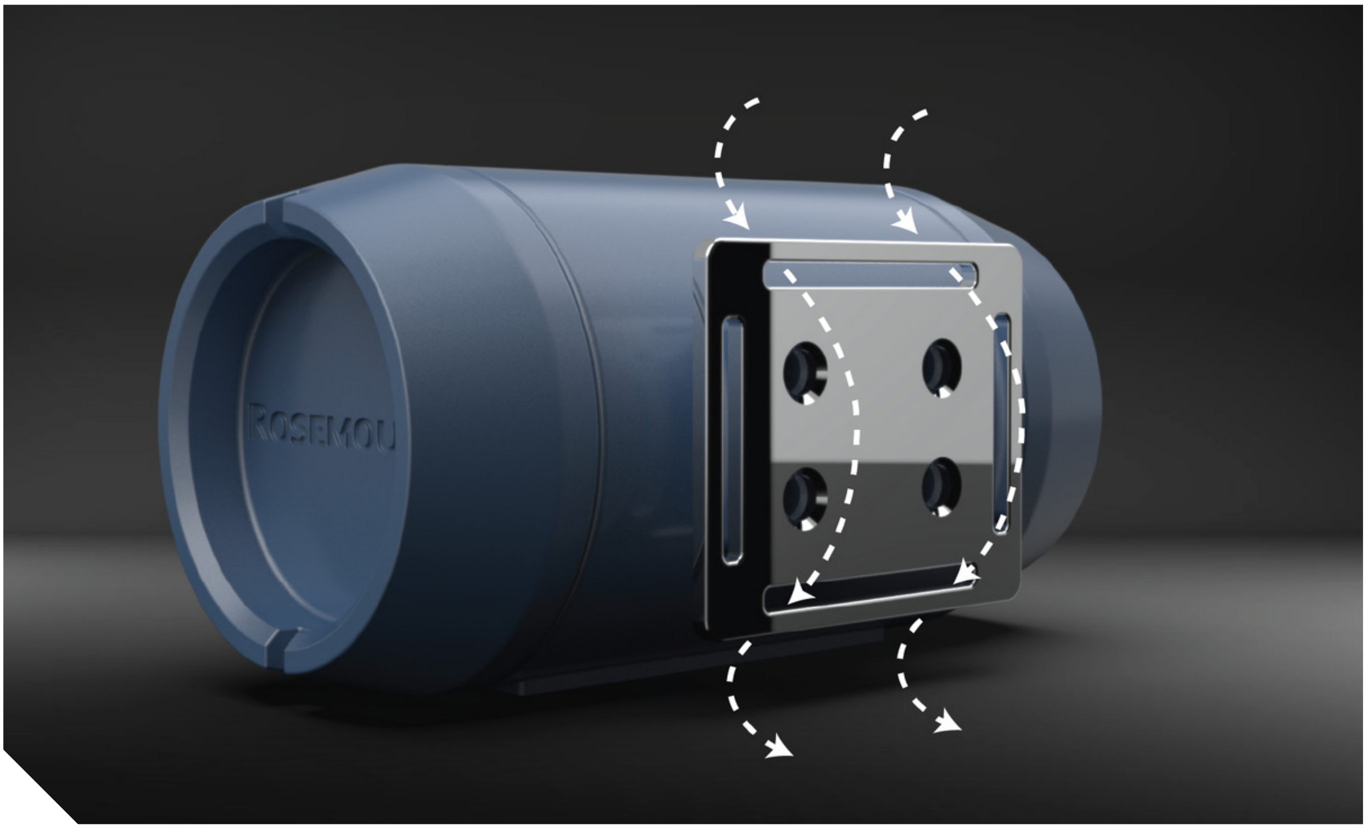



*Figure 6.10. The strap attachment.*

green when it is connected to the ethernet, and when there is a fault with the connection, the attention symbol will light up instead and more info will be shown on the display. The Bluetooth symbol will light up in blue when connected to Bluetooth, and blink when it is ready to connect, similar to other Bluetooth devices.

**Protective glass**
A protective glass has been added to the front lid as well as in front of the antenna, see Figure 6.7. The glass in front of the display is added to keep the sensor waterproof, while the user still will be able to read the display. The glass in front of the antenna is to protect it, as it can be sensitive and expensive to replace. Today's level measurement products do not have any protective glass; however, they are generally mounted once and then left on for their entire product lifecycle. Since this product is meant to be a more portable solution, this will likely be necessary.

**Waterproof**
An important part of the product to be able to use in all the use cases is to have it waterproof. To be able to achieve this, O-rings will be added to both lids. This is a common way of waterproofing products and is used in Emerson's products today.

**Inputs**
Depending on what model the user chooses to buy, there might be a wired input on the product, see section 6.3 Product Options. This will be placed on the bottom of the product together with a label, see Figure 6.8. Wiring will allow for easier continuous measurement.

**Label**
An information label, containing all important information by Emerson will be placed at the bottom of the product to be visible to the user, see Figure 6.8.

**Reflector**
To get a strong signal from the radar and ensure the correct point is being measured in the same position each time, a reflector is needed. This will be provided along with the sensor. At each desired measuring point, a reflector will be mounted by, for example, drilling, welding, or gluing it. The design and functionality of the reflector has not been developed in this project as it is outside the project scope.

**M6 threaded holes**
There are four M6 threaded holes placed on the sensor attachment, see Figure 6.9. The purpose is to offer the option to screw the sensor directly onto something.

**Strap attachment**
If the users want to use straps or similar to attach the sensor easily and semi-permanently, they can choose to buy a strap attachment, see Figure 6.10. It is a flat metal piece with the same hole pattern as the sensor. It has four cutouts where a strap can be inserted and then attached around, for example, a beam or pipe. Since it is just a flat piece of metal, it can easily and cheaply be produced and be sold as a cheaper option for the users instead of the costlier camera attachment, see below.

**Camera attachment**
A camera attachment can be used whenever it is necessary to direct the radar. This could be when, for example, a measuring point is located 45 degrees off from a wall, not making it possible to place the sensor parallel or perpendicular to the wall. One option for Emerson is to buy camera attachments with modular camera mount adapter and arms from the external company RAM® Mounts which specializes in modular industrial mounting, see an example in Figure 6.13. This is probably a cheaper and easier solution for Emerson instead of producing their own ones. The camera adapter is attached with a ¼"-20 threaded screw that is attached to the middle hole of the sensor's hole pattern. The camera attachment is permanently mounted onto, for example, a wall, and the sensor can then be installed there permanently or just for a short while. It is then possible to direct the radar in whichever direction is desired, making it possible to measure several different measuring points in the production site from one starting point. There are also different lengths of the arms, where a longer arm offers more degrees of directing the radar.

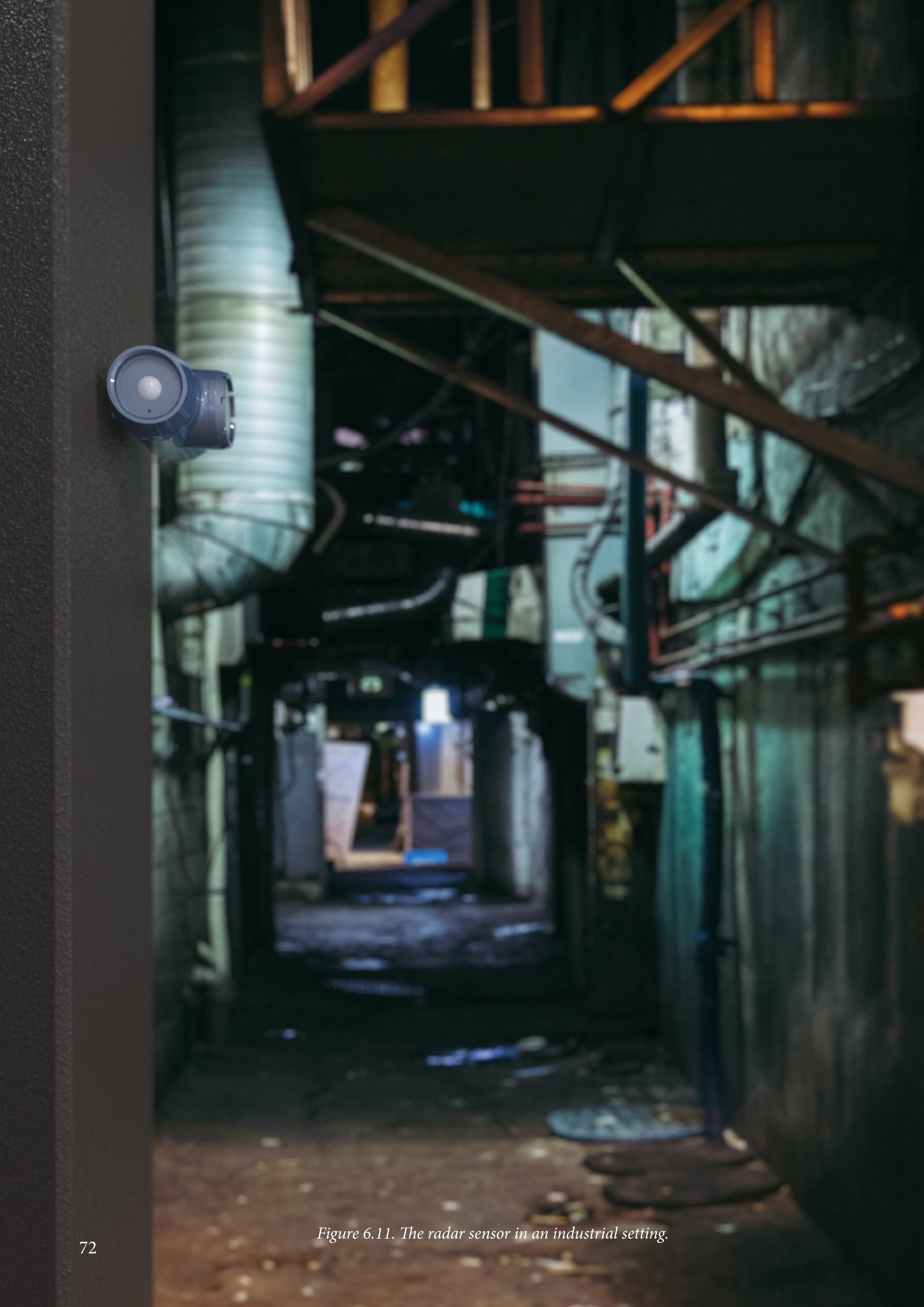


*Figure 6.11. The radar sensor in an industrial setting.*

*Figure 6.12. The radar sensor in an industrial setting.*

*Figure 6.13. A RAM® Mount attachment that could be used with the product.*

*Note.* From *RAM® Tough-Ball™ with 1/4"-20 x .25" Threaded Stud*, by RAM® Mount, n.d. (https://www.rammount.com/part/RAP-B-379U-252025). Copyright 2022 National Products Inc. Reprinted with permission.

## 6.3 Product Options

As a way of making the product flexible, a suggestion is to offer different ways of modularity when selling the product as the user need varied a lot from site to site. Three main concept options should be available, as well as different attachment solutions.

**Sensor options**

*Wired sensor*

- No battery
- No Bluetooth
- With wire input

*Wireless sensor*

- With battery
- With Bluetooth
- No possibility to wire

*Both*

- With battery
- With Bluetooth
- With wire input

With these different solutions, it will be possible to offer greater flexibility for the users, see the options in Figure 6.14. The wired version will be cheaper, since it will not require a battery,

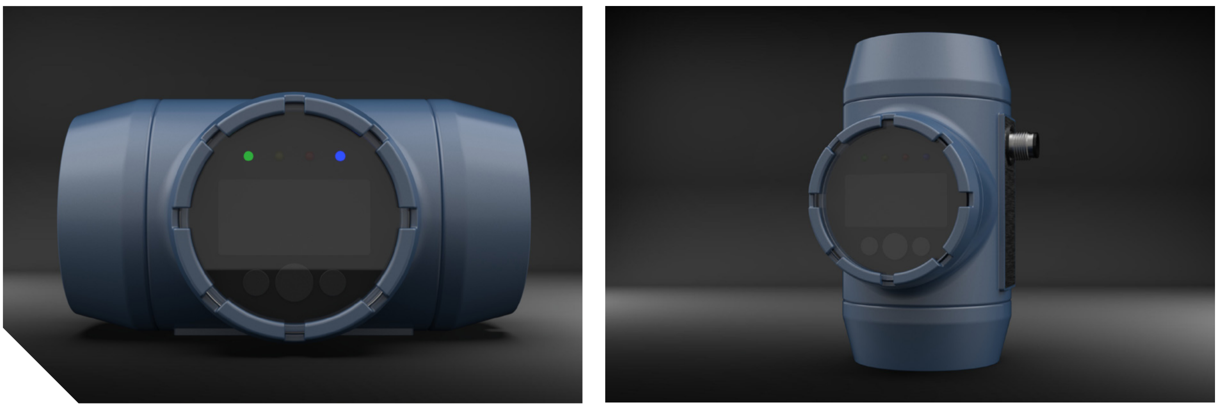


*Figure 6.14. The wireless sensor (left) and the wired sensor & combined (right).*

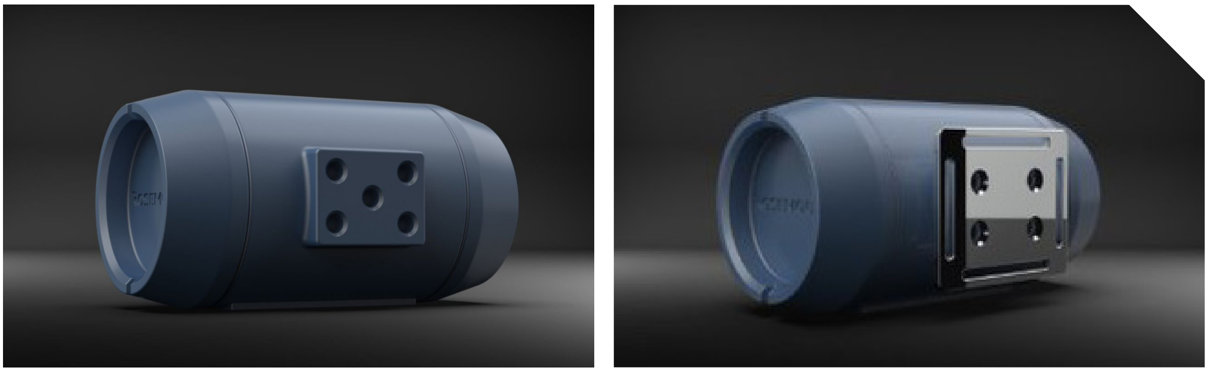


*Figure 6.15. The M6 holes with the ½"-20 hole for the camera attachment (left) and the strap attachment (right).*

and can be used completely permanently for continuous measuring as well, however, wiring can become expensive. The completely wireless version can only be connected via Bluetooth and be powered by a battery, and therefore becomes a more portable solution and avoids the costs of wiring. However, the most flexible version would be the product that offers both power via battery and connection to Bluetooth, as well as connected via wire. In that case, the product can be used to measure continuously more permanently and be used as a more portable solution. However, this version will be the most expensive option. Based on the needs and pre-conditions the users can choose the option that fits their production site the best.

With the different product options, the LED lights on the screen interface will be adapted to the available features of that specific product version. For the the screen LED lights, see Figure 6.16.


*Figure 6.16. The LED lights indicating status. From left: (1) status, (2) battery, (3) wire connection, and (4) bluetooth.*

**Attachment options**
The different attachment options are:

- M6 threaded holes
- Straps attachment
- 1/4"-20 thread camera attachment

The attachment solutions will be, as previously mentioned, to use screws to mount the product directly onto something, buy the separate straps attachment, or buy the camera attachment, see the first two options in Figure 6.15. Based on the conditions each production site has, the users can choose what will create the most value at their specific site. When it comes to the camera attachments from RAM® Mounts, there is additional modularity to choose from by picking arm length, camera mount size, number of adjustments, and more.

## 6.4 Visual Design

Throughout the design process, it was important to stick to the Emerson and Rosemount brand identity. The design attributes were partly inspired by the design guidelines, but also the design format analysis. The most important attributes for the brand characteristics can be seen in the design format analysis in Figure 5.9.

**Color scheme**
Today, the Rosemount products come in Rosemount Blue as its primary color, see Figure 6.17. Therefore, it is natural for this new product concept to also come in the same blue color as it is highly characteristic of the Rosemount brand and their brand identity. In addition, the color pops and catches the eye in an industrial setting.

This makes it easy to find in its environment, which was one of the guidelines in the design specification.


*Figure 6.17. Rosemount Blue.*

**Glossy finish**
The product has a glossy finish to match the Rosemount product catalog. This also adds to the premium expression of the product.

**Symmetrical shape**
Much emphasis was put into keeping the shape symmetrical as that is a strong characteristic of the current product catalog. As seen in Figure 6.18, the product has a two-dimensional symmetry from the front view. In addition, the two cylinder ends have been designed to have the same shape on both sides, although they both have different functions: one side stores the antenna with a protective glass, while the other end is openable for the user to access the battery compartment. Another symmetrical detail is the splines on the lid to the battery compartment. As only one of the cylinder ends is openable, only one of the ends has splines for functional reasons. This makes for an asymmetrical design but has been solved by only adding two discrete splines to the design, not visible from the front view.

**Rounded edges**
The characteristic of the Rosemount products is that they all have rounded edges to varying degrees. However, the design trends have moved more and more towards an angular expression. When designing the product, the focus was on combining rounded and angular expressions into the design. The product is quite angular in its shape with small round radiuses along each edge. At the same time, the cylindrical shape adds to a smoother and more rounded expression.

**Cylindrical shape**
Characteristic of the Rosemount products is that they all have a cylindrical shape in one way or another. Therefore, it was important to stick to the cylindrical form language. Although it was experimented with different shapes early in the design process, it quickly became evident that the cylindrical shape more or less was crucial to maintain the Rosemount brand identity.

**Splines**
Although the splines have a highly functional purpose in Rosemount products, they are also, according to the design format analysis, characteristic to the brand. However, as splines communicate functionality to the user, a lot of

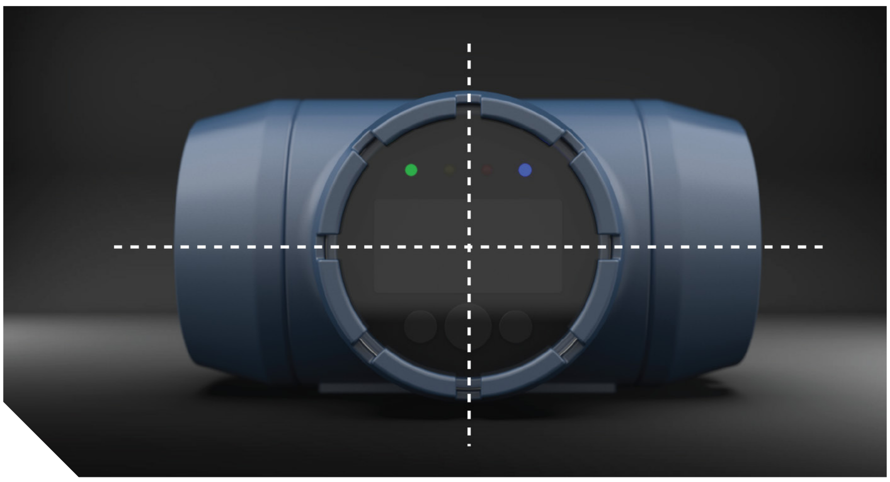


*Figure 6.18. The product has a two-dimensional symmetry from the front view.*

thought had to be considered when incorporating them into the design. Only one of the cylinder body ends is openable, meaning splines are only necessary on one end. To maintain symmetry, only two discrete splines were added to that side. Instead, emphasis was put on the screen frame where more prominent splines were added to incorporate the characteristic splines for the Rosemount brand. As this part of the product is interactable, it made sense to emphasize its functionality together with the brand characteristic splines.

**Split lines**
Although split lines in most cases have a functional purpose, they can also be added to the design by sectioning off a product's body, interrupting form continuity, and adding visual interest. Visible split lines have been added to the produc.

## 6.5 Case Verification

In chapter 4.2.5 Use cases, three potential use cases were presented where there was a need for radar vibration monitoring. In this chapter, the three cases will be looked at again to make sure the final concept solves the problems that were stated.

**Case 1**
In the first case, there was a need for a wireless, waterproof product, with a stable attachment. The completely wireless version or the version with both wireless and wired options can be used. Either the camera attachment or screws can be used to make it stable, and if it were to vibrate a little, the accelerometer on the inside will subtract those vibrations from the total measured value. By attaching reflectors to several places, the product can be left to measure several points at once, troubleshooting where the vibrations are coming from.

**Case 2**
In the second case, the company preferably wanted to do regular inspections with a handheld accelerometer but could not. With this concept, it would be possible to have a permanently placed camera attachment to a wall nearby, where the sensors are quickly snapped on when a measurement is to be taken. Either a wire can be installed close to the attachment, or the product can be used completely wirelessly. See an application example in Figure 6.19.

**Case 3**
The third case could, similar to the other cases, have an attachment placed permanently nearby and have the sensor be snapped on quickly when doing inspections. If it is only that a machine starts sounding as if vibrations increased, a more flexible attachment could be used to measure continuously for a short period.

*Figure 6.19. The product rendered in a production site measuring vibrations several meters from the ground.*

*Note. Adapted from Production line for packaging cut greens in an urban farm, by P. Magera, 2021 (https://unsplash.com/photos/KR9j7uqFhnI).*

## Chapter 7

# Discussion

**In this chapter the results including the final concept and the market are discussed, as well as the methodology used and sustainability consequences. In the last chapter, future recommendations for Emerson's continuation of the development are presented and discussed.**

## 7.1 Final Concept

The final concept was decided on after several evaluation steps. It was discussed whether The Hub would be a better option, as it was evaluated as an eye-catching and expressive concept when presented during the feedback sessions. To stand out in a product catalog was a part of the design specification. However, the eye-catching design of The Hub was not necessarily only positive. It was seen as extremely robust and potentially a high-end product, something that might scare off companies not having harsh environments in their production or are looking for a cheaper alternative. It is important that the product's expression reflects its price point. Furthermore, the chosen final concept has a more neutral expression in comparison to the Hub; the design is cleaner, sleeker, and more timeless due to its simpler design details.

The Rosemount blue was chosen for the concept as it has a very strong brand identity, among other important expressions. However, it can also be perceived as cheaper than other colors, as it can look less premium than other colors, for example, gray. A gray product would have likely expressed more of the premium, high-end expressions, but at the same time would not have fulfilled the requirements of being eye-catching. As this was seen as an important factor during the interviews, it was seen as more important to fulfil that requirement than having a more premium-looking color. For future products, it can be investigated whether the product should keep the blue color or if gray could be an option. In addition, the colors and the size of the product would need to be investigated further and tested in context with its users, to make sure it is the optimal size of not being too bulky to carry around, but not too small to be lost in production. Size also matters when it comes to mounting the product within the production area, as it needs to be small enough to fit in narrow spaces.

An advantage, as well as a drawback of the concept, is its attachment solutions. It offers great flexibility as the user can choose what attachments are best to use with the products. If one can find a spot to put the directable camera attachment for the sensor to detect several measuring points at the same time, this would make inspections a lot easier as the operator can measure several points from the same spot. However, if no such spot can be found, the user would need to install several attachments around their facility which quickly could become expensive. In these cases, there are other cheaper attachment options that offer flexibility such as the strap attachment. Here, support is something Emerson should provide their user to make sure they can install the correct attachments in optimal locations.

Furthermore, the display was chosen to be incorporated into the product as this was described as valuable and desired by the users. However, it was also mentioned by the users that the displays are rarely looked at apart from making sure the measuring value is acceptable then all the analysis is done via a computer. An alternative solution is to only use diodes to show if the measurement value is acceptable. However, this would mean the users would have to have great trust in the software as the product needs to be accurate enough to analyze the data well enough to make that judgment. This could be a challenge for such a novel product on the market as users might already be skeptical of it but could potentially be investigated for a future lower-end display-less product.

Another realization during the user studies was that it was difficult for some users to visualize how they would use this kind of product as there is no similar vibration monitoring technology on the market today. This could potentially be challenging for Emerson when the product is initially launched as they would need a lot of marketing to convince the users of what value the product would bring them. However, as with all new technology, there will be early adopters jumping at the opportunity to try new technology, and there will be laggards that need to see others use the product and be happy with it before trying it themselves.

Looking at sales, a disadvantage with a portable or handheld unit is that it could potentially result in fewer sales, as companies only need one or a few units. From a supplier business perspective, it would, of course, be more enticing with a product that a customer would buy many units of. However, for a customer to buy many units it would also need to be a convincing product that the users see great enough value in. However, as radars generally are more expensive compared to accelerometers, it is believed that this is the right business model for a product of this kind as a radar vibration monitoring device will not compete against the cheaper and popular accelerometers. Instead, this product should be marketed as a premium complement to accelerometer which offers flexibility as it can be used for semi-permanent measuring as well as troubleshooting.

To sum up, the concept did fulfill most requirements and guidelines stated in the design specification. Many of them were solved by added features, such as the camera attachment to offer easy direction of the radar. Flexibility is also offered by enabling the customer to customize the product by, for example, picking if they want it to be wired or wireless. Flexibility has been a keyword throughout the entire project and was kept in mind when adding features and customizable product options. By adding the mentioned options and features, the vision is to offer a product solution the users will be able to use for as many applications as possible in many kinds of facilities.

## 7.2 The Market

It was emphasized at the beginning of the project to keep an open mind towards finding a different market than what was initially thought of by Emerson, which was monitoring pipelines. There is still a possibility of using this product there, however, there has to be more research done specifically on pipes to make sure that it is possible. The reason Emerson chose piping in the pre-study was that those industries are part of their brand Rosemount's existing clientele. The market of companies that have problems with vibrations in pipes is quite narrow and could be more difficult to penetrate than the market of companies that have rotating equipment as bearings, for example, are present in almost every production facility.

Had the project only interviewed users with problems in pipes, the final concept would likely have been very different from this final concept. It would likely not have become the same flexible solution that can be applied to a myriad of industries, but rather a more permanent monitoring system that gives alerts when vibrations increase. This could be a potential area for a future product in the same product line as this concept but needs to be investigated further.

As found in the project pre-study, radar-based vibration monitoring have been studied in the literature today but no available products on the market could be found. However, this raises questions about why there are no existing commercial products on the market today. There could be several reasons for this - one potentially being that companies do not see the value of developing such a product, as the solutions available today are quite popular. It can be challenging for a company to be first on the market with any product, and here Emerson has the benefit of already having radar technology as their area of expertise and the technology needed already on the market.

The market gap that was found in monitoring rotating equipment where today's solutions are not satisfactory is quite a broad market. It is also not necessarily targeting the customers Rosemount has today or has historically had. This is a great business opportunity for Emerson that can find new customers in a new area but will at the same time require some effort.

## 7.3 Methodology

This project was, according to the project brief, a very research-based project, meaning that phase 1 was prioritized higher in the project than phase 2. This means that Emerson will have a broad base when making decisions about this product in the future, however, it also means that they have a less developed product to continue developing. There could have been some methods that would have enriched the product, had more priority been put on the second phase from the beginning. For example, verifying the concept with users would have created bigger certainty in how the concept fulfills the requirements. However, as it was difficult for the users to visualize vibration monitoring with radar already in the user studies, there is a risk that involving users in evaluating the concepts might not have had as much feedback as involving people with greater insight in the project and its possibilities. Considering the scope of the project and the demarcations that were made, the evaluations that were made were considered the best choice.

The user studies were divided into two parts to first gain an understanding of the market and the problem in order to leave it open to potentially interviewing other companies in the second round. However, considering the results, it would have been possible to conduct both interviews at once, making the process more efficient. However, it is believed the right choice was made, as it gave a great understanding of the problem and the opportunity of asking more in-depth questions in the second round.

The user studies incorporated some company visits as well, showing very different production sites. It was challenging to book the company visits as the beginning of the project was still affected by the Covid-19 pandemic, limiting potential visits. However, as the world is more adapted to digital solutions, perhaps it could have been of value to perform digital visits in the future.

Since the users mainly saw value in functionality over looks, the concept was ideated in two parts: functions, expression, and design to fit into the Emerson product portfolio. Fitting into the Emerson product portfolio was a challenging process, as it turns out that most of the products available today were created by function-driven design. Which meant that many of the characteristics of the products were only there to serve a function. This made it challenging to make the product "look Emerson". However, with the evaluating steps and ideation methods that were used, the concept looks to fit inside the portfolio.

Overall, a design thinking approach was applied to structure the project which worked very well. During the process, no clear process was used, but rather just following the workflow that felt the most natural. It was not until afterward it was realized this was the approach that was used. The first and second stages of understanding and defining the problem became the parts where the most focus was placed. However, the design thinking process was a part of the ideation phase as well, considering the divergence and convergence between the different rounds. There is a myriad of ways to plan the project process, depending on the characteristics of the project. In this particular case, the design thinking process is a great way to structure and visualize the work.

## 7.4 Future Recommendations

This project was a research-heavy project, emphasizing the discovery of the needs of the users and problems of vibration monitoring today. Due to this, less focus was put on the development of the concept, meaning that there still are topics that need to be researched further. This chapter presents next step recommendations for Emerson to consider when continuing to develop the product further.

A challenge in this project has been to make sure the radar is stabilized enough to not affect the measurement. This could potentially be solved with a stable attachment solution and/or incorporating an accelerometer in the device to subtract potential external factors. By modifying the software, some external vibrations can be filtered out. A future research question for Emerson would be to see if this would be enough to stabilize the device, or to see if it is possible to solve the external vibration issue at its root. If the attachment can make sure the radar is not affected at all by external vibrations, the accelerometer would not be needed inside the device.

An important next step is to create a prototype to test the product with the users. This is important to make sure the product fulfills all requirements in the design specification in context, both when it comes to the hardware as well as the software. Preferably, the product should be tested in different production sites to make sure it is flexible enough to be used in most production sites. One challenge is to make sure the radar can be positioned in such a way that the radar signal can reach the desired measuring point(s), and that the device is not significantly disturbed by external factors such as structural vibrations.

As this concept would be the first product of its kind to measure vibrations using radar, there are great possibilities for Emerson to create a whole new product family. Something to investigate for further products in the vibration product family is if there is a need for other classifications on the devices. For example, Emerson should research if there should be an explosion classified vibration monitor, one adapted for more harsh environments, and/or if there should be one specifically suited for hygienic applications. Another market to investigate is if there is a demand for low-end and high-end options as well.

During the project, the conclusion was made that reflectors are required and should be a part of the product solution as well to receive a strong enough signal. The results showed that the users do not mind attaching the reflectors permanently to their machines. However, the best way to attach a reflector is still to be investigated. The design of the reflector to optimize attachment and signal reflection is also an area that needs to be investigated further.

Some different versions of the product were presented in chapter 6.3 Product Options. However, to maximize flexibility in the product, it could be further investigated if even more modularity would create value for the users. For example, what could be investigated further is if the product should have different sized batteries and thereby different sized lids.

The software is already under development, however, there still needs to be some development to make sure the product follows the guidelines presented in chapter 4.2.9 Design Specification. During the user studies, it was found that compatibility, usability, and user experience of the software are equally, if not more, important than the actual hardware.

Support was mentioned by the users as something very important and a considerable factor when picking suppliers. Emerson should investigate whether this should be a service to provide the users buying their vibration monitoring products.

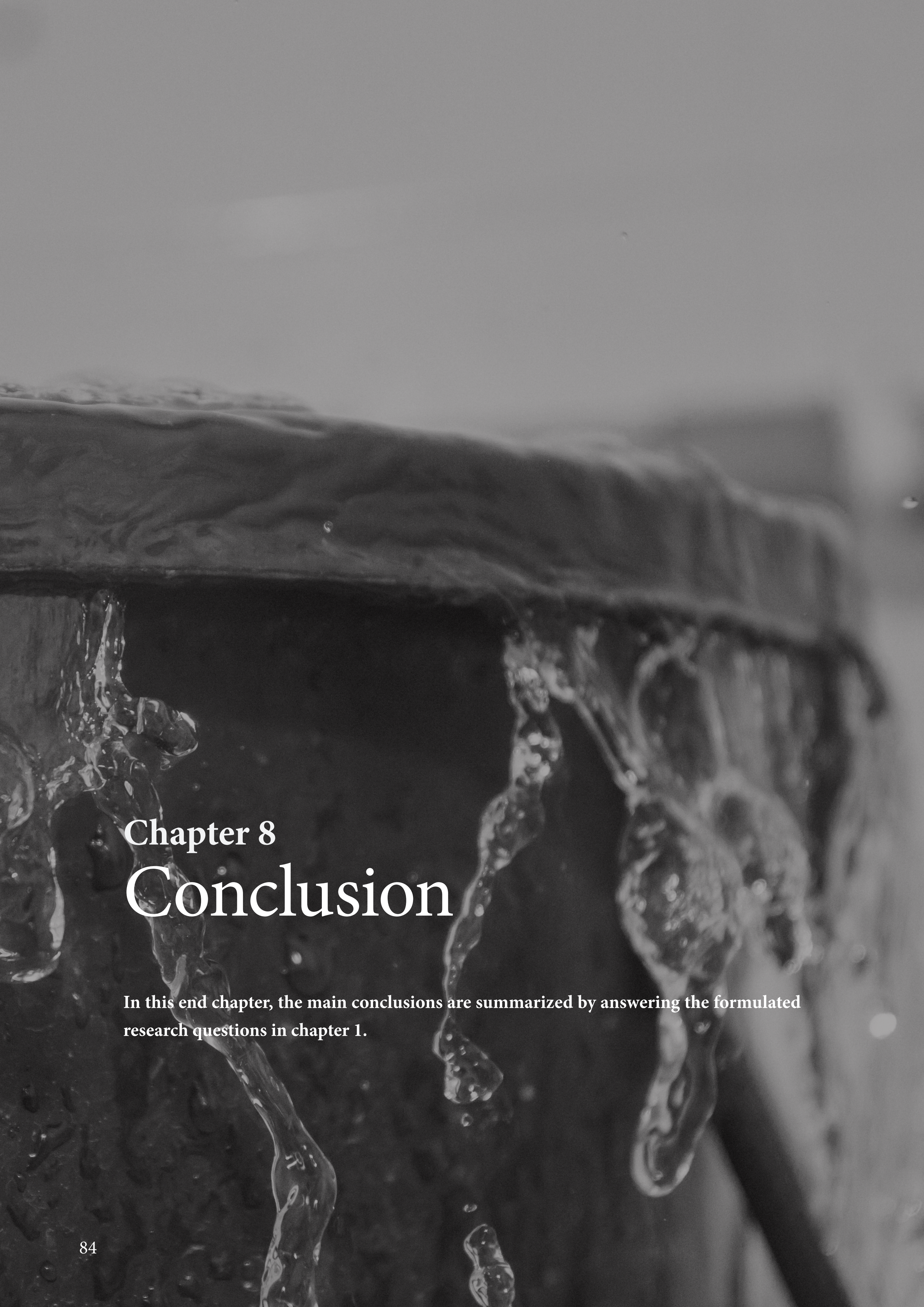
A possibility mentioned in chapter 4.2.8 SWOT Analysis was that the product potentially could be used to measure deformation as well as vibration. A future development area for Emerson is to study the need for deformation monitoring in combination with vibration monitoring and investigate if and how it should be implemented in this concept, or perhaps if it should be another product in the vibration monitoring product family.

## 7.5 Sustainable Development & Ethical Considerations

This concept will be able to close a gap where current vibration monitoring solutions are not sufficient today. Vibration monitoring and monitoring of machines, in general, can be seen as very positive for the environment as components can be replaced when they break or are about to break, instead of at a specified time interval. This could reduce the number of components having to be discarded when they are still possible to use and increase the life length of many components and machines. Furthermore, when measuring continuously, it is sometimes possible to know what the cause of the vibration is, for example, it could just be a bearing that needs to be relubricated.

Vibration monitoring can have economical winnings as well. As monitoring means a component can be replaced before a break down, it can avoid stops in production. This is of course great for the company in question, which can plan their maintenance stops better. Thereby they can avoid costly stops, but it is also beneficial for the whole society when it comes to, for example, the food or power industry as those deliver vital resources for all households.

When looking at ethical considerations, however, no significant ethical aspects could be identified connected to the study or concept.



# Chapter 8
# Conclusion

**In this end chapter, the main conclusions are summarized by answering the formulated research questions in chapter 1.**

- **Why is vibration monitoring needed in an industrial setting?**

Vibrations are a problem since they may cause damage to products and machine components that can cause a stop in production. An unplanned stop in production could quickly become very costly for a company, not rarely up to millions of SEK. With proper vibration monitoring, failure can be anticipated months in advance

- **Where is vibration monitoring needed in an industrial setting?**

Rotating equipment in production sites creates vibrations and needs to be monitored as they might damage machine components or affect product quality. Rotating equipment can be, for example, bearings, turbines, or fans.

- **What market gap exists for vibration monitoring with radar today?**

An area where vibration monitoring solutions are not satisfactory today is the monitoring of rotating equipment in hard-to-reach areas or extreme or dangerous environments. This can be, for example, equipment positioned in the ceiling or machines placed in extreme heat.

- **What needs and requirements do the users and context pose in a vibration monitoring product?**

It is of great importance that a product in this market gap is flexible and reliable. It should be able to fit into many applications as production sites and user needs might vary a lot. It should also offer accurate and reliable measurements.

- **How could a product be designed to fulfil these needs?**

The concept is designed with a flexible attachment, is customizable to the user's specific needs, and comes in a small size to fit into many applications and areas. The product design and features as well as the software guidelines will provide

# References

Adobe. (n.d.a). *Accessibility Tools: Color Blind Safe*. Adobe Color. https://color.adobe.com/create/color-accessibility

Cappellini, A., Cigada, A., Vanali, M., Leva, D., & Rivolta, C. (2014). *Advantages and drawbacks in the use of non-contact radar techniques to perform dynamic measurements.* Journal of Civil Structural Health Monitoring, 4(4), 303–311. https://doi.org/10.1007/s13349-014-0080-9

Carpio, J. N., Cruz, F. R. G., & Chung, W. Y. (2016). *An earthquake activated power interrupting device using a triaxis accelerometer.* 2016 IEEE Region 10 Conference (TENCON). https://doi.org/10.1109/tencon.2016.7848464

Cîrlanaru, A., & Ionescu, S. (2020). *Employee Perceptions of Vision.* FAIMA Business & Management Journal, 8(4), 64–74.

Cruz, F. R. G., Garcia, R. G., Manait, K. J. B., Jastillano, W. J. D., Guzman, D. J. L., Manebo, M. B., Payawal, J. M. G., & Uy, F. A. A. (2018). *Structural Health Monitoring of Footbridge Using Wireless MEMS Accelerometers With Fast Fourrier Transform.* 2018 IEEE 10th International Conference on Humanoid, Nanotechnology, Information Technology,Communication and Control, Environment and Management (HNICEM). https://doi.org/10.1109/hnicem.2018.8666353

Ding, L., Ali, M., Patole, S., & Dabak, A. (2016). *Vibration parameter estimation using FMCW radar.* 2016 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP). https://doi.org/10.1109/icassp.2016.7472072

El-Zahab, S., Mohammed Abdelkader, E., & Zayed, T. (2018). *An accelerometer-based leak detection system.* Mechanical Systems and Signal Processing, 108, 276–291. https://doi.org/10.1016/j.ymssp.2018.02.030

Emerson Automation Solutions. (2022a, February). *Design Language Guidelines* (Rev 2.03). Emerson Automation Solutions.

Flores-Colen, I., & de Brito, J. (2010). *A systematic approach for maintenance budgeting of buildings façades based on predictive and preventive strategies.* Construction and Building Materials, 24(9), 1718–1729. https://doi.org/10.1016/j.conbuildmat.2010.02.017

Gomathi, K., Ganesh, T., Bharanidharan, J., Arvindh Prajathkar, A., & Aravinthan, R. (2021). *Condition Monitoring of 3D Printer Using Micro Accelerometer.* IOP Conference Series: Materials Science and Engineering, 1055(1), 012035. https://doi.org/10.1088/1757-899x/1055/1/012035

Guan, S., Rice, J. A., Li, C., Li, Y., & Wang, G. (2015). *Dynamic and static structural displacement measurement using backscattering DC coupled radar.* Smart Structures and Systems, 16(3), 521–535. https://doi.org/10.12989/sss.2015.16.3.521

Han, B., Tan, D., Jiang, Z., Li, L., & Zhu, X. (2013). *Monitoring of vortex-induced vibration based on fiber Bragg grating technology for pipelines subjected to flood impacting.* Proceedings of the 32nd Chinese Control Conference, 7357–7360.

Ismail, M., Dziyauddin, R. A., & Salleh, N. A. A. (2015). *Performance evaluation of wireless accelerometer sensor for water pipeline leakage.* 2015 IEEE International Symposium on Robotics and Intelligent Sensors (IRIS). https://doi.org/10.1109/iris.2015.7451598

Jamieson, S. (2017, September 27). *Likert scale.* Encyclopedia Britannica. https://www.britannica.com/topic/Likert-Scale

Jin, B., Wang, Y., Wang, Y., & Wang, D. (2016). *Application research of distributed optical fiber sensing technology used in safety monitoring of coalbed methane pipelines.* 2016 Progress in Electromagnetic Research Symposium (PIERS). https://doi.org/10.1109/piers.2016.7735789

Jobber, D., & Ellis-Chadwick, F. (2019). *Principles and Practice of Marketing* (9th ed.). McGraw-Hill Education.

Li, C., Chen, W., Liu, G., Yan, R., Xu, H., & Qi, Y. (2015). *A Noncontact FMCW Radar Sensor for Displacement Measurement in Structural Health Monitoring. Sensors,* 15(4), 7412–7433. https://doi.org/10.3390/s150407412

Li, G., Zhu, J., Sun, R., Lin, X., Yang, W., Zeng, K., Wang, F., Wang, C., & Zhou, B. (2018). *Pipe Line Safety Monitoring using Distributed Optical Fiber Vibration Sensor in the China West-East Gas Pipeline Project.* 2018 Asia Communications and Photonics Conference (ACP). https://doi.org/10.1109/acp.2018.8596159

Martin, B., & Hanington, B. (2019). *Universal Methods of Design: 125 Ways to Research Complex Problems, Develop Innovative Ideas, and Design Effective Solutions* (Expanded and Revised edition). Rockport Publishers.

MLT Maskin och Laserteknik. (2022). *IRIS M med motion amplification.* MLT. Retrieved May 20, 2022, from https://www.mlt.se/iris-m/?gclid=Cj0KCQjw-JyUBhCuARIsANUqQ_KwtcInqgtaYBoxbVwqHXH4-4k4BU6-lNz8b-LjA9C5Ex9TtwNzycoaAh4MEALw_wcB

Mobley, R. K. (2011). *Maintenance Fundamentals.* Elsevier Gezondheidszorg.

RAM® Mounts (n.d.a). *Camera Mounts, Holders and Bases.* National Products Inc. Retrieved May 20, 2022, from https://www.rammount.com/consumer/device-mounts/camera-mounts

OptoMET. (2022). L*aser Doppler Vibrometers.* OptoMET Laser Vibrometry. Retrieved May 20, 2022, from https://www.optomet.com/?gclid=Cj0KCQjw-JyUBhCuARIsANUqQ_J1UINviOp4QVLQG1D-qsy7_c8fgwsuVV2Ry2NWVILksU81qLOaqZgaAraSEALw_wcB

Piotrowsky, L., & Pohl, N. (2021). *Spatially Resolved Fast-Time Vibrometry Using Ultrawideband FMCW Radar Systems.* IEEE Transactions on Microwave Theory and Techniques, 69(1), 1082–1095. https://doi.org/10.1109/tmtt.2020.3038080

Pomorski Linessio, R., Sousa, K. D. M., da Silva, T., Bavastri, C. A., Antunes, P. F. D. C., & Cardozo Da Silva, J. C. (2016). *Induction Motors Vibration Monitoring Using a Biaxial Optical Fiber Accelerometer.* IEEE Sensors Journal, 16(22), 8075–8082. https://doi.org/10.1109/jsen.2016.2604850

Pugh, S. (1990). *Total design: Integrated methods for successful product engineering.* Addison-Wesley.

Ragam, P., & Devidas Sahebraoji, N. (2019). *Application of MEMS-based accelerometer wireless sensor systems for monitoring of blast-induced ground vibration and structural health: a review.* IET Wireless Sensor Systems, 9(3), 103–109. https://doi.org/10.1049/iet-wss.2018.5099

Rakshit, R., Roy, D., & Chakravarty, T. (2018). *On Characterization of Vibration Measurement Using Microwave Doppler Radar.* 2018 IEEE SENSORS. https://doi.org/10.1109/icsens.2018.8589725

Randall, R. B. (2011). *Vibration-Based Condition Monitoring: Industrial, Aerospace and Automotive Applications* (1st ed.). John Wiley & Sons, Incorporated. https://doi.org/10.1002/9780470977668

Rao, S. (2017, April 28). *Introduction to mmWave Sensing: FMCW Radars* [Slides]. Texas Instruments. https://training.ti.com/sites/default/files/docs/mmwaveSensing-FMCW-offlineviewing_0.pdf

Roque, A., & Sobral, J. (2018, June). *Motion Amplification Technology as a Tool to Support Maintenance Decisions.* MPMM 2018 – Maintenance Performance Measurement and Management Conference, Coimbra, Portugal. https://www.researchgate.net/publication/326881537_Motion_Amplification_Technology_as_a_Tool_to_Support_Maintenance_Decisions

Roy, D., Misra, P., Chakravarty, T., Sinharay, A., Rakshit, R., & Pal, A. (2018). *A Novel Unobtrusive Vibration Sensing System for Machine Inspection.* Modern Sensing Technologies, 349–365. https://doi.org/10.1007/978-3-319-99540-3_18

Roy, D., Sinharay, A., Bhowmick, B., Rakshit, R., Chakravarty, T., & Pal, A. (2020). *A Novel RF-Assisted-Strobe System for Unobtrusive Vibration Detection of Machine Parts.* IEEE Sensors Journal, 20(18), 10924–10935. https://doi.org/10.1109/jsen.2020.2995513

Rozic, N., Despalatovic, M., Sutlovic, E., Marusic, M., & Basic, P. (2019). *Electric Machine Vibration Measurements Based on Fiber Optic Sensor Technology - Preliminary Results.* 2019 2nd International Colloquium on Smart Grid Metrology (SMAGRIMET). https://doi.org/10.23919/smagrimet.2019.8720356

SKF Evolution. (2013, September 27). *Contactless vibration measurement for condition monitoring.* Evolution Technology Magazine from SKF. Retrieved May 20, 2022, from https://evolution.skf.com/contactless-vibration-measurement-for-condition-monitoring/

Tan, T. D., Anh, N. T., & Anh, G. Q. (2011). *Low-cost Structural Health Monitoring Scheme Using MEMS-based Accelerometers.* 2011 Second International Conference on Intelligent Systems, Modelling and Simulation. https://doi.org/10.1109/isms.2011.42

The Interaction Design Foundation. (n.d.). *What is Design Thinking?.* Retrieved May 6, 2022, from https://www.interaction-design.org/literature/topics/design-thinking

de la Torre, R. D., Pasobillo, G. A. E., Rebueno, M. F., Sunga, D. P., Esguerra, B. J. J., & Concepcion, R. (2020). *Vibration-based Structural Health Monitoring System for Bridges using ADXL345 Accelerometer with MATLAB Standalone Application.* 2020 IEEE 12th International Conference on Humanoid, Nanotechnology, Information Technology, Communication and Control, Environment, and Management (HNICEM). https://doi.org/10.1109/hnicem51456.2020.9400068

Warell, A. (2001). *Design Syntactics: A Functional Approach to Visual Product Form.* Chalmers University of Technology.

Wikberg-Nilsson, Å. W., Ericson, Å., & Törlind, P. (2015). *Design - Process och metod* (1:1 ed.). Studentlitteratur AB.

Xiong, Y., Peng, Z., Xing, G., Zhang, W., & Meng, G. (2018). *Accurate and Robust Displacement Measurement for FMCW Radar Vibration Monitoring.* IEEE Sensors Journal, 18(3), 1131–1139. https://doi.org/10.1109/jsen.2017.2778294

Yang, Y., Dorn, C., Mancini, T., Talken, Z., Nagarajaiah, S., Kenyon, G., Farrar, C., & Mascareñas, D. (2017). *Blind identification of full-field vibration modes of output-only structures from uniformly-sampled, possibly temporally-aliased (sub-Nyquist), video measurements.* Journal of Sound and Vibration, 390, 232–256. https://doi.org/10.1016/j.jsv.2016.11.034

Yang, Y., Zhang, H., & Li, Y. (2021). *Long-Distance Pipeline Safety Early Warning: A Distributed Optical Fiber Sensing Semi-Supervised Learning Method.* IEEE Sensors Journal, 21(17), 19453–19461. https://doi.org/10.1109/jsen.2021.3087537

Österlin, K. (2003). *Design i fokus för produktutveckling* (1/1 ed.). Liber ekonomi.

# Image Sources


Adobe. (n.d.b). *Accessibility Tools: Color Blind Safe* [Graphics]. Adobe Color. https://color.adobe.com/create/color-accessibility

Emerson. (n.d.). *Machinery Health Triax Accelerometers* [Image]. Emerson. https://www.emerson.com/en-us/catalog/ams-machinery-health-triax-accelerometers

Emerson Automation Solutions. (2022b, February). *Design Language Guidelines* (Rev 2.03). Emerson Automation Solutions.

Kowalik, K. (2019). *The zinc rolling mill* [Photograph]. Unsplash. https://unsplash.com/photos/djdoRnnKLyo

Kumar, L. (2021). *Textile Finishing unit setup* [Photograph]. Unsplash. https://unsplash.com/photos/HpPmiduLDC0

Kwok, C. (2017). *Liquid washing equipment* [Photograph]. Unsplash. https://unsplash.com/photos/xD5SWy7hMbw

Magera, P. (2021). *Production line for packaging cut greens in an urban farm.* [Photograph] Unsplash. https://unsplash.com/photos/KR9j7uqFhnI

RAM® Mounts. (n.d.b). *Camera Mounts, Holders and Bases.* [Graphics]. National Products Inc. https://www.rammount.com/consumer/device-mounts/camera-mounts

RAM® Mounts. (n.d.c). *RAM® Tough-BallTM with 1/4"-20 x .25" Threaded Stud* [Image]. National Products Inc. https://www.rammount.com/part/RAP-B-379U-252025

Senoner, A. (2022). *Inside an apple processing company in northern Italy* [Photograph]. Unsplash. https://unsplash.com/photos/8V56CnwVJRE

Senoner, A. (2022). *Inside an apple processing company in northern Italy* [Photograph]. Unsplash. https://unsplash.com/photos/bCgsKqFzUcg

# Appendix

# I - III

# Appendix I - Interview questions round 1

**Intro**

- Vad har du för roll i företaget?
- Hur är du involverad kring ert arbete för att motverka vibrationer?
- (Har ni egen produktion på plats?)

**Vibrationer**

- Hur påverkas ni av vibrationer idag?
- Var upplever ni att ni har mest vibrationer idag?
  - Specificera var (rör, axlar, maskindelar, pumpar)
- Var är det mest kritiskt att undvika vibrationer?
  - Var orsakar eller hade vibrationer kunnat orsaka mest skada?
  - Hur sker eller hade skadorna kunnat uppstå?
- Vad hade det fått för konsekvenser ifall något hade gått sönder till följd av vibrationer?

**Preventive maintenance**

- Sysslar ni med förebyggande underhåll eller liknande för att undvika konsekvenserna av vibrationer?
  - Kontinuerligt/inte alls? (Om inte alls: har ni förebyggande underhåll generellt/för något annat)
- Internt/externt?
- Använder ni idag någon typ av teknik för att mäta dessa vibrationer?
  - Hur ofta?
  - För och nackdelar? (gräv om eventuellt externa tjänster)
  - Vilket märke?
  - Vad kostar detta er (ungefär)?

**Visioner**

- (Om dem inte mäter alls eller själva idag: Vad hade krävts för att ni skulle börja mäta vibrationer internt idag?)
- Hur hade du helst velat mäta era vibrationer, om du helt fick välja?
  - Hade det varit av värde för er att kunna mäta kontaktlöst?
- Varför/varför inte?
- Hade det varit av värde att ha kontinuerlig mätning över ett område som ger larmsignal om nya/högre vibrationer uppstår? För att sedan gå in med annan utrustning och kolla exakta värden?

# Appendix II - Interview questions round 2

**Intro**

- Hur går beslutsprocessen till?
  - Vem bestämmer vilken teknik som ska köpas in?
  - (Flera olika intressenter som väger in?)
- Vad tittar ni på när ni köper er produkt?

**Mätning idag**

- Vilka frekvensband är ni i behov av att mäta?
- Hur många dimensioner är ni idag i behov av att mäta? (1D/2D/3D)
  - Mäter ni idag i 1D?
  - Om ja, i vilka avseenden?
  - Finns det några applikationer när ni måste mäta i flera dimensioner?
- Har ni någonsin märkt av att yttre faktorer påverkat er mätdata?
  - Gör ni något för att motverka vibrationer utifrån?
  - Gör ni något för att stabilisera givaren?

**Avläsning**

- Vilken information/data är ni i behov av att veta vid vibrationsmätning?
- Hur läser ni av data idag?
  - Display?
  - App? I telefon/platta
  - Datorsystem?
  - Annat ?
- Hur skulle ni helst läsa av data idag?
  - Display?
  - App? I telefon/platta
  - Datorsystem?
  - Annat?
- Vill ni veta exakta värden eller vill ni veta bra/dåligt?
  - Ex. Lampor som lyser på produkten eller i systemet?

**Produktspecifika**

- Hur är en användarvänlig produkt för dig?
  - Har du något exempel?
  - Hur upplever du mätarna ni har idag?

**Kontaktlösa frågor**

- Hade ni sett värde i att ha en handhållen kontaktlös produkt?
  - Hade ni kunnat tänka er att betala mer för en sådan produkt än en handhållen accelerometer?
- Hade ni sett värde i att ha en permanent kontaktlös produkt som eventuellt kan läsa av en eller flera punkter samtidigt?
  - Hade ni kunnat tänka er att betala mer för en sådan produkt än ett accelerometersystem motsvarande lika många punkter?
  - Hur många punkter hade den behövt mäta för att det ska vara värt att betala mer? (om man de värde i att mäta flera punkter)
- Från vilken distans hade ni sett ett behov av att mäta kontaktlöst? Det kan t.ex. vara där ni idag inte mäter/kommer åt idag i farliga miljöer, tak, svåråtkomliga punkter etc.)
- Kan ni tänka er att sätta upp flera givare för att mäta i flera dimensioner? (om de behöver 3D)

**Produktkrav**

- Finns det krav på klassningar ex. Explosionsklassning eller hygien eller liknande?
- Har ni några materialkrav för att undvika t.ex. korrosion eller dylikt?

**Montering**

- Hade ni kunnat tänka er att placera reflektorer på komponenterna/maskinerna för att ge ett noggrannare mätresultat?
  - Hur stor får i sådana fall en reflektor vara för att få plats? (bifoga exempelbild på reflektor)

# Appendix III - Likert scale

## Vad är viktigast när ni köper en produkt?

Pris

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inte alls viktigt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Den viktigaste faktorn |

Storlek

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inte alls viktigt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Den viktigaste faktorn |

Vikt (om handhållen)

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inte alls viktigt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Den viktigaste faktorn |

Utseende

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inte alls viktigt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Den viktigaste faktorn |

Användarvänlighet hårdvara

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inte alls viktigt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Den viktigaste faktorn |

Användarvänlighet mjukvara

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inte alls viktigt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Den viktigaste faktorn |

Enkel egenmontering/installation

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inte alls viktigt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Den viktigaste faktorn |

Extern hjälp med montering/installation

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inte alls viktigt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Den viktigaste faktorn |

Support från extern part (dataanalys/kalibrering)

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inte alls viktigt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Den viktigaste faktorn |

Kontinuerlig/onlinemätning

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inte alls viktigt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Den viktigaste faktorn |

Trådlös/batteridriven

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inte alls viktigt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Den viktigaste faktorn |

Trådad

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Inte alls viktigt | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Den viktigaste faktorn |

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