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Predictive Maintenance for Cableway Rollers:

Systematic Concept Evaluation and Experimental Validation of a Portable Condition Monitoring Device

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Abstract

Background. Unplanned stoppages in cableway roller systems cause significant financial losses and material waste in manufacturing environments like NKT in Karlskrona. Current maintenance strategies are mostly reactive or rely on manual inspections, creating a need for practical predictive maintenance solutions.

Objectives. The objectives of the thesis are to firstly evaluate different predictive maintenance concepts for cableway rollers systematically. Secondly, following this evaluation, to empirically validate the diagnostic capabilities of the most suitable solution through physical testing.

Methods. The method for the thesis work combines Design Science Research and Design Thinking. Qualitative data from interviews and observations guided the ideation of several concepts. These were evaluated using the Analytic Hierarchy Process (AHP) and TOPSIS. Finally, the highest-ranked concept was prototyped and validated on a custom test rig using healthy, degraded, and failed rollers under different physical loads.

Results. From the AHP-TOPSIS evaluation, a Portable Condition Monitoring Device was identified as the most suitable concept. The experimental tests proved that the device successfully distinguished between the different roller states. The fault manifestation was highly load-dependent; under a 44.7 kg load, the failed roller produced a severe radial vibration peak of 1.4159 m/s^2, compared to 0.5071 m/s^2 for the healthy roller. Concurrent temperature and acoustic measurements directly supported these findings.

Conclusions. By using a structured multi-criteria decision-making framework, a suitable maintenance concept was selected without introducing unnecessary complexity. The validated multi-modal monitoring tool proves that combining vibration, acoustic, and thermal data offers a reliable way to detect roller degradation before a catastrophic breakdown occurs.

Keywords: Condition monitoring, Multi-Criteria Decision-Making, Predictive maintenance, Sensor fusion.

Sammanfattning

Bakgrund. Oplanerade driftstopp i kabelbanor orsakar stora ekonomiska förluster och materialsvinn i tillverkningsmiljöer som hos NKT i Karlskrona. Nuvarande underhållsstrategier är oftast reaktiva eller förlitar sig på manuella inspektioner, vilket skapar ett behov av praktiska lösningar för prediktivt underhåll.

Syfte. Syftena med detta masterarbete är först att systematiskt utvärdera olika koncept för prediktivt underhåll av rullar i kabelbanor. Därefter, utifrån denna utvärdering, att empiriskt validera den mest lämpade lösningens förmåga att upptäcka fel genom fysiska tester.

Metod. Metoden för examensarbetet kombinerar Design Science Research och Design Thinking. Kvalitativ data från intervjuer och observationer vägledde idéutvecklingen av flera koncept. Dessa utvärderades med hjälp av Analytic Hierarchy Process (AHP) och TOPSIS. Slutligen byggdes en prototyp av det högst rankade konceptet, vilken validerades i en specialbyggd testrigg med hela, slitna och trasiga rullar under olika fysiska belastningar.

Resultat. Genom AHP-TOPSIS-utvärderingen identifierades en bärbar enhet för tillståndsövervakning som det mest lämpade konceptet. De experimentella testerna bevisade att enheten framgångsrikt kunde skilja mellan rullarnas olika tillstånd. Felutvecklingen var starkt beroende av belastningen; vid en last på 44,7 kg producerade den trasiga rullen en kraftig radiell vibrationsstöt på 1,4159 m/s^2, jämfört med 0,5071 m/s^2 för den hela rullen. Samtidiga temperatur- och ljudmätningar bekräftade direkt dessa resultat.

Slutsatser. Genom att använda ett strukturerat ramverk för flerkriteriebeslut valdes ett lämpligt underhållskoncept utan att tillföra onödig komplexitet. Det validerade multimodala övervakningsverktyget bevisar att en kombination av vibrations-, ljud- och temperaturdata erbjuder ett pålitligt sätt att upptäcka slitage på rullar innan ett totalt haveri inträffar.

Nyckelord: Flerkriteriebeslut, Prediktivt underhåll, Sensorfusion, Tillståndsövervakning.

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List of Acronyms

Acronym	Unfolding
BTH	Blekinge Tekniska Högskola
NKT	Nordiske Kabel og Traadfabriker
AHP	Analytic Hierarchy Process
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
MCDM	Multi-Criteria Decision-Making
RQ	Research Question
pCMD	High-fidelity portable Condition Monitoring Device prototype developed in this thesis.
NKT-Tool	the name given to your high-fidelity prototype
RMS	Root Mean Square
RPM	Revolutions Per Minute
GUI	Graphical User Interface
DSR	Design Science Research
DT	Design Thinking
CAD	Computer-Aided Design
PCB	Printed Circuit Board
SNR	Signal-to-Noise Ratio
FOV	Field of View
IDE	Integrated Development Environment
REQ	Requirement
CR	Consistency Ratio
CI	Consistency Index
RI	Random Index
LCC	Life-Cycle Cost
MTTF	Mean Time To Failure
IR	Infrared
I2S	Inter-IC Sound (digital audio interface)
MEMS	Micro-Electro-Mechanical Systems

Chapter 1

Introduction

In a world where energy is essential across many sectors-powering cities, producing goods and services, and reaching individual consumers-power cables are critical infrastructure. As sustainability becomes increasingly essential in energy consumption, the world is shifting from fossil fuels to green energy sources, making reliable cable infrastructure more vital than ever for sustaining a modern, sustainable society.

NKT HV Cables plays a significant role in cable production as the world moves toward sustainable energy. As a Nordic company, NKT designs, manufactures, and installs low, medium, and high voltage power cable solutions that enable energy transmission across many sectors.[2]

NKT operates in an industry where production occurs in distinct stages, with manufacturing lines frequently improved, replaced, or redeveloped. These modifications often change the sequence of operations, which can complicate the transportation of products between machines or production stages. Regardless of these changes, product movement is typically managed through material handling systems that facilitate both transport and sorting. Furthermore, these systems enable the integration of automation and advanced technologies, which significantly improve production efficiency.

1.1 Background

Material handling systems comprise discrete or continuous resources to transport items from point A to point B. These systems are more prevalent in manufacturing industries than in service operations. Material transportation occurs throughout factories and warehouses, spanning the entire production flow from raw material intake through processing to final output.[3]

One of the key material handling equipment types is the conveying system [4]. Conveying systems are essential in large-scale production, as their reliable operation is crucial for connecting different machines and stages of the production process. While many types of conveying systems are designed for specific purposes [5], this thesis focuses on roller conveyors, which are widely used in material handling applications.

Investigating this area is important because conveying systems are equipment that improve efficiency and increase operational speed by replacing manual tasks with automated processes[5], which reduces costs and allows companies to reallocate workers to higher-value roles such as quality control. Therefore, investigating and developing such equipment results in significant benefits to industries, some of which are fundamental to modern society.

NKT HV Cables is one such company, relying on roller-based cable transportation systems known as cableways to move cables between production stages, where an unplanned stoppage can lead to several consequences such as material loss, energy waste, and costs related to delayed deliveries to customers. These factors make unplanned stoppages highly undesirable. However, the current situation is largely characterised by maintenance performed only when needed, supplemented by pre-walk inspections that are considered ineffective. Therefore, deploying a predictive-maintenance solution for NKT's cableways could provide several advantages, including reducing costs, minimising labour effort, and preventing unnecessary operational disruptions.

1.2 Terminology

To ensure clarity throughout this thesis, several terminologies have been defined as follows:

- **Conveyor systems:** Are internally referred to as cableway systems, and the rollers are correspondingly defined as cableway rollers at NKT HV Cables.
- **Roller:** The cylindrical component in the cableway; see Section 2.1.1.
- **Predictive maintenance:** A maintenance strategy in which machinery data is monitored to determine when maintenance is needed; see Section 2.2.3.
- **Baseline:** Refers to a machinery or component's characteristic value in a healthy state.
- **Unplanned Downtime:** Refers to a failure in machinery that forces it to stop performing its intended function.
- **Condition monitoring** The continuous or periodic measurement of a physical parameter such as vibration or temperature to assess the health of machinery.

1.3 Problem Statement and Scope

Since conveyor roller systems are critical in many industries, unplanned downtime can lead to unnecessary costs and, in some cases, intolerable financial losses. Continuous maintenance of the equipment saves time and costs; however, many unexpected failures still occur during machine operation. Without continuous monitoring, these failures are typically addressed reactively after damage has occurred. This problem can be mitigated by integrating the machine with a predictive maintenance concept.

Conveyor rollers have common failure modes. Since they are widely used, they are designed to fit each company's specific needs, with different sizes based on the items being transported and different rotational speeds based on operational requirements. This customization makes implementing the same predictive maintenance concept difficult across all types of conveyor rollers, as the same concept can perform differently on different conveyor roller types.

Therefore, the scope of this thesis is to compare predictive maintenance concepts, both mechanical and sensor-based, through a TOPSIS evaluation based on AHP weighting criteria including reliability, fault detection sensitivity, and total life cost. Subsequently, a proof of concept will be developed for the most promising concept using a simplified prototype.

1.4 Research Questions

RQ1: How do mechanical and electronic predictive maintenance concepts for cableway rollers compare with respect to reliability, fault detection sensitivity, and total lifecycle cost?

RQ2: To what extent can the selected monitoring solution distinguish between healthy, degraded, and failed cableway rollers under controlled test conditions?

1.5 Outline

This thesis consists of seven chapters, including this one, and follows a structure that outlines how the contribution has been developed.

2. **Knowledge Domain:** Includes the fundamental knowledge that helps increase the clarity of this work's objectives.

3. **Related Work:** Presents some of the reviewed papers that were relevant for providing insight into how similar problems have been addressed.

4. **Methods:** Presents the methodology underlying the full contribution of this thesis.

5. **Resultes:** Presents the results and findings generated by the applied methodology within the context of this work.

6. **Discussion:** Discusses the results and limitations, as well as the threats to validity associated with this work.

7. **Conclusion and Future Work:** Concludes the thesis and highlights the contexts in which this work may be reproducible, as well as potential future improvements based on the findings.

Chapter 2

Knowledge Domain

This chapter provides the foundational knowledge necessary to establish clarity about the objectives of this thesis. It covers the type of conveying system that is the focus of this thesis, it´s architecture, and common failure modes. The chapter examines different maintenance strategies available today and provides an overview of the Multi-Criteria Decision-Making Framework that will be used in this thesis.

2.1 Conveyor and Cableway Systems

A roller conveyor is a mechanical handling system that continuously transports items along a predetermined path. It utilizes uniformly spaced cylindrical rollers to move products via friction. To reduce wear and ensure smooth operation, the rollers contain internal bearings and are mounted within frames [5]

2.1.1 System Architecture

- **Frame:** The frame structure securely holds all rollers, screws, and other mechanical components in place. Regardless of its specific design, it must be engineered using precise physical calculations to ensure it is robust enough to sustain the weight and dynamic movement of the transported items. Ultimately, the frame guarantees the stability of the entire system and is typically constructed from steel or aluminum [5].

- **Roller:** The rollers serve as the cylindrical contact surface and are uniformly spaced to ensure efficient transportation. They are considered the primary component of the conveyor system, as they directly facilitate the movement of the transported items [5].

- **Bearing:** These components facilitate low-friction rotation between the rollers and the frame. They significantly extend the operational lifespan of the conveyor system and enhance energy efficiency in motorized applications [5].

2.1.2 Common Failure Modes

Failure Modes from Literature Review

Since the conveyor system consists of frame rollers and bearings, failure modes can occur in one component or in several simultaneously. This thesis does not focus on how failures affect the frame, but rather on how bearing failure modes affect the roller and lead to roller failure.

According to ISO 15243:2017 [6] , bearing failure modes can be classified into six groups: **Rolling contact fatigue**: includes both surface-initiated fatigue and subsurface-initiated fatigue. **Wear**: includes abrasive wear and adhesive wear. **Corrosion**: includes moisture corrosion and frictional corrosion, which encompasses fretting corrosion and false brinelling. **Electrical erosion**: includes excessive current erosion and current leakage erosion. **Plastic deformation**: includes overload deformation and indentations from particles. **Cracking and fracture**: covers forced fracture, fatigue fracture, and thermal cracking.

Regardless of bearing failure modes, the roller itself can also experience plastic deformation in the form of tilting, which can lead to uneven loading and creep stresses that further result in shaft failure. Additionally, fine material dust lodged between the frame and the roller causes shaft offset and leads to accelerated wear [7].

Failure Modes Based on NKT Internal Documents

According to an internal technical report[8], failures in conveyor rollers were classified as related to rollers or related to the frame.

The failures related to rollers were divided into six categories: **Problem with bearing**: which include factors that affect bearing life depending on whether they are installed in outdoor or indoor conveyor systems.

Problem with the bearing seat: An unprotected bearing seat is susceptible to corrosion, which increases the risk of corrosion in both the bearing and its seat. This necessitates replacing the entire roller with a new one. **Overload**: In certain sections or specific directions of the conveyor system, some rollers may be overloaded, which could necessitate replacing the roller or refurbishing it to restore functionality. **Frequence of use**: Some conveyor systems that are not used frequently may have a longer lifespan, while sporadic use of the conveyor system can impact its operational lifespan. Since the roller will not be rotating for extended periods, corrosion may develop on the roller surface and its bearing. **Design error**: When the roller is subjected to loads exceeding its design capacity, it can become scratched or collapse. **Accumulation of material**: In some production lines, material layers are added to products during transportation through the conveyor system. This material can accumulate on the roller, necessitating maintenance, repair, or replacement of the roller.

2.2 Maintenance Strategies

Maintenance is critical in industrial systems and equipment as it ensures reliability, longevity, and optimal performance. It has a positive impact on enhancing continuous operations, reducing downtime and costs, and improving overall efficiency in manufacturing and processing industries. Therefore, maintenance is an important area of research to identify different strategies, implementation methods, and their impact on productivity and performance metrics.[9]

2.2.1 Reactive Maintenance

A simple logic behind this strategy is to operate the machine or equipment until it fails, at which point maintenance occurs. This approach is classified as a "run-to-failure" or "no maintenance approach." It is a strategy where spending money on maintenance is considered less important unless a machine or equipment fails to operate. This is considered the most expensive approach because it requires high spare parts inventory and overtime labor costs, in addition to downtime and low production availability.[10, p.2]

Regarding spare parts, this maintenance strategy relies on having spare machines or most machine components available so that failed components can be replaced immediately. Otherwise, organizations depend on equipment vendors to enable fast delivery of spare parts. Therefore, analysis shows that this approach is approximately three times more expensive than preventive or scheduled maintenance.[10, p.3]

2.2.2 Preventive Maintenance

Preventive maintenance is a time-driven maintenance management program based on Mean Time To Failure (MTTF) statistics. MTTF represents the expected time before a machine fails and indicates that machines have a higher probability of failure in the initial weeks after installation. After this period, machines have a lower probability of failure during normal operation, but the failure probability increases again toward the end of the machine's lifetime. In preventive maintenance strategies, maintenance is scheduled based on MTTF statistics.[10, p.3]

All preventive maintenance programs are built on assumptions based on the expected lifetime of the machine. For example, if a machine is known to operate for 18 months before failure, maintenance will be scheduled accordingly, and the machine will be serviced before reaching that point.[10, p.3]

However, preventive maintenance has a significant limitation: the actual lifetime of equipment is directly affected by how it is used. The same machine used for two different purposes or in different environments will have different lifespans. Therefore, MTTF can vary, which may result in either unnecessary repairs or repairs that should have been performed earlier than scheduled.[10, p.4]

2.2.3 Predictive Maintenance

Predictive maintenance is an approach with many different definitions depending on its application, but in general, it involves monitoring equipment condition to detect and prevent failure. The common premise of predictive maintenance is that gathering data on actual mechanical condition, operating efficiency, and other parameters provides clarity regarding maintenance intervals and required repairs.[10, p.4]

Vibration monitoring, thermal imaging, lubricant analysis, and similar techniques are tools used in predictive maintenance. However, predictive maintenance is more accurately defined as a philosophy or approach that uses actual equipment data to schedule all maintenance activities accordingly. [10, p.5]

In other words, it uses actual machine data to determine when maintenance is necessary rather than relying on assumptions based on Mean Time To Failure (MTTF) or general equipment knowledge.Predictive maintenance is a condition-driven approach that differs from preventive maintenance. Instead of relying on statistics or general information about equipment to schedule maintenance activities, predictive maintenance relies on direct, actual operational data from the machine or equipment in its operating environment.[10, p.5]

A good predictive maintenance program provides real, clear information on how each machine or equipment is actually operating in the facility. This helps the maintenance team decide when maintenance should be scheduled, reducing costs and downtime resulting from mechanical failures. By detecting problems before they occur, predictive maintenance prevents more severe failures.[10, p.5]

Common techniques used in predictive maintenance include vibration analysis, thermal imaging, tribology, and visual inspection. Each technique provides specific data that helps the maintenance team schedule maintenance activities appropriately.[10, p.6]

2.2.4 Proactive Maintenance

Proactive maintenance is considered the opposite approach of reactive maintenance. It can be described as an approach where root causes are detected and corrected. In other words, the factors causing failure are identified and addressed.

Instead of simply detecting abnormal conditions and fixing them, proactive maintenance includes activities focused on correcting what causes those abnormal conditions. [11, p. 13]

Proactive maintenance addresses material degradation or incipient failures in a system or machine. It makes machines and systems highly reliable and available in the plant by preventing catastrophic failures, critical crises, and breakdowns. Essentially, this approach ensures that failures do not recur and provides long service life for mechanical components. [11, p. 13]

The initial step is to monitor key parameters to determine the stability or normalcy of the root cause of failure and identify whether a failure exists. It begins with discovering the root cause of failure, after which corrective actions address the critical operational factor. A limitation of this approach is that it requires trained personnel who understand how to detect root-cause failures and have a thorough understanding of how the machine operates and familiarity with the system. [11, p. 13]

2.3 Multi-Criteria Decision-Making Frameworks

The processes of concept generation, ideation, and benchmarking often make it difficult to determine which concepts merit further investment and development.

According to Araujo et al. [12], AHP-TOPSIS is a hybrid multicriteria decision-making method that combines the Analytic Hierarchy Process (AHP) with TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). AHP-TOPSIS results are based solely on mathematical models.

2.3.1 Analytic Hierarchy Process (AHP)

AHP is a mathematical framework that validates judgments in real-world applications. Since it is difficult to precisely estimate measurement values even with a known scale, and more challenging when dealing with intangibles (for example, if A is preferred to B twice and B to C three times, it may not follow that A is preferred to C five times)[13], AHP provides a more logical and precise approach for comparison.

AHP is considered one of the most comprehensive processes used in multicriteria decision-making. It allows decision-makers to formulate problems hierarchically and incorporates both quantitative and qualitative criteria. [1]

It begins by breaking down the main problem or goal into a hierarchical structure, as shown in Figure 1.

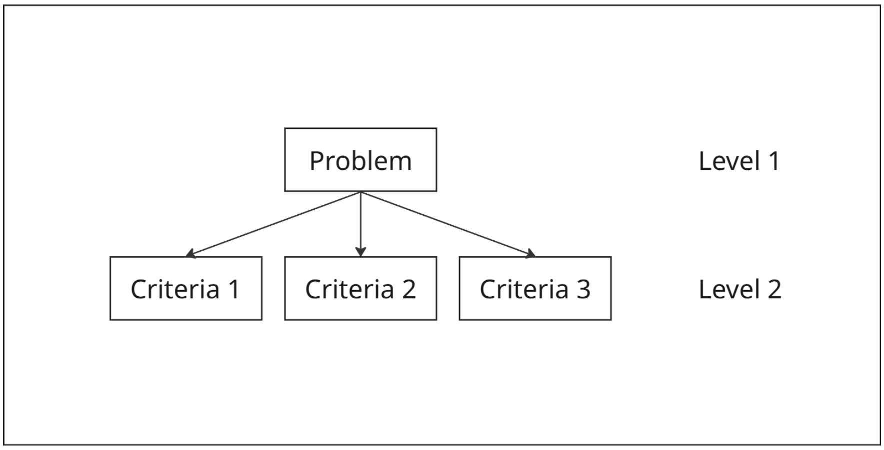

Figure 2.1: Figure 1 shows the initial step in the Analytic Hierarchy Process (AHP). [1]

The second step is to obtain input from an expert in the field where AHP is being applied. The expert provides pairwise comparisons of criteria, answering how each criterion compares to another (for example, how criterion A compares to B, and B compared to C). The expert quantifies these comparisons using a numerical scale from 1 to 9, where 1 represents equal importance and 9 represents extremely more important or strongly preferred.[1]

After that, the comparisons are converted into numerical values by using the geometric mean and inserted into a matrix, where each row and column represents a criterion and shows the relative importance of each criterion compared to the others.[1]. This is illustrated in the matrix below.

$$\begin{array}{c} \\ \text{criterion1} \\ \text{criterion 2} \\ \text{criterion 3} \end{array} \begin{array}{c} \begin{array}{ccc} \text{criterion 1} & \text{criterion 2} & \text{criterion 3} \end{array} \\ \begin{pmatrix} 1 & 4 & 5 \\ 2 & 1 & 3 \\ 5 & 9 & 1 \end{pmatrix} \end{array}$$

Matrix A: An example of a 3 × 3 AHP matrix.

Since judgments can include some inconsistency, AHP includes mathematical models that calculate the best possible weights. This is done by multiplying the matrix by a vector repeatedly [1], as shown in the formula below.

$$Aw = \lambda_{\text{max}} w, \quad \lambda_{\text{max}} \geq n \tag{2.1}$$

Where A is the pairwise comparison matrix, w is the column vector containing rows where each element represents the importance of a criterion, and λ_{max} is the maximum eigenvalue that indicates the consistency of the matrix [1], as checked by the following formula.

$$\lambda_{\max} = \frac{\sum a_j w_j - n}{w_1} \tag{2.2}$$

These values are then used to compute the Consistency Index (CI) and the Consistency Ratio (CR). A CR value below 0.10 indicates that the comparison results are acceptable. This step ensures the validation of the results.[1]

In this thesis, the output of the AHP procedure is a set of normalized numerical weights for each criterion (e.g., reliability = 0.05), which represent their relative importance.

2.3.2 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

Sitorus [14] introduced TOPSIS as a well-known multicriteria decision-making method used to evaluate the performance of different alternatives based on their distance from the ideal solution. The winning solution must be farthest from the negative ideal solution and nearest to the positive ideal solution. According to Sitorus, this method was originally developed by C.-L. Hwang and K. Yoon, who proposed implementing TOPSIS in six stages: first, a decision matrix is developed and normalized. A weighted normalized matrix is created, and both positive and negative ideal solutions are identified. Next, calculations are conducted to measure the distance of each alternative from the ideal solutions. Finally, the alternatives are ranked from best to worst based on their proximity to the ideal solution.

In the context of this thesis, The weights obtained from AHP will be used in TOPSIS to construct the weighted normalized decision matrix and used in TOPSIS to ensure that the winning alternative is the nearest to the positive ideal solution for NKT.

Chapter 3

Related Work

During a literature review conducted in this field, numerous studies were examined. Although belt conveyors may not be identical to the cableway being studied in this thesis, the reviewed literature addresses similar problems using comparable approaches. Therefore, reviewing these studies provided valuable information for this thesis.

In a research study [15] conducted to select a predictive maintenance technique for rotating machinery, an AHP evaluation based on defined criteria was performed.

First, the process began by studying information from related research and gathering feedback from experts in order to identify suitable criteria for evaluating predictive maintenance techniques.

The researchers then conducted a questionnaire that experts completed to analyze the importance of each factor through pairwise comparisons, which were then used to perform AHP calculations. The output provided a rating for each criterion to assess the selection of the most suitable predictive maintenance technique.

All results were presented as percentage ratings for each technique (for example, vibration analysis 45.5%), with the highest-rated technique identified as the most important criterion to consider when selecting a predictive maintenance technique for rotating machinery.

This research is relevant to review before completing this thesis because it demonstrates the use of AHP as a multicriteria decision-making method to determine which criteria are most weighted and should be considered during the selection process. The key difference in this thesis is that AHP is used to weight the criteria, which are then used to evaluate predictive maintenance concepts.

In another research study [16], the researchers also began by reviewing literature to gather information about the importance of the field and to identify common failure modes in idlers, bearings, and shafts. Additionally, they reviewed how other researchers addressed the same problem using different fault detection approaches and assessed their effectiveness.

The researchers built an experimental platform to simulate operating conditions. They included 18 idlers in the experiment, comprising 17 faulty idlers representing 11 different failure mode types at various stages. Data collection was performed using a BOURNS omnidirectional microphone with a signal-to-noise ratio of 70 dB and a frequency range of 20-20,000 Hz, recording idler sounds at 16 bit, 44.1 kHz sampling rate. Additionally, an infrared camera with 384×288 resolution, 17 μm pixel size, an 8-14 μm spectral band, and a temperature measurement range of -20°C to 120°C with 3°C resolution was used. The microphone was positioned 20 cm from the target idler, and the camera was placed 80 cm above. The belt speed was 1.6 m/s, and the load on the target idler was 50 N. Recording was conducted for 2 hours per idler, and the data was resampled 100 times with each sample lasting 1 second. Finally, the researchers extracted meaningful data using several approaches for each sensor.

As a result of this research, faults detectable by the sound sensor included those caused by corrosion, which produces abnormal noise. Most catastrophic faults could be detected, and incipient bearing faults could sometimes be detected. Faults caused by large defects in the bearing inner and outer rings could be detected, but small defects were difficult to detect. Temperature rise detection was effective in detecting catastrophic stages, as temperature increases often indicate more severe faults.

Reviewing this research provided important information. First, it identified common failure modes in the system and their expected characteristics and emissions. The information about the experimental platform is important for understanding how to conduct testing and evaluate different approaches. The data extraction process provided valuable insights into handling measurements after collection. Additionally, this research highlighted potential limitations and offered insights into overcoming them.

In a research paper [17] on low-speed bearing fault diagnosis, the researchers began by describing the importance of early fault detection in bearings to reduce machine downtime and increase operational efficiency. Since many machines include bearings as critical components that rotate at different speeds, and each speed level can exhibit its own failure modes, the focus of this study was on bearings rotating in the range of 0.33–10 Hz, which is 19.8–600 RPM.

First, the researchers used a frequency reduction technique to sample acoustic emission signals comparable to vibration-based approaches. Simultaneously, they used a tachometer to record shaft rotation. Later, the acoustic emission signals were resampled in sync with shaft rotation using zero-crossing timestamps from the tachometer. The resampled signal was averaged in the frequency domain, and the averaged spectrum was used to calculate condition indicators for bearing fault diagnosis. This methodology enabled the diagnosis of different bearing fault types at very low speeds.

This study is relevant to review because of its focus on low-speed rotating bearings. According to a constructor at NKT, bearings rotate in the range of 5–50 RPM [8], which means some rotation speeds overlap with the range studied in this research.

Among the reviewed literature, it was evident that belt conveyors are the most commonly investigated field, as they are widely used in mining industries. However, no study has tested or applied a predictive maintenance concept on a low-speed cableway system. Additionally, there was no comparison among different predictive maintenance concepts, whether mechanical or sensor-based, using AHP and TOPSIS. Furthermore, among the reviewed literature, no simple concept was presented; instead, only complicated concepts were found that require high competence and, in some cases, pre-trained staff to implement.

Chapter 4

Method

4.1 Research Design

To answer the defined research questions, which require both a deep understanding of an industrial problem and the development and physical validation of an artifact, this thesis follows a hybrid methodological framework that combines Design Science Research (DSR) and Design Thinking (DT). DSR provides the structure covering the process from identifying the problem through artifact development to evaluation [18]. In the early phases of this structure, Design Thinking activities are used to empathize with workers at NKT, observe company operations, and define the problem [19]. Then, the ideation phase is employed to generate concepts that address the problem. To select a suitable concept from the ideation phase, AHP and TOPSIS are applied as structured decision-making tools against defined criteria. Finally, the selected concept is developed, demonstrated, and evaluated in accordance with the DSR framework.

4.2 Data Collection Methods

To answer the defined research questions, the data collection combines both qualitative and quantitative approaches. Qualitative data was gathered to understand the industrial context, failure modes, and NKT's needs, primarily serving RQ1 by establishing the basis for concept generation and evaluation. Quantitative data was collected to measure, compare, and evaluate the concepts against defined criteria, primarily serving RQ2 by enabling the physical validation of the selected concept.

4.2.1 Systematic Literature Review

The method required an external literature review to clarify the problem being addressed and identify challenges faced by previous researchers. Additionally, internal documents were reviewed to provide information about the cableway system and its constraints.

The systematic literature review used in this thesis divided the process into three main phases: planning, conducting the review, and reporting the review.[20, p.1371]

Planning began after identifying the field, which in this case was predictive maintenance concepts applied to cableways. This phase involved reviewing previous research conducted in the same field to gather information about expected challenges, technical aspects that needed to be considered from the beginning, and potential issues. For internal documents, the planning phase involved reviewing documents related to the field and those providing information about the cableway system at NKT to identify constraints in the early stages.

The conducting phase was used to filter out information irrelevant to the work from both internal documents and literature. The reporting phase summarized the gathered information to inform the entire process and to assess whether the outcome of each stage was realistic.

4.2.2 Observations and Interviews

Interviews

Interviews were used as a data collection method to provide the ability to explore the perspectives, experiences, and meanings of participants in depth. Interviews are a method widely used in qualitative research projects. [21]

To ensure both flexibility and standardization, a semi-structured interview approach was employed. This approach included a prepared set of questions while allowing open-ended discussion and follow-up questions based on participant responses.[21]

The participants in the interviews conducted at NKT that provided relevant outcomes are presented in the following table:

In the interview with the supervisor, questions were designed to establish a clear plan for the entire project, define what would be accomplished, and set expectations. The interview also identified the next participants to be interviewed and explored possible solutions that would meet the company's needs.
In the interview with the mechanical engineer who works as a constructor in cableway systems, questions were prepared to gather information about different types of cableway systems and how their components vary by type. Additional questions addressed different roller types to further identify failure modes specific to each type. In an interview with another mechanical engineer with extensive company experience, questions were designed to extract information about how

Table 4.1: Participants and purpose of interviews

Participant	**Purpose**
Supervisor	Setting up the plan and expectations.
Mechanical Engineer 1	Exploring types of cableways and rollers in operation.
Mechanical Engineer 2	Exploring the cableway system functions and requirements.
Maintenance Technician	Identifying the most common failures and critical areas in cableway systems.
Project Manager	Understanding NKT's priorities for different processes and production lines.
Production Technician (Process Line)	Exploring the current situation when failures occur in process lines.

the current cableway functions and how the cable is transported along the system. Technical requirement questions addressed the load capacity the cableway should tolerate. In the interview with a maintenance technician, questions focused on the current maintenance situation, existing maintenance strategies at NKT, common failures in the cableway and critical areas, and how failures are currently addressed. Additional questions identified the maintenance team's needs for the cableway as a complete system and the time required to resolve failures. In an interview with a project manager who previously worked as a constructor, questions were designed to understand how NKT prioritizes process and production lines, how they operate, and how problems and errors are addressed. Questions also explored what would benefit the company regarding cableway maintenance. In an interview with a production technician responsible for a process line at NKT, questions were prepared to understand the line's needs, identify critical areas with high risk of failure, and understand how problems are addressed when they occur. Since the technician was responsible for one specific line, questions focused on the cableway within that line.

Observations

Beyond the interviews conducted, observations were used as an additional method to collect qualitative data. Observations are considered a valuable method for collecting data that participants cannot convey verbally.[21]

There were many aspects that did not require questioning since they were directly observable. The observations conducted in this work were designed to inform concept selection. Observations were performed at different stages and were structured to document the size of the cableways, how they connect one line to another, and their accessibility. The observations also included the operating environment of the cableways, staffing levels and the number of people involved in cableway operations, and activities before, during, and after cableway operation.

All documented observation data supported the establishment of practical usability requirements and user personas, ensuring that the generated concepts would be highly feasible in the existing environment.

4.2.3 Concept Generation

To ensure a beneficial output in this work, a concept generation phase was accomplished, which is considered the most important phase in new product development [22].

Several concepts were generated in the form of sketches and low-fidelity CAD models with descriptions of the core idea and how they are expected to work. During each concept generation session, data from observations and interviews were incorporated to accelerate the process and prevent time wastage. The concepts underwent early evaluations based on feasibility, cost, and whether they qualified as predictive maintenance solutions. This early filtering removed irrelevant concepts, allowing the remaining concepts to be evaluated in detail later in the work.

4.3 Concept Selection Method

Comparing concepts requires a structured approach to avoid biases. Therefore, AHP and TOPSIS were used because AHP provides stable and reliable results when dealing with criteria that are important in a particular field, while TOPSIS handles situations where trade-offs between criteria exist. [23]

Analytic Hierarchy Process (AHP)

To compare the concepts against defined criteria in a structured and non-biased manner, AHP was applied to determine the relative importance of each criterion. Three criteria were selected. The first is reliability, defined as the period during which the chosen concept operates without any breakdown [24]. The second is fault-detection sensitivity, which refers to the concept's ability to distinguish the failure being detected from uncertainties caused by external factors such as industrial noise or environmental disturbances[25]. The third criterion is life-cycle cost, which encompasses all costs associated with the concept throughout its entire lifespan, extending beyond initial acquisition to include operational, maintenance, and end-of-life costs [26].

Then pairwise comparisons were conducted with input from seven experts at NKT. The comparison input was collected through a survey in which experts were asked to choose which criterion they considered most important. The frequency of each expert input was then normalized to produce a set of relative weights. These normalized weights were converted to a pairwise comparison matrix using the following formula.

$$a_{ij} = \frac{w_i}{w_j} \tag{4.1}$$

This provides a pairwise comparison matrix A. The normalized principal eigenvector w, which represents the final criteria weights, and the maximum eigenvalue ($\lambda_{\max}$) were then calculated using the mathematical models established in Chapter 2 (Equations 2.1 and 2.2). Finally, a consistency check (CI) was performed using the following formula:

$$CI = \frac{\lambda_{\max} - m}{m - 1} \tag{4.2}$$

m here is defined as the number of criteria. Once the CI is found, the Consistency Ratio (CR) can be determined by:

$$CR = \frac{CI}{RI} \tag{4.3}$$

where RI is the Random Index corresponding to the matrix size, used to ensure the CR remains below the acceptable threshold of 0.10. The pairwise comparison matrix, priority vector, and consistency ratio were computed using a structured Excel spreadsheet.

The resulting criteria weights are presented in Table below.

Table 4.2: General pairwise comparison matrix for the selected criteria.

Criterion	**Reliability**	**Fault detection sensitivity**	**Lifecycle cost**
Reliability	1	a_{12}	a_{13}
Fault detection sensitivity	$1/a_{12}$	1	a_{23}
Lifecycle cost	$1/a_{13}$	$1/a_{23}$	1

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS was then utilized to finalize the concept selection. Each concept was evaluated against the established criteria: Reliability, Fault Detection Sensitivity, and Lifecycle Cost. Scores were assigned on a standardized scale of 1 to 10 to populate the initial decision matrix $X = [x_{ij}]$. Because physical prototypes had not yet been constructed or empirically tested at this stage, the scoring of each concept was based on a rigorous theoretical assessment. These theoretical scores were heavily informed by the operational needs of NKT, the established design requirements, and fundamental engineering principles.

First, the matrix was normalized using vector normalization 4.4 to obtain a normalized matrix R. Then, the AHP criteria weights wj were applied to normalize the matrix so that expert input became the primary focus in the TOPSIS evaluation 4.5.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \tag{4.4}$$

$$v_{ij} = w_j \cdot r_{ij} \tag{4.5}$$

Next, the positive and negative ideal solutions were determined using 4.6, where A^+ represents the positive ideal solution and A^- represents the negative ideal solution. The distance for each concept was then calculated using 4.7.

$$A_j^+ = \max(v_{ij}), \quad A_j^- = \min(v_{ij}) \tag{4.6}$$

$$S_i^+ = \sqrt{\sum_{j=1}^{m} (v_{ij} - A_j^+)^2}, \qquad S_i^- = \sqrt{\sum_{j=1}^{m} (v_{ij} - A_j^-)^2} \tag{4.7}$$

Finally, the relative closeness to the ideal solution was calculated using the following formula:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{4.8}$$

The concept with the highest closeness value C_i, resulting from 4.8, was further built and developed.

The TOPSIS calculations, including the normalized decision matrix, weighted normalized matrix, ideal and negative-ideal solutions, and the relative closeness coefficients, were performed using a structured Excel spreadsheet.

4.4 Experimental Prototyping and Validation

This section outlines the experimental prototyping and validation phase, which was specifically designed to answer the second research question (RQ2): To what extent can the selected monitoring solution distinguish between healthy, degraded, and failed cableway rollers under controlled test conditions? By constructing physical prototypes and developing a controlled experimental setup, the theoretical concept could be practically evaluated.

The most promising concept, which was evaluated through TOPSIS and weighted by the AHP, was designed as an experimental prototype using a performance-based investigation approach [27]. Since the chosen solution was the most promising, its perrmance was tested and evaluated under different conditions.

Iteration 1 : Low-fidelity Prototype

To evaluate the feasibility of the chosen concept, an initial low-fidelity prototype was constructed. This setup was assembled using readily available equipment to provide an initial indication of the system's potential output and to validate the integration of the available sensors.

The system is built around an Arduino Nano V3.0 [28], which serves as the central microcontroller, and is interfaced with a Temperature and Humidity Sensor, a Knock Sensor, and a microphone breakout sensor mounted on a breadboard, as illustrated in Figure 4.1.

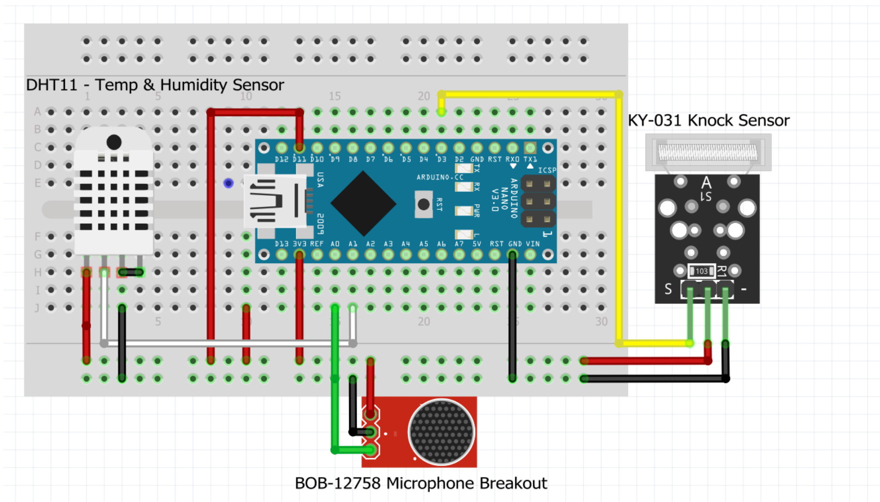

Figure 4.1: Illustration of the wiring diagram of the experimental prototype iteration 1, using an Arduino Nano and the sensors.

The specific components utilized in this experimental setup are detailed in Table 4.3 and include the following:

- **Knock Sensor (KY-031):** This sensor is utilized to detect sudden physical impacts and vibrations. It provides a binary digital output, indicating the presence or absence of a vibration event [29]. The sensor's signal pin is connected to digital pin D3 on the microcontroller, to ensure high responsiveness and guarantee that no rapid transient signals are missed enabling the use of hardware interrupts.
- **Temperature and Humidity Sensor (DHT11):** Environmental conditions are monitored using a DHT11 sensor, which acts as a temperature and humidity difference detector. It offers a temperature measurement accuracy of ±2°C and a relative humidity accuracy of ±5% RH [30]. The data line is connected to pin A4, which is configured as a digital input for this setup.
- **Electret Microphone Amplifier (BOB-12758):** An analog microphone breakout board is incorporated to capture acoustic signals. It detects ambient noise and outputs an analog voltage corresponding to the audio amplitude [31]. This varying voltage is continuously read via the analog input pin A0.

Table 4.3: Key specifications of the components used in the experimental prototype.

Component	**Key specifications**
Knock Sensor KY-031	Operating voltage: 3.3V–5V, Digital binary output (0/1), detects physical shock/vibration [29].
Temp & Humidity Sensor DHT11	Operating voltage: 3.3V–5V, Temp. accuracy: ±2°C, Humidity accuracy: ±5% RH [30].
Microphone Breakout BOB-12758	2.7V–5.5V Electret Mic Module, 100Hz–10kHz, 60x Amplified Analog Output [31].
Arduino Nano V3.0	Microcontroller: ATmega328P, Operating voltage: 5V, features hardware interrupts [28].

To test the sensors and observe the results on the Arduino Nano board, the code was developed using the Arduino Integrated Development Environment (IDE). The functions and logic behind this code are detailed in Table 4.4 below.

Table 4.4: Overview of the code and logic implemented for the iteration 1 prototype.

Code Routine	**Associated Component**	**Description**
Initialization	Sensors and microcontroller	Starts the sensors and applies an internal electrical pull-up to the shock sensor to prevent false triggers and ensure a stable reading.
Acoustic Monitoring	BOB-12758 Microphone Breakout Sensor	Continuously measures the sound level. Triggers an alert on the computer screen if the noise is unusually loud or drops below expected baseline levels.
Shock Detection	KY-031 Knock Sensor	Checks for physical impacts. Uses a short, programmed pause after an impact is detected to prevent a single vibration from being counted multiple times.
Environmental Monitoring	DHT11 Temp & Humidity Sensor	Measures temperature and humidity every two seconds without pausing the rest of the system. Includes safety checks to automatically ignore invalid sensor readings.

Iteration 2 : High-fidelity Prototype

To systematically manage technical risks and ensure the validity of the final evaluation, the prototype development transitioned from a low-fidelity to a high-fidelity portable Condition Monitoring Device (pCMD). The findings from the initial phase indicated that the data acquisition limits of the Arduino Nano were insufficient to capture the subtle anomalies required for reliable predictive maintenance in an industrial setting. Consequently, the hardware architecture was significantly upgraded for the final pCMD iteration.

The central processing unit was transitioned to an ESP32 microcontroller. This selection is justified from an electrical integration perspective, as the ESP32 operates at a 3.3V logic level, which aligns with modern sensor suites, eliminating the need for logic level converters and enabling a compact circuit design. Furthermore, its dual-core processor and integrated Wi-Fi provide a critical foundation for handling real-time data transmission without bottlenecking sensor acquisition [32].

The sensory equipment was upgraded to specialized digital components based on performance metrics established in recent literature and component specifications to minimize signal degradation:

- **3-Axis Accelerometer (ADXL345):** Selected for its capability to generate highly detailed vibration patterns. When configured to a range of ±4 g or ±8 g, it provides a resolution of 10-bit to 13-bit, enabling the detection of minute acceleration changes down to approximately 4 mg/LSB to 15.6 mg/LSB [33]. This precision guarantees that genuine physical vibrations from the rollers can be distinguished and recorded effectively.
- **Infrared Temperature Sensor (MLX90614-DCI):** Traditional contact-based sensors are impractical for continuously rotating machine parts. The MLX90614, a non-contact infrared sensor, was chosen. The specific DCI variant is optimized for 3V operation and features internal thermal gradient compensation. It is equipped with a highly directional 5° Field of View (FOV). It provides a high measurement resolution of 0.02°C [34]. This narrow FOV allows the sensor to target a specific roller accurately from a safe distance without capturing interfering heat radiation from the surrounding steel structure.
- **Acoustic Sensor (INMP441):** Chosen to capture transient acoustic anomalies indicative of mechanical wear. The INMP441 is an omnidirectional MEMS microphone that utilizes a 24-bit I2S digital interface, connecting directly to the microcontroller without an external audio codec. This digital transmission shields the acoustic signal from electromagnetic

interference prevalent in industrial environments. The sensor features a flat wideband frequency response from 60 Hz to 15 kHz and a high Signal-to-Noise Ratio (SNR) of 61 dBA [35].

Figure 4.2 provides a detailed illustration of the system's wiring, highlighting the digital connections between the sensor suite and the ESP32 microcontroller. Further technical specifications for each of these integrated components are presented in Table 4.5.

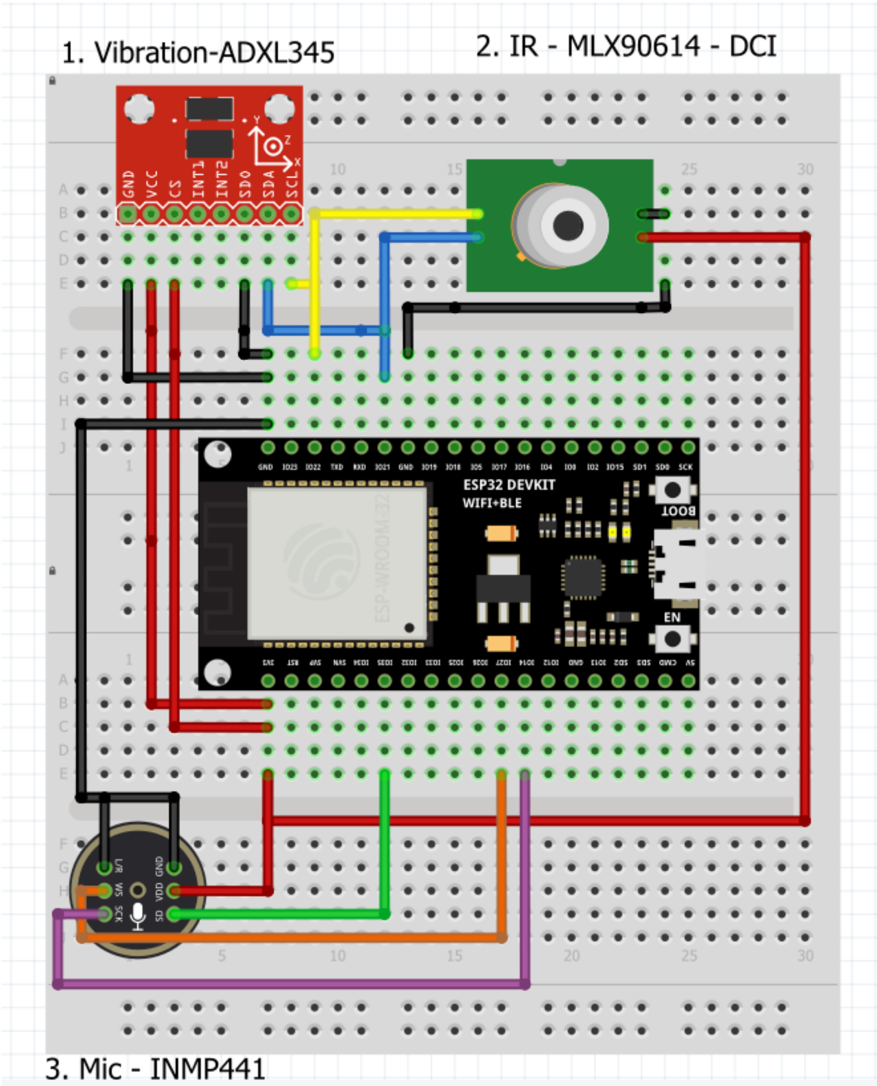

Figure 4.2: Illustration of the updated wiring diagram of the experimental prototype using an ESP32 board and the sensors.

Table 4.5: Key specifications of the components used in the advanced experimental prototype.

Component	Key Specifications
3-Axis Accelerometer (ADXL345)	Detects accelerations up to ±16 g, up to 13-bit resolution, low power consumption [33].
IR Temperature Sensor (MLX90614-DCI)	3.0V supply, targeted 5° narrow FOV, thermal gradient compensated, measurement resolution of 0.02°C [34].
Acoustic Sensor (INMP441)	24-bit I2S interface, 60 Hz – 15 kHz frequency response, 61 dBA SNR [35].
ESP32 Microcontroller	3.3V logic, dual-core, features integrated Wi-Fi and Bluetooth capabilities [32]

For the advanced pCMD prototype, the software implements digital filtering directly on the edge device to reduce environmental noise and calculate stable average values before the data is displayed. Furthermore, the ESP32 is configured to act as its own local Wi-Fi network. It hosts an embedded web page that provides real-time data visualization and logging capabilities without relying on an external internet connection. An overview of the core code routines for pCMD is detailed in Table4.6

Table 4.6: Overview of the code and logic implemented for the pCMD prototype.

Code Routine	**Associated Component**	**Description**
Initialization	Sensors and ESP32	Starts the sensors and configures the microcontroller to act as a local Wi-Fi network, allowing a user to connect to it directly.
Vibration Signal Processing	ADXL345 3-Axis Accelerometer	Continuously reads vibration data. Applies a digital filter to subtract the effect of static gravity, calculating a steady average (RMS) value for the actual movements.
Acoustic Signal Processing	INMP441 Acoustic Sensor	Streams audio data continuously in the background. Calculates the average sound level and applies a digital filter to smooth out sudden spikes, outputting a stable noise reading.
Temperature Monitoring	MLX90614-DCI IR Temp Sensor	Measures the object temperature every 250 milliseconds. Includes safety checks to automatically ignore invalid measurement errors.
Network & Data Export	ESP32 Microcontroller (Web Server)	Hosts a local web page that updates the sensor readings multiple times per second for real-time monitoring. It also temporarily saves the data to generate downloadable summary reports of the session.

To address this, custom sensor mounts and protective enclosures for the microcontroller board were designed using Computer-Aided Design (CAD) software. These components were subsequently fabricated using Additive Manufacturing (3D printing). To realize the high-fidelity portable Condition Monitoring Device (pCMD), hereafter referred to as the NKT_Tool as a robust testing unit, the electronic components were integrated into a custom-designed physical enclosure.

Figure 4.3 illustrates the complete set of components used in the final assembly. This includes the 3D-printed main body and sensor housing, the ESP32 DEVKIT microcontroller, the digital sensor suite, neodymium magnets for secure mounting onto the test rig, a dedicated power supply (9V battery), and a custom-engraved acrylic front plate.

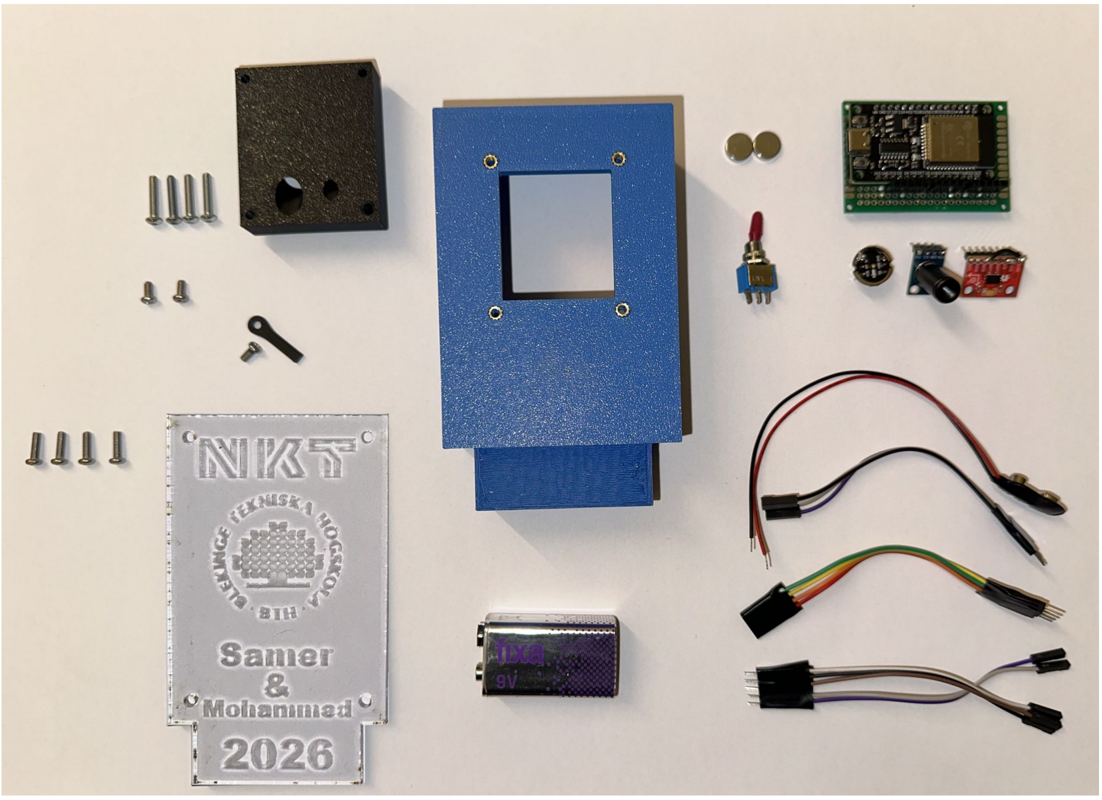

Figure 4.3: Exploded view of the NKT-Tool hardware components.

To facilitate a secure and seamless attachment to the test rig and future cableway structures, neodymium magnets were integrated directly into the main housing during the Additive Manufacturing process. As shown in Figure 4.4, the 3D printing cycle was intentionally paused at a calculated layer height to insert the magnets into precisely designed internal circles.

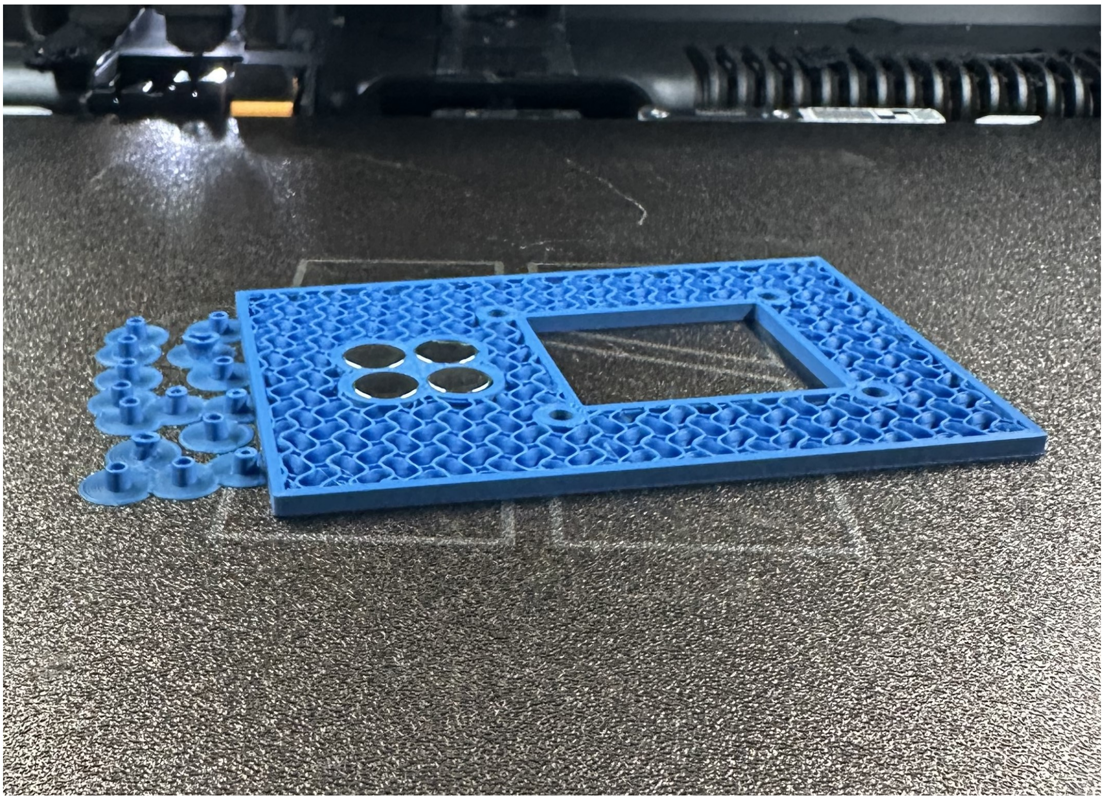

Figure 4.4: Embedding neodymium magnets into the casing by pausing the 3D printing process.

A user-friendly interaction with the collected sensor data has also been provided. The embedded web server hosts a dedicated Graphical User Interface (GUI), accessible through any standard web browser connected to the ESP32's local network. The interface is designed to bridge the gap between complex raw data and practical maintenance workflows, allowing the operator to select specific rollers, set recording durations, and monitor live sensor readings directly on the factory floor.

Validation

In this thesis, an internal concept validation approach was carried out to ensure that the selected concept fulfills the specifications for its intended use [36]. Since implementing the concept directly at NKT's production line was not feasible within the project timeframe, an experimental setup was constructed to simulate cableway roller conditions and test the functionality of the concept under controlled operating scenarios representing healthy, degraded, and failed roller states.

Three rollers of the same type were used, and according to NKT's statement, the rollers fall into three conditions outlined below:

- **Roller A:** Healthy roller
- **Roller B:** Half-failed roller
- **Roller C:** Failed roller

To simulate a one-directional rotation as if the cable is continuously passing over the roller, a hoverboard wheel and motor were dismounted and connected to a controller that maintains the wheel's RPM, allowing the rollers to rotate at the same speed as in NKT's cableway. All components were mounted on a wooden construction. The setup was designed so that rollers could be replaced without dismounting anything other than the rollers themselves. It was also intentionally constructed to allow different weights to be placed on a plate, enabling the study of roller behaviour under varying loads. The components included in the setup are presented in the following figure.

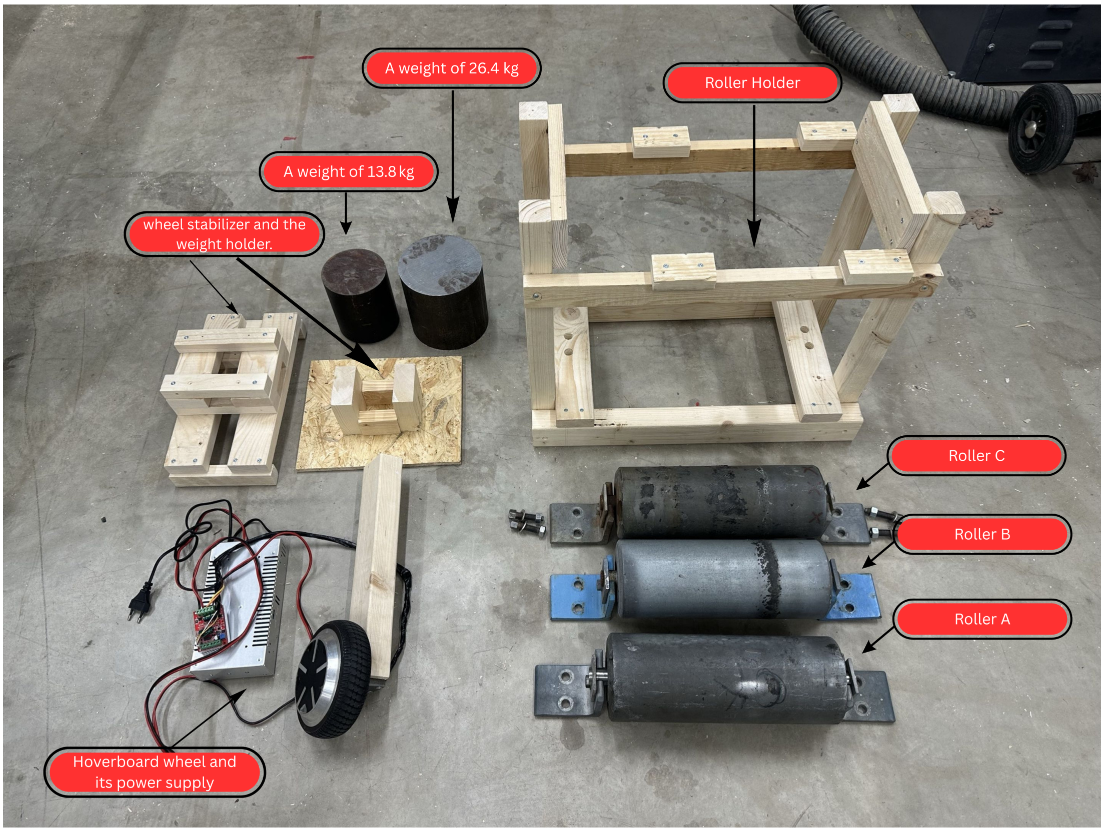

Figure 4.5: Components used in the experimental setup. (See Appendix A)

The weights shown in the figure do not include the mass of the wheel and its components. However, the weight holder together with the wheel and its components has a combined mass of 3.4kg.

This experimental setup constitutes the validation stage of the thesis, as it evaluates whether the chosen concept can detect vibration, noise, and temperature differences among rollers under different operating conditions. The concept was mounted in the same position on each roller during a 30-minute recording for each roller, allowing the output results to be analyzed and compared to determine whether the concept detected the differences.

Chapter 5

Results

5.1 Problem Scoping and Design Constraints and Requirements

Problem Scoping

The system boundaries and usability requirements were defined by conducting semi-structured interviews with six key personnel at NKT, where qualitative data from this phase was used to formulate the specific problem statements and usability requirements for this thesis. The problem was scoped based on the data collected from the interviews.

NKT currently has a cableway system that transports cables through different production stages. The cableway is separated into two categories: indoor and outdoor. Some cableways are designed for specific needs, such as a particular production order, while temporary cableways may be used only once. The cableway system is not standardized, meaning each production stage can have its own cableway, and the same cableway may consist of different types of rollers.

NKT's current maintenance approach is primarily reactive; when a roller or another component in the cableway fails, it is maintained, repaired, or replaced. This is in addition to the manual inspections performed before operating the cableway systems. However, it was stated that this approach is still not fully effective, as some cableways are unreachable and operators may miss routine checks. In some production stages, the cable is not affected if a roller fails and stops rotating, while in others the opposite is true, and replacing the roller becomes urgent. In certain stages, especially those within process lines, it is not possible to stop production to replace a roller; therefore, predicting a failure even one or two hours before it occurs is valuable.

When an operator detects a failure, a maintenance order is placed. Additionally, some rollers may be replaced before failure based on the production technician's judgment - for example, if a roller appears old or rusty.

The most critical areas where failures often occur are in curves, where rollers become overloaded and may collapse, and in areas where the cable transitions from an upper cableway to a lower one, causing the cable to strike the roller due to the absence of a guide. Indoor cableways are not often fully stopped, while outdoor ones frequently are. Beyond full stops, indoor rollers may also become scratched due to missed operator routines.

Design Constraints and Requirements

To ensure the practical effectiveness of the final solution, qualitative data from interviews and on-site observations were synthesized to establish the design constraints outlined below.

1. **Technical & Performance Constraints:** The final predictive maintenance solution may also be a purely mechanical concept, as long as it can predict a failure. Moreover, the failure detection does not need to provide an early warning far in advance; it is sufficient if the concept alerts operators on the same day, since operators are always present around the cableways and can quickly address issues.

2. **Operational & Architectural Constraints:** The solution must not introduce unnecessary complexity into the system. Therefore, no AI integration or additional software requiring IT specialists should be part of the final concept. Furthermore, a solution that requires installing permanent sensors on every roller is unfeasible and potentially very costly due to the large number of rollers. A more effective approach would be a solution that can be placed only in critical areas and easily relocated, especially since some cableways are temporary.

3. **Project Scope Constraints:** To ensure that a functional output can be delivered, the solution must be physically testable within a short time frame so that it can be validated within the time limits of this thesis project.

Therefore, a set of requirements that the concept must meet has been structured and is outlined in the table below.

Table 5.1: System design requirements derived from stakeholder interviews.

REQ	**Description**
REQ1	The solution must be modular and maintainable, ensuring that if a component fails, it can be easily repaired or replaced.
REQ2	The solution must be simple to use and must not require AI integration or complex software.
REQ3	The solution must be portable, easy to replace, and must not require permanent installation.
REQ4	The solution may be mechanical or based on simple sensors.
REQ5	The solution must have a low cost relative to the value it delivers.

5.2 Concept Generation and Screening

Ideation was an activity that extended throughout the entire thesis, from the beginning to the end. In the early stages, several concepts emerged during the ideation phase. These concepts were gradually filtered using the set of requirements that was developed in parallel with the initial ideation work, while the concepts that satisfied all defined requirements proceeded to be evaluated in greater depth.

5.2.1 Preliminary Ideation and Filtered Concepts

One of the early ideas was a magnetic sensor installed on each roller holder to detect the roller's rotational speed. This idea was filtered out based on Requirement3 (REQ3).

Another idea involved installing a gear wheel connected to two pins, one positioned above and one below , so that the pins would move up and down as the roller rotated . This concept was excluded due to Requirement (REQ5), as it only indicated whether the roller was rotating and was also unfeasible to install on NKT's cableway.

A further idea was a visual indicator based on a plastic bevel gear. It consisted of a ring pressed into the roller and a long pin with a visual element at its lower end. As the roller rotated, the gear would increase the rotational speed transmitted to the pin, and the visual element would stop moving when the roller slowed down. However, this idea was filtered out by Requirement1 (REQ1), since it included a bearing, which would introduce additional maintenance to the cableway system.

5.2.2 Shortlisted Concepts for TOPSIS Evaluation

Concept 1: Acoustic Roller Inspection Tool

This concept is based on a ring-shaped tool intended to be manually installed on the cable and travel through the cableway. It includes a noise sensor along with four pins designed to rotate the rollers that the cable does not contact. The tool is intended to warn operators when it detects abnormal noises generated by the rollers. More specifically, it is designed to follow the cable while simultaneously measuring the acoustic emissions from all rollers, including those that are not in direct contact with the cable. The concept is outlined below.

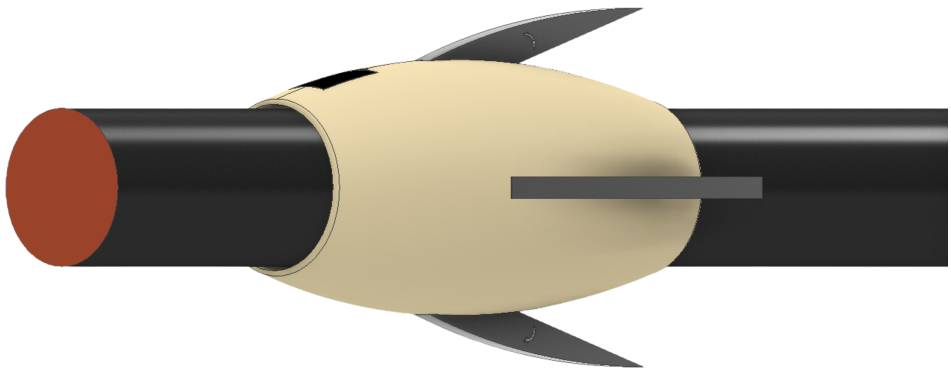

Figure 5.1: Illustration of the underlying idea of Concept1

The pins extending from the tool are intended to rotate the rollers that the cable does not touch. They are designed to be spring-loaded, allowing them to move up and down to reach the rollers. In the illustration, the cable is represented by the black cylinder, and the black box houses the electronics required for the tool's functionality. The concept shown in the figure is a low-fidelity sketch intended for further evaluation and development.

The concept is intended to function as a modular device that can be installed and removed by operators. It is envisioned to be connected to a system that allows operators to see warnings and their corresponding locations. Such a system could support predicting failures before catastrophic breakdowns occur and simplify the monitoring of rollers that are otherwise difficult or impossible to access.

Concept 2: Visual Rotation Indicator

The concept consists of a cover that can be mounted onto the roller without affecting its rotation or the movement of the cable being transported. It is intended to be manufactured from plastic and held in place either by embedded magnets or by a low-tolerance press fit. The cover is marked with reflective colours to make the roller's rotation clearly visible. It is designed with minimal thickness and a small contact surface that grips the roller. The underlying idea is to avoid the use of sensors or components that require maintenance, while utilising only the area of the roller that the cable never touches. The idea is presented in the figure below.

Figure 5.2: Illustration of the underlying idea of Concept2.

The intended function of this concept is to provide operators with a clear visual indication of whether a roller is rotating. Even a roller that rotates more slowly than the others would be noticeable, enabling operators to detect deviations from normal behaviour. In this way, the concept functions as a failure indicator that relies solely on visual inspection.

Concept 3: Portable Condition Monitoring Device

This concept is based on a portable device that can be used on any type of cableway. It is intended to include three sensors that monitor key parameters relevant to predictive maintenance: vibration, temperature, and noise. All three sensors are integrated into a single device that measures these parameters simultaneously.

The device is intended to be used by operators, who can place it on the cableway either for routine inspection or when a potential issue is suspected. In other words, it can be deployed at any time and at any location along the cableway. The idea behind the device, including how it can be positioned on the cableway, is illustrated below.

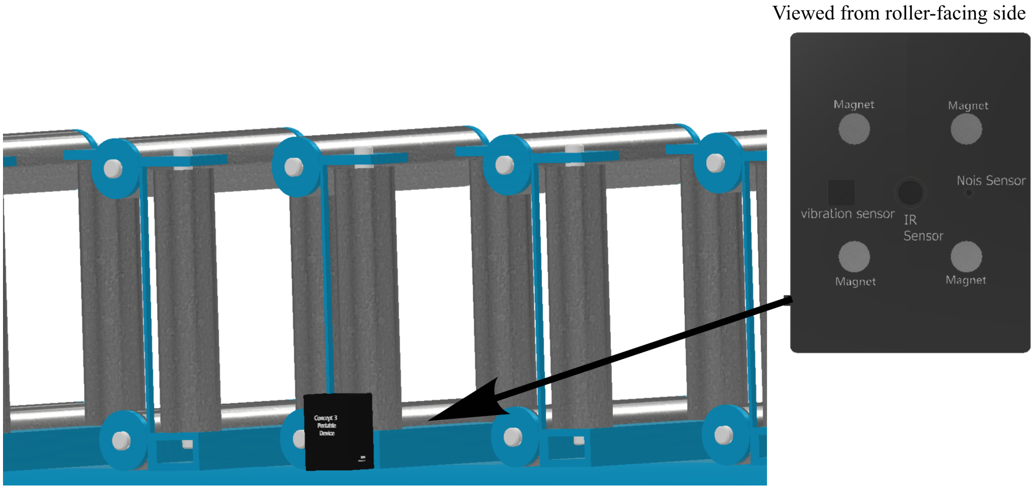

Figure 5.3: Illustration of the underlying idea of Concept3.

The concept is designed to function within a cableway context by relying on predefined baseline values for the parameters being measured, representing the conditions of a healthy cableway. After the device is placed on the system, it monitors the current condition for a short period. Any deviation between the current measurements and the predefined baseline would indicate a potential developing failure in critical sections of the cableway.

5.3 AHP and TOPSIS Results

To evaluate the concepts against the defined criteria derived from expert input, this section presents the results from the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

5.3.1 AHP

AHP was applied by distributing a survey containing the defined criteria to seven experts. The results revealed a clear hierarchy: four experts prioritised Reliability, two prioritised Life-Cycle Cost (LCC), and one prioritised Fault-Detection Sensitivity, as shown in the following table.

By using the formula 4.1 the raw expert votes were translated into the standard AHP pairwise comparison scale. Reliability received twice as many votes as Life-Cycle Cost. In the AHP scale, this corresponds to an intermediate preference, which can be expressed numerically as a score of 2 in favour of Reliability. When comparing Reliability with Fault-Detection Sensitivity,

Table 5.2: Voting results for evaluation criteria.

Criteria	**Vote**
Reliability	4
Fault detection sensitivity	1
Lifecycle cost	2

Reliability received four times as many votes, which in the AHP scale represents a strong importance and can be expressed numerically as 4. For Life-Cycle Cost compared with Fault-Detection Sensitivity, Life-Cycle Cost received twice as many votes, corresponding to a score of 2 in favour of Life-Cycle Cost. These relationships are summarised in the table below.

Table 5.3: Pairwise comparison matrix and column sums for evaluation criteria.

Criterion	**Reliability**	**Detection Sensitivity**	**Lifecycle Cost**
Reliability	**1**	4	2
Detection Sensitivity	0.25	**1**	0.5
Lifecycle Cost	0.5	2	**1**
Column Sum	**1.75**	**7**	**3.5**

By applying formulas (2.1 and 2.2) and performing the consistency check using formula (4.2), a value of 0.0 was obtained. Finally, applying formula (4.3) resulted in a consistency ratio of 0.0, which is well below the standard acceptable threshold of 0.10. Together, these steps resulted in the final ranking of the criteria, as shown in the following table.

Table 5.4: Calculated weights and ranks for evaluation criteria.

Criteria	**Calculated Weight**	**Rank**
Reliability	57.1%	1
Lifecycle Cost (LCC)	28.6%	2
Fault Detection Sensitivity	14.3%	3

The resulting weights were subsequently applied in the TOPSIS method to evaluate the three generated concepts.

5.3.2 TOPSIS

To rank the generated concepts, Concept 1 (Acoustic Roller Inspection Tool), Concept 2 (Visual Rotation Indicator), and Concept 3 (Portable Condition Monitoring Device), they were evaluated against the three defined criteria using their calculated weights: Reliability (57.1%), Life-Cycle Cost (28.6%), and Fault-Detection Sensitivity (14.3%).

Table 5.5: Concept evaluation scores against criteria and AHP weights.

Concept	**Reliability**	**Detection Sensitivity**	**Lifecycle Cost**
AHP Weight	**0.5714**	**0.1429**	**0.2857**
Acoustic Roller Inspection Tool	5	4	4
Visual Rotation Indicator	8	2	8
Portable Condition Monitoring Device	6	8	5

Table 5.5 presents the initial decision matrix, detailing the theoretical scores assigned to each concept.

Concept 1 (Acoustic Roller Inspection Tool) received a Reliability score of 5. This assessment reflects the inherent mechanical risks associated with its operating mechanism; because the tool is designed to physically grip the cable, it is highly susceptible to structural strain from the cable's substantial weight. Additionally, dynamic impacts encountered when traversing rollers during vertical movements increase the risk of tool breakage. Furthermore, these physical constraints introduce the potential for the device to become lodged on a roller, which could critically interfere with the continuous movement of the cable.

The score of 4 for Fault-Detection Sensitivity is based on the tool's Operational sequence. The tool is intended to be mounted at the beginning of the cable and travel along the cableway, functioning as if an operator were inspecting the rollers as the cable reaches each section. However, based on observations and interviews, rollers may collapse or fail after the cable has already travelled a considerable distance. In such cases, the tool would be positioned ahead of the failure, which may increase uncertainty in the detection process.

The score of 4 for Life-Cycle Cost is based on the observation that requiring an operator to manually mount the tool onto the cable and remove it after transportation introduces an unnecessary labour cost that could be more effectively invested elsewhere. Additionally, the tool's relatively low reliability, stemming from the risk of breakage due to the cable's weight, may require either the use of more expensive materials or repeated maintenance or replacement. There is also a potential risk of damaging the cable itself if the tool becomes stuck on a roller.

Concept 2 (Visual Rotation Indicator) received a score of 8 for Reliability. This is based on the fact that the concept is purely mechanical, requiring no sensors, electronics, or power supply to function. Its simplicity contributes to high availability, and the risk of maintenance or replacement is low because the indicator is placed on the surface of the roller where the cable never makes contact.

The low score of 2 for Fault-Detection Sensitivity is supported by observations and interviews indicating that some cableways are long, and certain rollers are relatively small, making them difficult to see with the naked eye. Placing a visual indicator on the roller does not fully resolve this issue and may even increase uncertainty. For example, if the cable bends in a way that prevents a roller from rotating, the operator may incorrectly assume that the roller has failed and needs replacement. Furthermore, the indicator provides limited information about whether a roller is about to fail, making the concept a weak predictive-maintenance solution.

Regarding Life-Cycle Cost, this concept received the highest score of 8. This is due to its one-time purchase nature: it only needs to be mounted once on the roller and can remain in place even when the roller is replaced. As a result, the concept is expected to have low operational, maintenance, and risk-related costs throughout its lifespan.

Concept 3 (Portable Condition Monitoring Device) received a score of 6 for Reliability. This is because the concept is intended to have a modular design, allowing failed components to be replaced when necessary. Additionally, the device is mounted on the outer side of the cableway, which reduces the risk of mechanical damage. However, the sensors may malfunction if exposed to dust, oil, or other contaminants in the operating environment.

The high score of 8 for Fault-Detection Sensitivity is justified by the concept's intended use: it is placed by an operator directly at the location that requires temporary monitoring. This allows the device to measure a specific roller or section, producing precise and localised results that reduce uncertainty. Furthermore, the integration of three sensors: noise, temperature, and vibration, provides a higher probability of detecting failures that manifest across these parameters.

The score of 5 for Life-Cycle Cost reflects the fact that the device requires an operator to carry it, position it, and retrieve the results, which introduces labour-related costs even though it adds value to the cableway system. Additionally, due to the large number of rollers, a single device would not be sufficient for the entire company; multiple units and additional operators may be required for comprehensive inspection. However, interviews revealed that operators sometimes hear abnormal noise from a section but cannot determine which roller is failing. In such cases, this concept becomes highly beneficial, as it can be placed directly at the suspected location, helping prevent unplanned cableway downtime.

By applying the mathematical formulas (4.4) and (4.5) to ensure that the expert-derived weights were the primary focus of the evaluation, and then determining the distance from the positive and negative ideal solutions using formulas (4.6) and (4.7), the relative closeness C_i was calculated using formula (4.8). This process resulted in the ranking of the concepts shown in the following table, where the winning concept is the one with the highest closeness C_i.

Table 5.6: Combined concept rankings, closeness, and distances.

Concept	**Rank**	**Closeness $\mathbf{C_i}$**	**$\mathbf{S_i^+}$ (dist to best)**	**$\mathbf{S_i^-}$ (dist to worst)**
Concept 3	1	0.5612	0.10595	0.13548
Concept 2	2	0.5130	0.14555	0.15333
Concept 1	3	0.4116	0.16552	0.11581

Therefore, **Concept 3** (Portable Condition Monitoring Device) will be further developed and tested in the experimental setup under different conditions.

5.4 Test Results

Iteration 1 (Low-Fidelity)

In the first experimental iteration, the objective was to validate the basic integration of the sensors and observe the initial data output during roller rotation. The data was captured via the Arduino Serial Monitor. The results for this phase are as follows:
The DHT11 Temp. and Humidity sensor recorded stable ambient conditions, with temperature readings consistently at 23.90 °C and relative humidity fluctuating between 25.00% and 26.00%.
Regarding acoustic and vibration alerts during operation, the software generated binary text-based alerts in response to predefined thresholds. As illustrated in the Serial Monitor output (see Figure 5.4), the system successfully triggered the messages "SHOCK DETECTED!" and "LOUD SOUND DETECTED!".

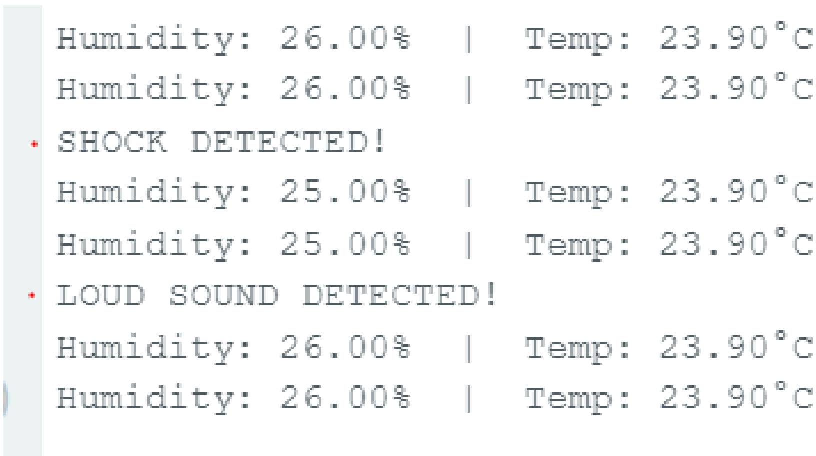

Figure 5.4: Data output from the Concept 1 prototype displayed in the Arduino Serial Monitor

The sensors did not provide numerical amplitudes or frequency data for the acoustic or vibration events. The output remained limited to a "true/false" detection of the events based on the thresholds set in the code.

Iteration 2 (High-Fidelity)

This section presents the quantitative data captured by the high-fidelity pCMD (NKT_Tool). Tests were conducted on Roller A (Healthy), Roller B (Degraded), and Roller C (Failed) over 30-minute intervals. To evaluate the impact of mechanical stress, the rollers were subjected to varying loads: 3.4 kg (baseline motor and holder), 18.2 kg, 30.8 kg, and 44.7 kg. A target rotational speed of 26 RPM was maintained for the lower loads. However, under the 30.8 kg and 44.7 kg loads, the rotational speed for Roller C fluctuated significantly due to the severity of the internal bearing damage, which introduced substantial mechanical resistance.

To ensure high-fidelity data acquisition, the spatial arrangement of the sensors within the NKT_Tool was strategically designed to optimize signal integrity. Figure 5.5 illustrates the internal and external sensor topology.

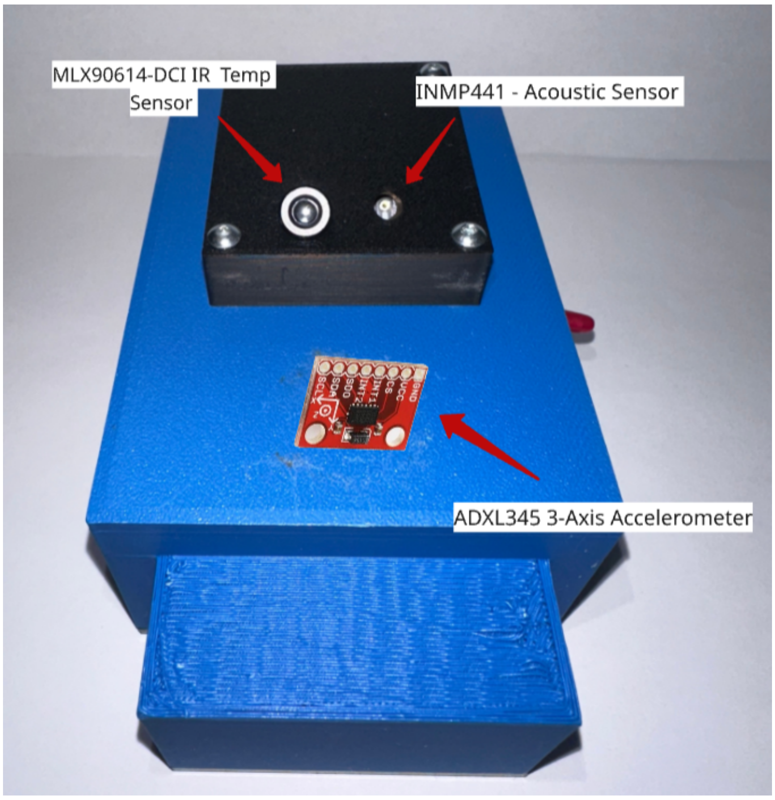

Figure 5.5: Sensor topology of the NKT_Tool. The external black enclosure houses the thermal and acoustic sensors, while the ADXL345 accelerometer is mounted internally.(See Appendix B)

The MLX90614-DCI infrared sensor and the INMP441 acoustic sensor were mounted in the protruding external black enclosure Figure 5.6. This placement minimizes physical obstruction and prevents internal heat buildup from the microcontroller from affecting the thermal readings, allowing the sensors to directly target the bearing seal.

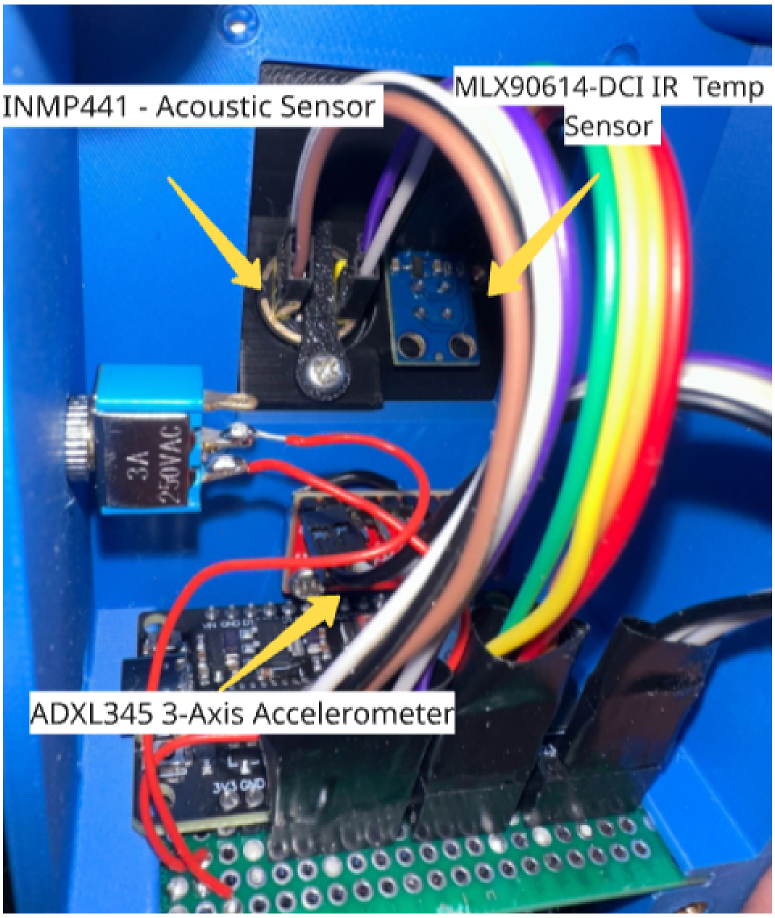

Figure 5.6: Internal view of the NKT_Tool, showcasing the microcontroller wiring and the internal placement of the sensor modules.

Conversely, the ADXL345 3-axis accelerometer was mounted internally within the main casing. The sensor was positioned on the inner wall directly opposite the embedded neodymium magnets. As illustrated in Figure 5.7, the ADXL345 vibration sensor was mounted internally with its Z-axis pointing radially toward the bearing center, the Y-axis pointing vertically downward, and the X-axis running axially.

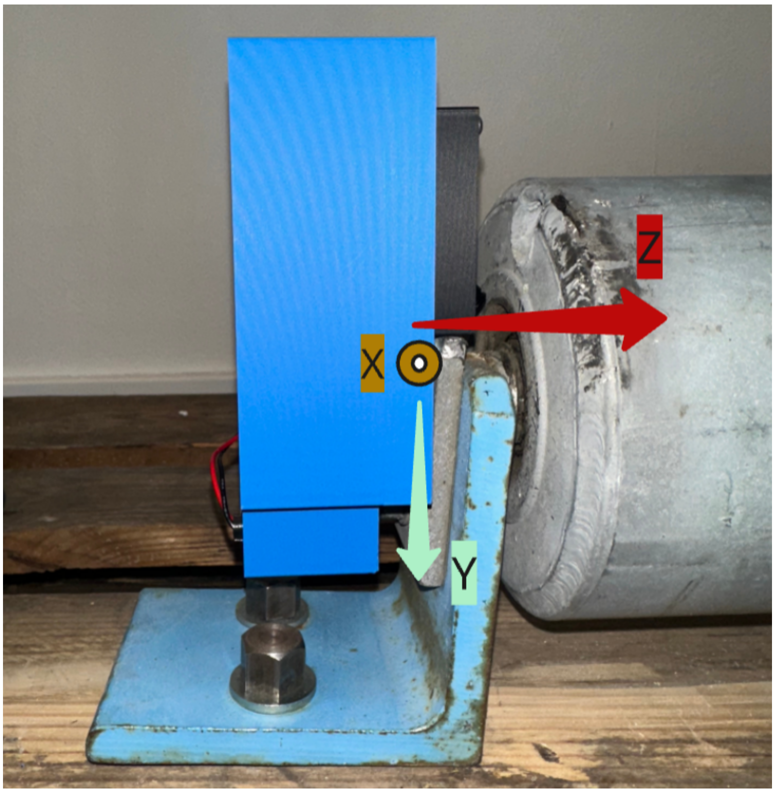

Figure 5.7: Vibration sensor orientation of the NKT_Tool relative to the roller structure. The Z-axis (red) isolates radial forces, the Y-axis (light blue) isolates vertical forces, and the X-axis (brown) isolates axial forces.

The vibration data was recorded as Root Mean Square (RMS) values to provide a stable representation of the kinetic energy generated during rotation. The Z-axis (radial direction) was isolated for this presentation as it captured the highest amplitude variations.

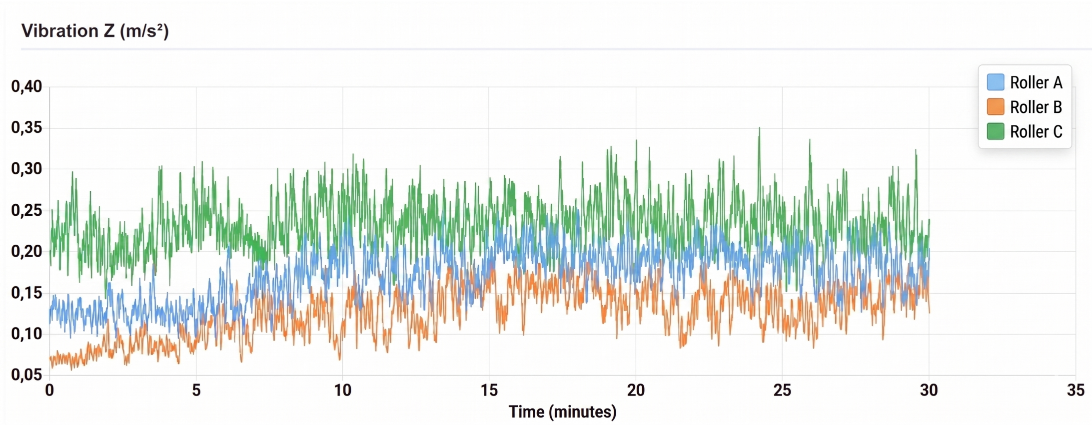

Figure 5.8: Vibration RMS (Z-axis) for Rollers A, B, and C under a 3.4 kg baseline load at a constant 26 RPM.

As shown in Figure 5.8, under the baseline load of 3.4 kg, Roller C exhibited consistently higher vibration amplitudes compared to Rollers A and B. Roller A recorded the lowest baseline, while Roller B presented intermediate values with slight fluctuations

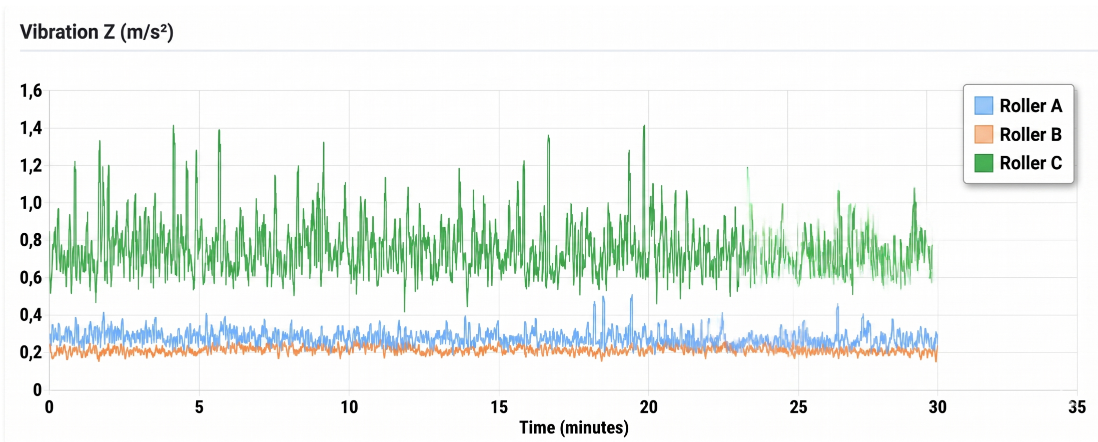

Figure 5.9: Vibration RMS (Z-axis) for Rollers A, B, and C under a 44.7 kg baseline load at a constant 26 RPM.

When the maximum load of 44.7 kg was applied Figure 5.9, the vibration profile for Roller C became highly erratic, presenting severe transient spikes. In contrast,

the RMS values for Roller A and B remained relatively stable despite the increased weight, maintaining a distinct numerical separation from Roller C.
To summarize the vibration trends across all load cases, the estimated peak RMS values are compiled in Table 5.7.

Table 5.7: Summary of observed Vibration RMS characteristics (Z-axis) across varying loads.

Applied Load	**Roller A (Healthy)**	**Roller B (Degraded)**	**Roller C (Failed)**
3.4 kg	0.2516 m/s^2	0.2077 m/s^2	0.3508 m/s^2
18.2 kg	0.4605 m/s^2	0.3016 m/s^2	1.1467 m/s^2
30.8 kg	0.4136 m/s^2	0.3533 m/s^2	1.1586 m/s^2
44.7 kg	0.5071 m/s^2	0.2886 m/s^2	1.4159 m/s^2

The non-contact infrared sensor recorded the continuous 30-minute temperature trend for each load case.

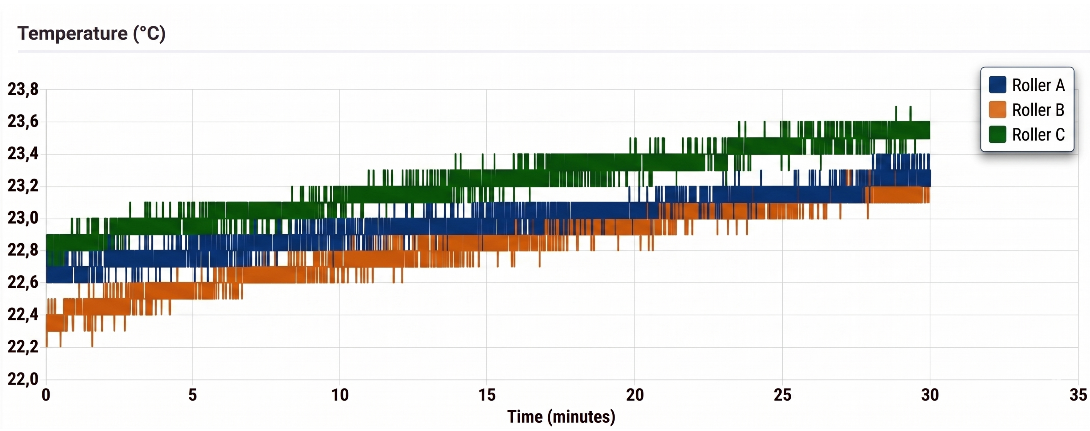

Figure 5.10: Illustrates the results from the temperature measurements.

Under the baseline load of 3.4 kg, the temperature divergence between the three rollers remained minimal. However, as the load increased, a thermal separation emerged. As illustrated in Figure 5.10 for the 44.7 kg load case, Roller C exhibited a continuous temperature rise throughout the 30-minute session, peaking significantly higher than the ambient baseline. Roller A and Roller B maintained stable and lower operating temperatures throughout the same duration. The acoustic RMS levels were captured concurrently to log the sound intensity generated by the rollers.

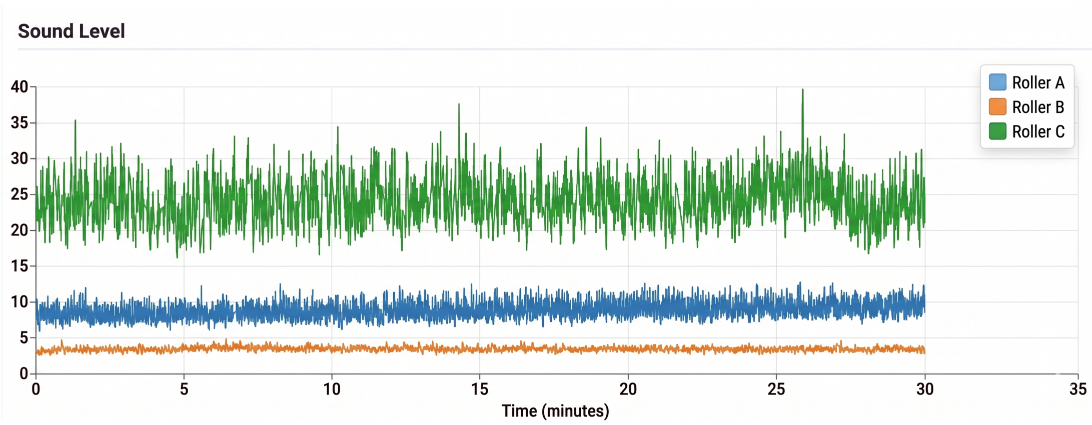

Figure 5.11: Illustrates the results from the temperature measurements.

The acoustic data presented in Figure 5.11 demonstrates that Roller C produced a consistently higher noise floor, punctuated by frequent, high-amplitude acoustic spikes. Roller A maintained the lowest acoustic signature, while Roller B showed moderate elevations compared to the healthy baseline. This separation in sound intensity was consistently observed across the intermediate and heavy load scenario.(see Appendix C)

5.5 Analysis

Iteration 1 (Low-Fidelity)

Analysis of the experimental results from the first iteration indicates that while basic sensor integration was successful, the system's capacity to address Research Question 2 (RQ2) was fundamentally limited. The primary constraint was the binary nature of the vibration and acoustic data, which was programmed in the Arduino IDE to trigger simple text-based alerts based on fixed thresholds. Consequently, the system lacked the data granularity required to differentiate between healthy, degraded, and failed roller states. Without numerical magnitude or frequency data, a catastrophic bearing failure appeared identical to a minor transient vibration on the serial monitor, as both only met the criteria to trigger a generic alert.
Furthermore, the thermal data obtained from the DHT11 sensor reflected general ambient conditions rather than the localized friction-induced heat characteristic of bearing degradation. Because the sensor measured the surrounding air temperature, the resulting uncertainty was too high for it to serve as a reliable indicator of specific roller health. Ultimately, these findings suggest that the low-fidelity setup functioned as a reactive alarm system rather than a predictive monitoring tool. This validation phase was critical as it confirmed that identifying the subtle differences between roller conditions would require the more advanced digital sensors and edge-based signal processing subsequently implemented in the High-fidelity pCMD iteration.

Iteration 2 (High-Fidelity)

The quantitative data collected by the NKT_Tool provides a framework for evaluating the system's diagnostic capabilities. This section analyzes the mechanical implications of the observed sensor data to directly address the secondary research question (RQ2).
To interpret the vibration data, the mechanical orientation of the sensor must be correlated with the physical forces within the bearing. The Z-axis of the ADXL345 accelerometer isolates radial forces. In rolling-element bearings, structural defects such as spalling on the raceways generate impact forces primarily in the radial direction. Therefore, the Z-axis provides a direct, objective measurement of internal mechanical impacts.

The empirical data establishes a clear quantitative distinction between the functional states of the rollers:

- **Roller A (Healthy)** and **Roller B (Degraded)** maintained stable maximum RMS values, remaining below 0.51 m/s^2 and 0.36 m/s^2 respectively across all test scenarios.
- **Roller C (Failed)** demonstrated a distinct divergence. While the baseline radial vibration was 0.3508 m/s^2 under a 3.4 kg load, it escalated significantly to 1.4159 m/s^2 under the maximum 44.7 kg load.

Analytically, this high-amplitude, erratic profile in Roller C confirms a severe loss of internal structural integrity. The continuous generation of severe radial shocks captured by the Z-axis correlates directly with moving elements striking physical deformations within the bearing housing.

The supplementary sensor data objectively corroborates the mechanical deterioration captured by the accelerometer.

Thermal Correlation: The distinct temperature rise in Roller C under the 44.7 kg load correlates analytically with an increase in kinetic friction. The structural failure within the bearing dissipates rotational energy as heat, a condition correctly captured by the MLX90614-DCI sensor.
Acoustic Correlation: The elevated acoustic RMS levels and frequent transient spikes for Roller C correlate with the mechanical impacts registered by the vibration sensor, providing a redundant, objective verification of internal grinding and friction.

The recorded data indicates that fault manifestation is load-dependent. Under the 3.4 kg baseline, the amplitude difference between the rollers was narrow. As the applied load increased to 30.8 kg and 44.7 kg, the vibration amplitudes for Roller C multiplied, and the rotational speed (RPM) visibly dropped. This objectively demonstrates that the internal mechanical resistance of the failed bearing increases non-linearly when subjected to external physical stress.

The analytical correlation of the multi-modal data confirms that the high-fidelity pCMD (NKT_Tool) can accurately differentiate between healthy, degraded, and failed conveyor rollers. By mechanically isolating radial forces (Z-axis) and capturing correlating thermal and acoustic friction data, the system successfully identifies distinct failure signatures. This satisfies the requirements of RQ2.

Chapter 6

Discussion

6.1 Concept Selection

Comparing predictive-maintenance concepts with respect to Reliability, Fault-Detection Sensitivity, and Life-Cycle Cost was systematically addressed using a hybrid multi-criteria decision-making (MCDM) approach combining AHP and TOPSIS. The use of a structured quantitative method was essential to avoid subjective bias, particularly given the uncertainty associated with evaluating ideas that exist only as conceptual designs rather than physically testable prototypes.

AHP and TOPSIS were preferred and considered more suitable than other approaches because AHP supports decision-making when both qualitative and quantitative criteria are involved, while TOPSIS evaluates the performance of alternatives based on their similarity to an ideal solution using Euclidean distance [12]. Although other approaches such as Pugh's method were considered as potential alternatives, they were deemed less suitable because they rely primarily on qualitative comparison and do not incorporate weighted criteria or hierarchical decision structures [37]. In this thesis, the criteria defined during the problem-scoping phase included both qualitative aspects, such as the concepts' Reliability, and quantitative aspects, such as Life-Cycle Cost and Fault-Detection Sensitivity. The AHP approach enabled the assignment of weights to these criteria, thereby providing a structured basis for guiding the concept-selection process.

Integrating AHP and TOPSIS provided a systematic basis for evaluating and selecting among the generated predictive maintenance concepts, thereby directly addressing RQ1.

The consistency ratio of 0.00 indicates that the pairwise comparisons were fully consistent and that the resulting weighting is valid, as values below 0.1 are considered acceptable; ratios above this threshold would require the judgements to be re-examined [38]. The weighting of 57% assigned to Reliability can be explained by the operational conditions at NKT, where unplanned downtime is very costly. In addition, a stopped cableway may negatively affect the cable itself, potentially requiring rework of the damaged section or, in the worst case, scrapping the entire cable. Consequently, the Reliability criterion dominated over Fault-Detection Sensitivity and Life-Cycle Cost.

This weighting, however, may differ in other companies depending on their size, organisational environment, technological readiness, asset landscape, and willingness to accept associated costs [39]. Conducting the same study in a different organisational context could therefore result in different weightings, or even an entirely different set of criteria.

A limitation of the AHP framework in this thesis is the relatively small expert group of seven participants from NKT. This may be partly explained by some experts choosing not to respond to the survey to avoid providing input they were not fully confident about. Another limitation is that standard AHP does not capture potential interdependencies between criteria, such as the relationship between Reliability and Fault-Detection Sensitivity. Additionally, relying solely on internal experts introduces the risk of bias, as their judgements may be influenced by their own previous experiences and operational perspectives.

The set of identified requirements enabled the generation of several concept types. However, some mechanical concepts failed to satisfy the remaining requirements, which explains the relatively small number of mechanical concepts included in the evaluation. Another limiting factor in the concept generation phase was whether a proposed idea could genuinely be classified as a predictive maintenance concept.

A further limitation is that the evaluated concepts were internally developed design proposals rather than alternatives drawn from literature or benchmarking. This constrained the solution space and may have excluded potentially superior concepts that could have performed better in the evaluation. Consequently, the TOPSIS assessment was limited to concepts derived from internal interviews, observations, and fundamental engineering principles.

Another limitation to consider is that none of the concepts were physically built or tested. This restricted the evaluation to assessing ideas solely against predefined requirements, which in turn required estimating the Fault Detection Sensitivity of each concept rather than measuring it empirically. This limitation aligns with the purpose of applying AHP and TOPSIS at the concept selection stage namely, to identify the most promising concept before committing resources to building and testing prototypes, thereby reducing the risk of developing an unsuitable solution.

Concept 1, the Acoustic Roller Inspection Tool, was found to be conceptually paradoxical. Although intended to be mounted on the cable, its reliability score was low because the tool itself could break under the cable's weight, thereby introducing additional failure modes into the system it was meant to protect. If not designed with highly robust materials capable of withstanding harsh conditions and overload, the tool could cause more downtime rather than prevent it. Moreover, because it only inspects the rollers it physically passes over, it cannot be used to investigate areas where abnormal noise is detected, limiting its usefulness as a targeted diagnostic tool.

Concept 2, the Visual Rotation Indicator, was ranked second due to its passive, mechanical, and largely maintenance free design, which justified its high scores in Reliability and Life Cycle Cost. However, its near zero score in Fault Detection Sensitivity highlights a critical distinction between reactive and predictive maintenance. The concept cannot provide quantitative data about roller health and relies entirely on visual observation by operators when rollers slow down or after a failure has already occurred. Since it does not detect or trend degradation over time before failure, it does not meet the definition of predictive maintenance [10, p.5].

Concept 3, the Portable Condition Monitoring Device, was ranked first. Its strong performance can be explained by its intended use as a portable device that operators can temporarily mount at critical locations. Its multi-modal sensing combining vibration, acoustic, and temperature measurements enhances its Fault-Detection Sensitivity by covering the most common failure modes that manifest through these parameters. Its high Life-Cycle Cost score reflects its modularity, ease of replacing failed sensors or components, and portability, which makes it useful across different production stages and cableways. Although it requires operator involvement, the labour cost is outweighed by the device's ability to prevent unplanned stoppages, which are significantly more expensive.

Evaluating the three concepts revealed several trade-offs. For example, Concept 2 performed well in the Life-Cycle Cost estimation but scored very low in Fault-Detection Sensitivity. This highlights a trade-off showing that a low-cost concept does not necessarily guarantee strong predictive-maintenance performance. Another trade-off emerged between passive and active sensing approaches: passive concepts such as Concept 2 offer simplicity and robustness but lack the ability to detect early degradation, whereas active sensing in Concept 3 provides richer diagnostic information.

The evaluation of Concept 1 revealed a trade-off between operational risk and diagnostic capability. Increasing diagnostic capability introduced operational risks, as the tool's design contradicted its intended purpose by potentially adding new failure modes to the system. This made Concept 3's non-intrusive sensing approach more appropriate. A further trade-off was observed between simplicity and information richness: concepts that were easy to implement provided limited diagnostic insight, while Concept 3 required more components but delivered significantly more useful information about cableway conditions.

The alignment of Concept 3 with NKT's production environment can be explained by insights from interviews and observations. In several cases, a failed roller does not immediately damage the cable, meaning that a stationary monitoring solution is not required everywhere but only in critical locations. Additionally, operators are already present around the cableways during operation, and when abnormal noise or vibration is detected, they naturally approach the area to investigate. Concept 3 fits this workflow by providing a tool that operators can deploy to detect failures before a catastrophic stoppage occurs.

Ultimately, the concept selection in this thesis should be viewed as a decision-support approach rather than definitive proof that the chosen concept is universally the most suitable. The generated concepts may perform poorly when compared with alternatives not included in this study, and the criteria used should not be considered absolute, as they may differ with additional or external input. Therefore, answering the second research question, through experimental validation will determine whether the selected concept is truly suitable for NKT's equipment.

6.2 Validation Results

The secondary research question guiding this study RQ2: *To what extent can the selected monitoring solution distinguish between healthy, degraded, and failed cableway rollers under controlled test conditions?*

The empirical data firmly demonstrates that the selected multi-modal monitoring solution can accurately and quantitatively distinguish between the three functional states, provided that sufficient mechanical stress is applied. The primary line of evidence stems from the radial vibration profiles (Z-axis). When analyzing the data patterns, Roller A (healthy) and Roller B (degraded) maintained relatively stable kinetic profiles, with maximum RMS values not exceeding 0.51 m/s^2 and 0.36 m/s^2, respectively, regardless of the applied weight. Roller C (failed), however, demonstrated a severe, non-linear escalation in vibration amplitude, peaking at 1.41 m/s^2 under the maximum load of 44.7 kg.

An unexpected finding during the data collection further solidifies this conclusion. Under the 30.8 kg and 44.7 kg loads, the internal friction of Roller C generated such substantial mechanical resistance that it overcame the torque of the test rig's driving motor, causing observable drops and fluctuations in rotational speed (RPM). While this introduced a slight variable inconsistency regarding continuous speed, it inadvertently served as an undeniable, physical confirmation of severe bearing failure. This highlights that fault manifestation is highly load-dependent; under the 3.4 kg baseline, the amplitude difference between the rollers was narrow. Therefore, it could be argued that the device's diagnostic extent is somewhat limited under no-load conditions, but highly accurate and reliable when the components are subjected to operational stress.

These vibration trends are strongly supported by the additional sensor data. The clear temperature rise and higher acoustic levels observed in Roller C directly match the mechanical vibrations measured by the accelerometer. By analyzing all three data sources together, the system avoids the common problem of false alarms that can occur when relying on just one sensor. This demonstrates that the monitoring solution can reliably determine the condition of the rollers.

Furthermore, the specific thermal behavior observed in Roller C under elevated loads aligns perfectly with the previously published knowledge established in the Related Work section of this thesis. As highlighted in the review of common idler failure modes [16], temperature monitoring is particularly effective at identifying catastrophic or severe fault stages, because significant thermal emissions typically only occur when internal friction has reached a critical level. It could be argued that while a localized temperature rise is a robust and undeniable indicator of a completely failed bearing (such as Roller C at 44.7 kg), it is inherently less sensitive to early-stage wear compared to acoustic or vibration data. Single-measurement approaches relying solely on temperature risk missing these early-stage issues [16].

On the one hand, thermal data provides absolute confirmation of late-stage failure, but on the other hand, detecting incipient faults before they generate significant heat requires high-resolution acoustic and vibrational analysis, especially at lower operational speeds. This aligns directly with the literature reviewed on low-speed bearing diagnostics [17]. Traditional vibration energy may be insufficient to trigger clear diagnostic thresholds at low rotational speeds. However, as demonstrated in the related work [17], acoustic emission techniques combined with appropriate signal processing can successfully capture periodic fault signatures even at extremely low shaft speeds ranging from 0.33 to 10 Hz.

Therefore, by successfully integrating acoustic measurements alongside thermal and vibration sensors, the NKT_Tool effectively addresses the theoretical limitations identified during the literature review, bridging the gap between early incipient fault detection and late-stage catastrophic failure confirmation.

During the analysis, an unexpected anomaly was observed in both the acoustic and vibration data that needs to be addressed. It was logically anticipated that Roller B, categorized as "degraded," would consistently produce higher vibration amplitudes and acoustic signatures than the "healthy" Roller A. However, as clearly illustrated in the quantitative results (e.g., Table 5.7 and Figures 5.8–5.9), the empirical data revealed the opposite trend across all load cases; Roller A consistently generated higher radial vibrations (Z-axis RMS) and acoustic noise levels than Roller B. For instance, under the maximum 44.7 kg load, Roller A recorded a vibration RMS of 0.5071 m/s^2 compared to Roller B's 0.2886 m/s^2.

Another possible explanation may be traced back to the physical assembly and seating dynamics of the bearings. While Roller A was functionally healthy, it utilized a newly replaced bearing within an older roller casing. It could be argued that microscopic variations in installation tolerances, seating tension, or internal clearances during the manual bearing replacement process can introduce subtle structural shifts. These minute assembly variations can translate into elevated mechanical vibrations and acoustic noise when subjected to radial stress. On the one hand, Roller B suffered from internal wear, but on the other hand, its original bearing remained perfectly seated in its factory-installed position, resulting in a significantly quieter and smoother rotation, albeit degraded.

This unexpected divergence underscores a critical aspect of condition monitoring: maintenance interventions and assembly variations can introduce new mechanical variables that mimic or mask fault signatures. Consequently, this highlights a clear limitation regarding the sample size used in this validation phase. To establish a definitive, statistically reliable baseline for distinguishing between a healthy assembly and a degraded roller, a significantly larger batch of identical rollers must be tested in future studies to account for these natural mechanical and installation variances.

6.3 Validation Results: The Custom Test Rig

The validation of the NKT_Tool heavily relied on the custom-built test rig. From a methodological standpoint, the rig successfully fulfilled its primary objective: to safely and consistently simulate the mechanical stress and radial loads required to evaluate conveyor roller degradation. By allowing the controlled application of weights up to 44.7 kg, the test rig made it possible to observe the non-linear relationship between load, friction, and vibration amplitudes in a secure and controlled environment.

However, it is crucial to address the material composition and structural design of the rig. The test rig framework was constructed primarily from wood, whereas industrial conveyor systems at the NKT facility are built from heavy-gauge steel. This material divergence has mechanical implications, as wood inherently possesses higher vibration-damping characteristics and lower structural rigidity than steel. Consequently, the acoustic and vibrational propagation through the wooden frame likely differed from how fault frequencies would travel through a solid steel industrial structure.

To investigate the potential interference of the wooden frame, manual vibrations were physically applied to the rig structure during preliminary testing. However, because the NKT_Tool utilizes strong neodymium magnets to couple directly to the metallic roller shaft, the ADXL345 accelerometer did not register these external structural vibrations unless the roller itself was in motion. This confirms that the magnetic coupling successfully isolated the tool from external rig noise, ensuring that the sensor primarily captured the internal dynamics of the bearing.

Regarding the absolute accuracy of the output, it must be acknowledged that the quantitative data cannot be considered 100 percent flawless due to the physical design of the tool casing. Discussions within the team raised concerns about whether the PLA plastic housing was excessively dampening the vibration signals before they reached the internal ADXL345 sensor. To test this hypothesis, an experiment was conducted where the bare accelerometer was taped directly onto the roller shaft, bypassing the PLA casing. The data recorded from the taped sensor did not differ significantly from the data recorded when the sensor was housed inside the NKT_Tool.

On the one hand, relying on tape for sensor mounting introduces severe inconsistencies, as the pressure and angle of the tape cannot be perfectly replicated when moving the sensor between Rollers A, B, and C, rendering the taped data less reliable for comparative analysis. And on the other hand, even if the PLA casing introduces a slight dampening effect, all official tests were conducted under the exact same conditions with the sensor mounted inside the casing. Therefore, any potential signal attenuation was constant across all test cases, meaning the relative differences and resulting trends between the healthy and failed rollers remain entirely valid and unaffected.

It could also be argued that the physical design of the tool significantly improved the data quality for the supplementary sensors. The MLX90614-DCI temperature sensor and the INMP441 acoustic sensor were housed within an external black enclosure. Because the MLX90614-DCI has a narrow 5° Field of View (FOV), this specific enclosure design ensured that the sensor only measured the temperature in the exact gap between the bearing and the roller body, effectively filtering out ambient environmental temperatures. This targeted reading successfully captured the localized heat generated by kinetic friction, as demonstrated in the final results.

Another possible explanation may be that this black enclosure acted as a crucial acoustic isolator for the INMP441 microphone. During testing, it was observed that talking or clapping next to the active test rig did not significantly alter the acoustic RMS output. The enclosure functioned as a directional channel, isolating the sensor from surrounding environmental noise and ensuring it only received the specific sound waves emanating directly from the targeted bearing housing.

Furthermore, the physical dimensions of the rig were specifically tailored to accommodate the exact size of the selected sample rollers. It is not currently adjustable for significantly shorter or longer roller variants. However, it is important to emphasize that the core objective of this research phase was to validate the diagnostic capabilities and multi-modal sensor fusion of the NKT_Tool itself, rather than engineering a universally modular test bench. The rig and the subsequent sensor validation tests effectively isolated the variables under investigation, proving that the theoretical concept of low-cost condition monitoring translates effectively into physical practice when evaluating isolated components.

6.4 Limitations and Threats to Validity

To ensure the comprehensive scientific integrity of this research, it is necessary to outline the remaining limitations and threats to validity that extend beyond the immediate physical and structural constraints discussed previously. A primary threat to external validity is the fundamental environmental discrepancy between the controlled laboratory setting and an active industrial production line. While the test rig effectively simulated mechanical stress, it operated in a clean, ambient environment. In contrast, heavy-duty cable manufacturing facilities are typically characterized by high levels of airborne particulate matter, temperature fluctuations, and a highly complex acoustic noise floor generated by adjacent heavy machinery. The prolonged exposure of low-cost components, such as the INMP441 acoustic sensor, to such harsh environmental conditions raises valid concerns regarding their long-term reliability and potential sensor drift, which could not be fully evaluated within the timeframe of this study [40].

Furthermore, a significant threat to internal validity exists regarding the nature of the applied load during the validation phase. The custom test rig utilized static hanging weights to simulate radial stress on the rollers. However, in an active industrial cable transport system, rollers are subjected to highly dynamic and unpredictable loads caused by varying cable tension, the immense weight of continuous high-voltage cables, and sudden kinetic impacts as heavy cables shift or are pulled across the line. These dynamic forces could introduce transient vibration spikes that the current RMS threshold logic might temporarily misinterpret as bearing degradation. Processing continuous, dynamic audio and vibration data streams on ESP-series microcontrollers under such erratic conditions demands highly optimized hardware resource and buffer management to prevent latency issues or false diagnostic alerts [41].

Regarding construct validity, it must be acknowledged that the developed tool relies primarily on overall vibration and acoustic RMS values to determine component health. While this method effectively and affordably flags general mechanical degradation, it inherently lacks the diagnostic granularity of advanced frequency-domain techniques, such as Envelope Analysis or Fast Fourier Transform (FFT) utilized in high-end, seismic-grade industrial equipment [42]. Consequently, it could be argued that while the device can successfully alert an operator to a failing roller, it cannot precisely pinpoint the specific internal defect, such as differentiating between an inner race spall, an outer race fracture, or a ball defect.

Additionally, a larger dataset involving numerous rollers at continuous stages of degradation would be required in the future to train precise predictive algorithms, as the expansion of dataset scale is critical for comprehensive model learning in condition monitoring [43]. Despite these limitations, the findings remain highly relevant; the system is not intended to replace complex vibration analyzers, but rather to serve as an accessible, first-line early warning system. Recognizing these constraints simply paves the way for future implementation algorithms and vital environmental calibration on the actual factory floor.

6.5 Sustainability and Economic Implications

In most production environments, unplanned stoppages inevitably introduce unnecessary costs, additional labour, and rework [44]. This highlights why economic considerations are essential in engineering decision-making: solving the problem of unplanned stoppages directly reduces substantial operational losses. This also explains why the Life-Cycle Cost criterion received a relatively high weighting in this context, and why the economic benefits of the proposed concept align with NKT's operational needs.

Interviews conducted at NKT further emphasised this point. Although the exact cost of one hour of unplanned stoppage is confidential, it was consistently described as significantly high. This implies that even a concept that might appear expensive in another context becomes economically justified at NKT, as its cost remains negligible compared with the financial impact of a single unplanned stoppage.

It is also important to acknowledge that the proposed concept has only been tested in prototype form. Therefore, estimating the cost of upgrading it into a fully functional predictive-maintenance product is necessary. Initial cost indications include a customised printed circuit board (PCB) costing between 500 and 2000 SEK[45], a microcontroller costing approximately 216 SEK, an alternative vibration sensor costing around 655 SEK [46], an acoustic sensor costing up to 338 SEK [47], and an infrared sensor costing approximately 386 SEK [48]. These figures should be interpreted cautiously, as component prices vary and additional components may be required depending on the final design.

Regarding sustainability implications, the findings of this work indicate that maintenance activities can enhance sustainability performance As maintenance contributes to economic, environmental, and social benefits [49]. At NKT, unplanned stoppages sometimes lead to material waste or rework, particularly in severe cases where parts of the cable must be discarded. This increases material consumption and energy use, which contradicts sustainability goals. Therefore, deploying a predictive-maintenance concept aligns with sustainability by reducing waste, preventing unnecessary energy consumption, and supporting more stable and efficient production.

Chapter 7

Conclusions and Future Work

This chapter presents the conclusions derived from the main contributions of this work, along with recommendations for future research that address the limitations identified throughout the study.

7.1 Conclusions

This thesis was conducted to address the problem of reducing the cost of unplanned stoppages in a production environment where even one hour of downtime is unacceptable. The work focuses on developing a predictive-maintenance concept that aligns with a set of predefined requirements and constraints. A systematic concept-selection process was applied through a hybrid framework that actively involved stakeholders, not only in identifying the need but also in defining the criteria, weighting, and requirements. The selected concept was subsequently implemented in an experimental setup to investigate its functionality.

To answer RQ1, a hybrid MCDM framework integrating AHP and TOPSIS was applied. The findings showed that the Reliability criterion dominated with a weighting of 57%, highlighting the need for a highly reliable predictive-maintenance solution to address the increasing cost of unplanned stoppages at NKT. A Consistency Ratio (CR) of 0.00 confirmed the validity of the calculations and expert judgments, indicating that the weighting results were robust and suitable for use in the TOPSIS evaluation. The Portable Condition Monitoring Device (pCMD) emerged as the top-ranked concept with a closeness value of 0.5612, reflecting its suitability for the deployment context.

Concept 1 was filtered out due to its operating mechanism, which introduced new failure risks to the cableway system it was intended to protect. Concept 2, although highly reliable, was disqualified because it could not detect or trend degradation before failure occurred, meaning it did not satisfy the definition of a predictive-maintenance solution. Therefore, the selection of Concept 3 (pCMD) was not merely a qualitative conclusion but a conceptually justified outcome grounded in NKT's specific operational context.

To answer the second research question, the NKT-Tool successfully distinguished between healthy, degraded, and failed rollers under controlled conditions, primarily through vibration RMS measurements on the Z-axis. The empirical results demonstrated that fault manifestation is highly load-dependent, meaning the separation between the roller states became much clearer at higher operational loads. For example, under the maximum tested load of 44.7 kg, the failed roller generated a severe vibration peak of 1.4159 m/s^2, which was significantly higher than the healthy roller (0.5071 m/s^2) and the degraded roller (0.2886 m/s^2). These distinct vibration patterns were directly supported by concurrent increases in localized temperature and acoustic noise, confirming that the multimodal solution can accurately evaluate roller health when subjected to sufficient mechanical stress. An unexpected finding was that Roller A produced higher vibration readings than Roller B across all load cases, which was attributed to bearing seating dynamics following a manual bearing replacement, highlighting that assembly variations can introduce mechanical variables that complicate fault signature interpretation.

Combining the two research findings demonstrates that a systematic concept-selection process leads to an effective final choice. When selection is performed systematically using a hybrid framework such as AHP-TOPSIS, stakeholders become directly involved. In this work, stakeholders did not only express their needs and requirements, they also enhanced the understanding of the problem and contributed to identifying a solution that is both suitable and context-appropriate. This approach increases the effectiveness of the work and avoids time wasted on exploring unsuitable alternatives.

However, the validation of this work and the NKT-Tool was conducted in a laboratory setting, which highlights that the conclusions regarding the concept's detection capability are bounded by the experimental setup. A full confirmation of its performance requires field validation to assess the concept's sustainability and robustness in NKT's real operating environment over a longer time frame. Nevertheless, this work demonstrates that developing a low-cost, portable, multimodal condition-monitoring concept is technically feasible. No prior study has evaluated and compared mechanical and sensor-based predictive-maintenance concepts for low-speed cableway systems using AHP–TOPSIS, nor demonstrated multimodal portable condition monitoring for this type of application. This work therefore contributes both a systematic evaluation methodology and a validated sensing approach to a problem that existing literature has not previously addressed. By doing so, it supports NKT in maintaining the essential production infrastructure on which the modern sustainable-energy sector depends.

7.2 Future Work

The most natural and important next step is testing the NKT_Tool in NKT's actual production environment rather than solely on the custom laboratory test rig. While the lab environment provided a controlled baseline, field testing would expose the device to the true conditions of the factory floor, including airborne dust, oil, varying cable tension, and a complex acoustic noise floor generated by adjacent heavy machinery. Testing the device in this active environment is essential to establish real detection thresholds based on actual operational stresses, rather than relying on laboratory estimates. Furthermore, this exposure will allow for necessary long-term reliability testing. The impact of harsh environmental conditions on the sensors' performance could not be fully evaluated within the timeframe of this experimental work. Extended durability testing is required to determine whether the current 3D-printed enclosure provides adequate environmental protection and to identify what periodic maintenance the diagnostic device itself might require to function reliably over time.

To build upon the initial findings, future work must also involve testing a significantly larger and more varied sample of rollers. The validation phase of this study was limited to a sample size of three specific rollers: one healthy, one degraded, and one failed. Evaluating components at continuous, incremental stages of degradation will help establish statistically meaningful detection thresholds. This expanded sample size is necessary to assess whether the observed vibration RMS patterns remain consistent across identical rollers. Additionally, as NKT's cableway architecture is not standardized, future research should evaluate whether the current multi-modal detection approach generalizes easily across different roller geometries and rotational speeds, or if separate baseline profiles must be calibrated and saved for each specific roller variant utilized within the facility.

On the hardware level, the current high-fidelity prototype was assembled using an ESP32 development board and sensor modules soldered onto a basic prototype board. While this approach successfully validated the concept, the hardwired components mean that replacing a single faulty sensor is currently not a quick process. A practical future step is the design of a custom Printed Circuit Board (PCB) featuring modular, plug-and-play connectors. As noted in the sustainability and economic implications (Section 6.5), transitioning to a custom PCB is a cost-effective upgrade. Developing a dedicated, modular board would improve the device's structural robustness against industrial vibrations and ensure that it fully satisfies the maintainability requirements for long-term, routine use. Furthermore, the physical form factor of the device is expected to evolve alongside these internal electronics. The current enclosure was specifically dimensioned to facilitate validation on the custom test rig and does not represent a final product design. In future iterations, the external casing can be redesigned, such as adopting a circular profile or a significantly lower height, to accommodate the specific spatial constraints and mounting requirements of different cableways across the production lines.

Finally, while the prototype successfully detects and logs multi-modal sensor values through a graphical user interface, it does not yet automatically classify roller health or trigger independent alerts. An important next step is the development of an automated classification system. Whether through rule-based thresholds or a simple machine learning classifier, the software must be advanced to process the raw sensor data and provide operators with a clear, immediate health status indication without requiring manual data interpretation.

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Appendix A

Test Rig with different Weights

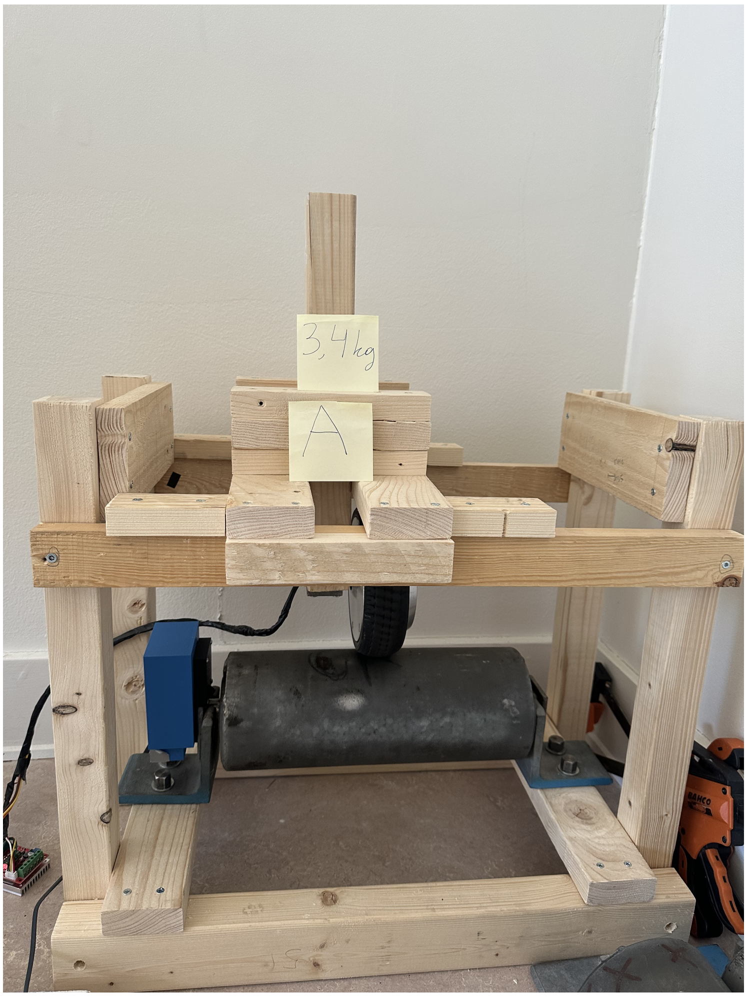

Figure A.1: Components used in the experimental setup - Roller A, 3.4kg load.

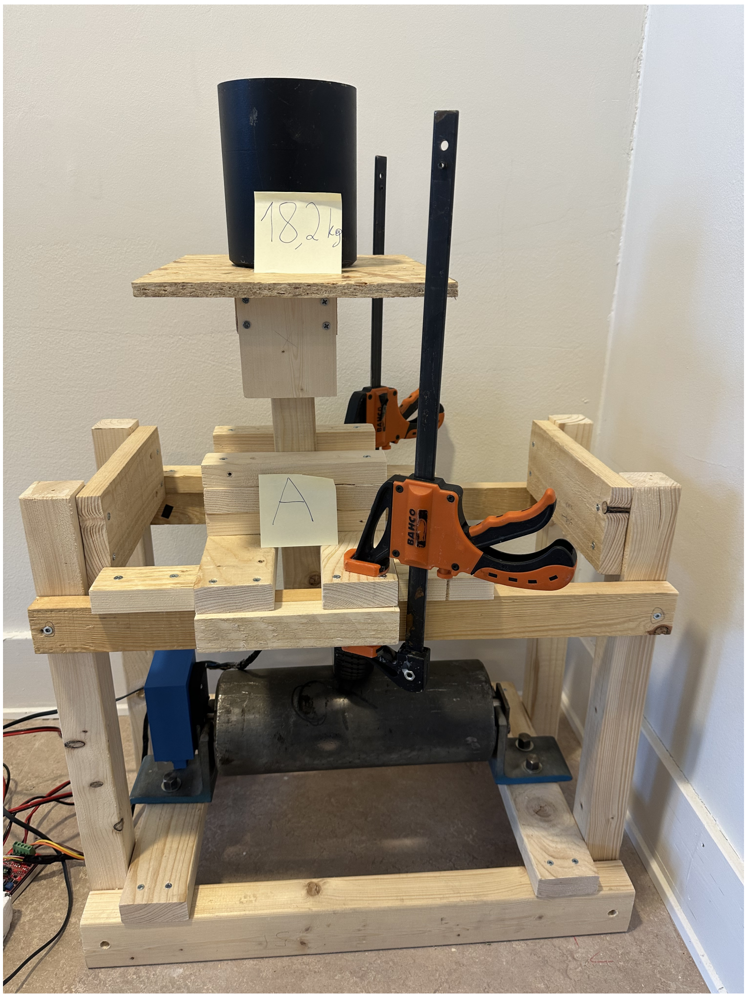

Figure A.2: Components used in the experimental setup - Roller A, 18.2kg load.

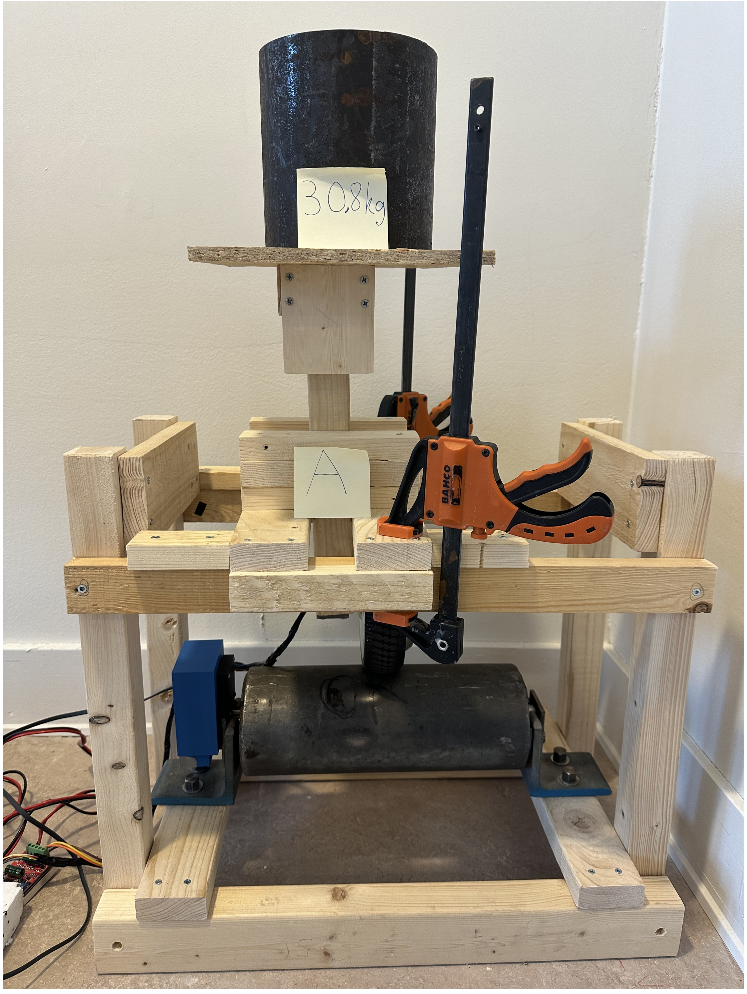

Figure A.3: Components used in the experimental setup - Roller A, 30.8kg load.

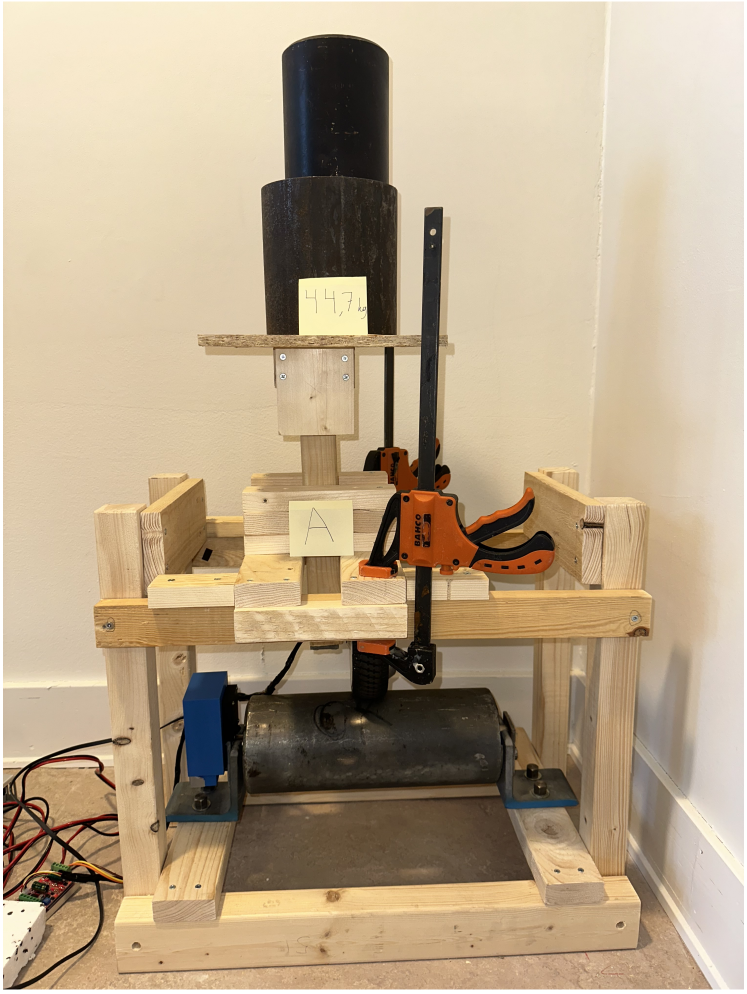

Figure A.4: Components used in the experimental setup - Roller A, 44.7kg load.

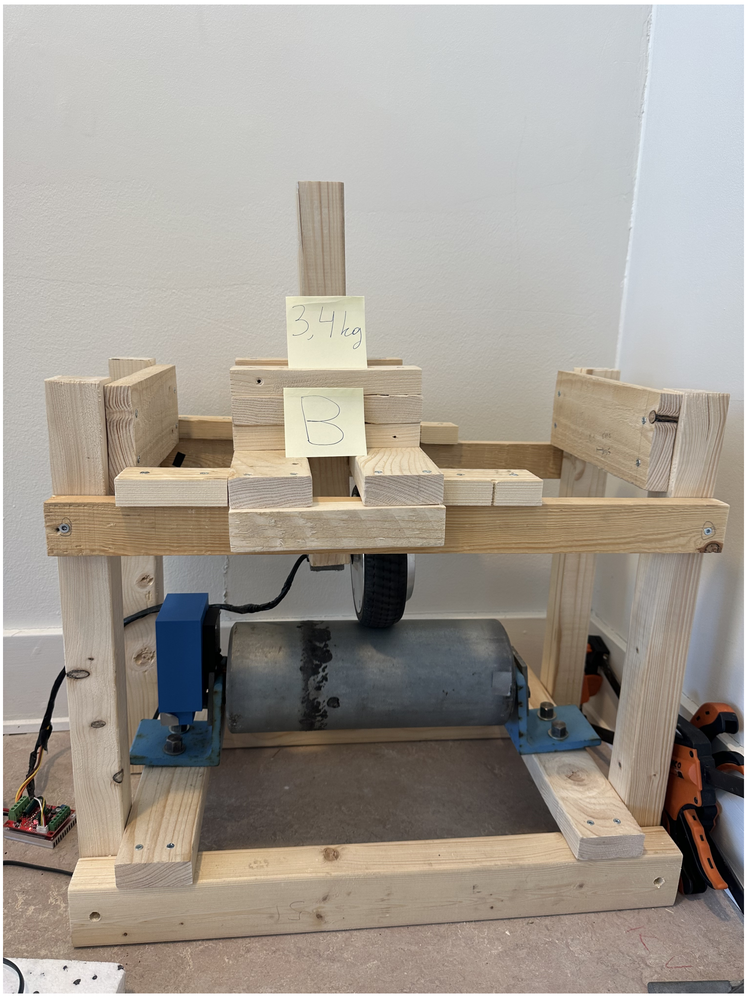

Figure A.5: Components used in the experimental setup - Roller B, 3.4kg load.

Figure A.6: Components used in the experimental setup - Roller B, 18.2kg load.

Figure A.7: Components used in the experimental setup - Roller B, 30.8kg load.

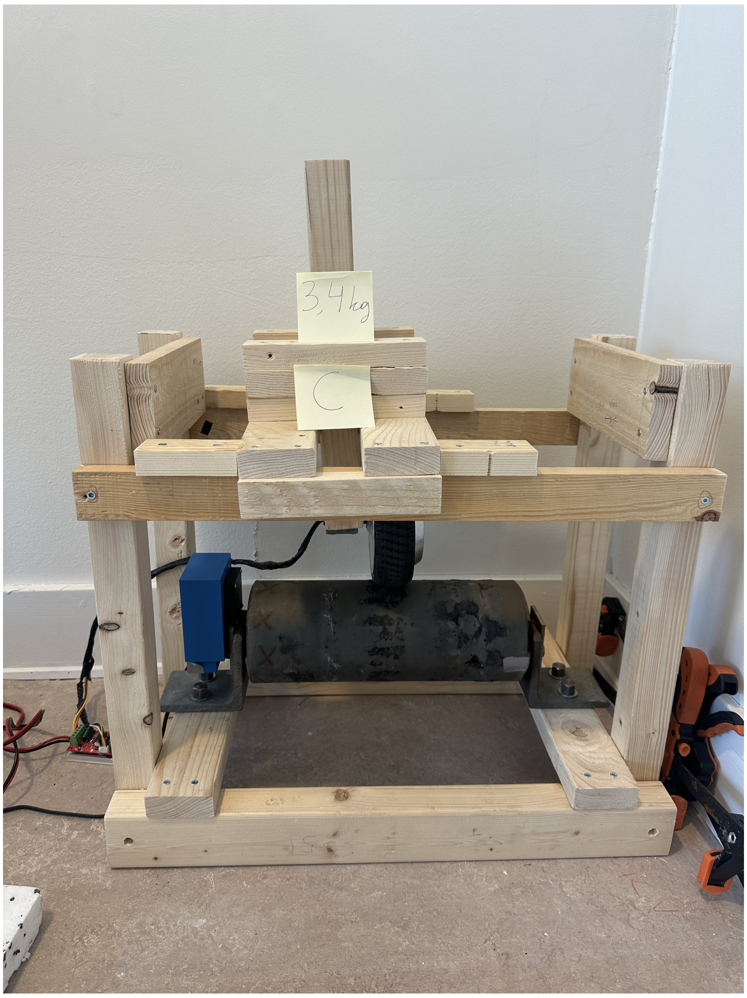

Figure A.8: Components used in the experimental setup - Roller C, 3.4kg load.

Figure A.9: Components used in the experimental setup - Roller C, 18.2 kg load.

Figure A.10: Components used in the experimental setup - Roller C, 30.8 kg load.

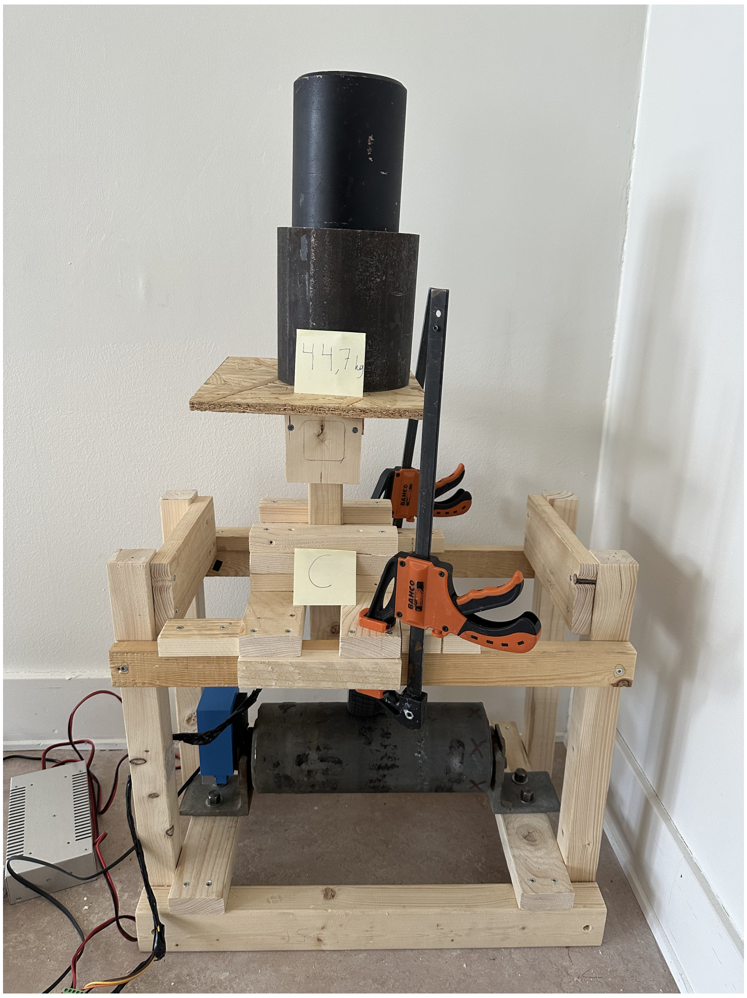

Figure A.11: Components used in the experimental setup - Roller C, 44.7kg load.

Appendix B

Aseembled NKT_Tool

Figure B.1: Front view of the assembled NKT_Tool showing the internal electronics, LED display, and transparent casing.

Figure B.2: Side view of the NKT_Tool prototype featuring the manual power toggle switch and charging port access.

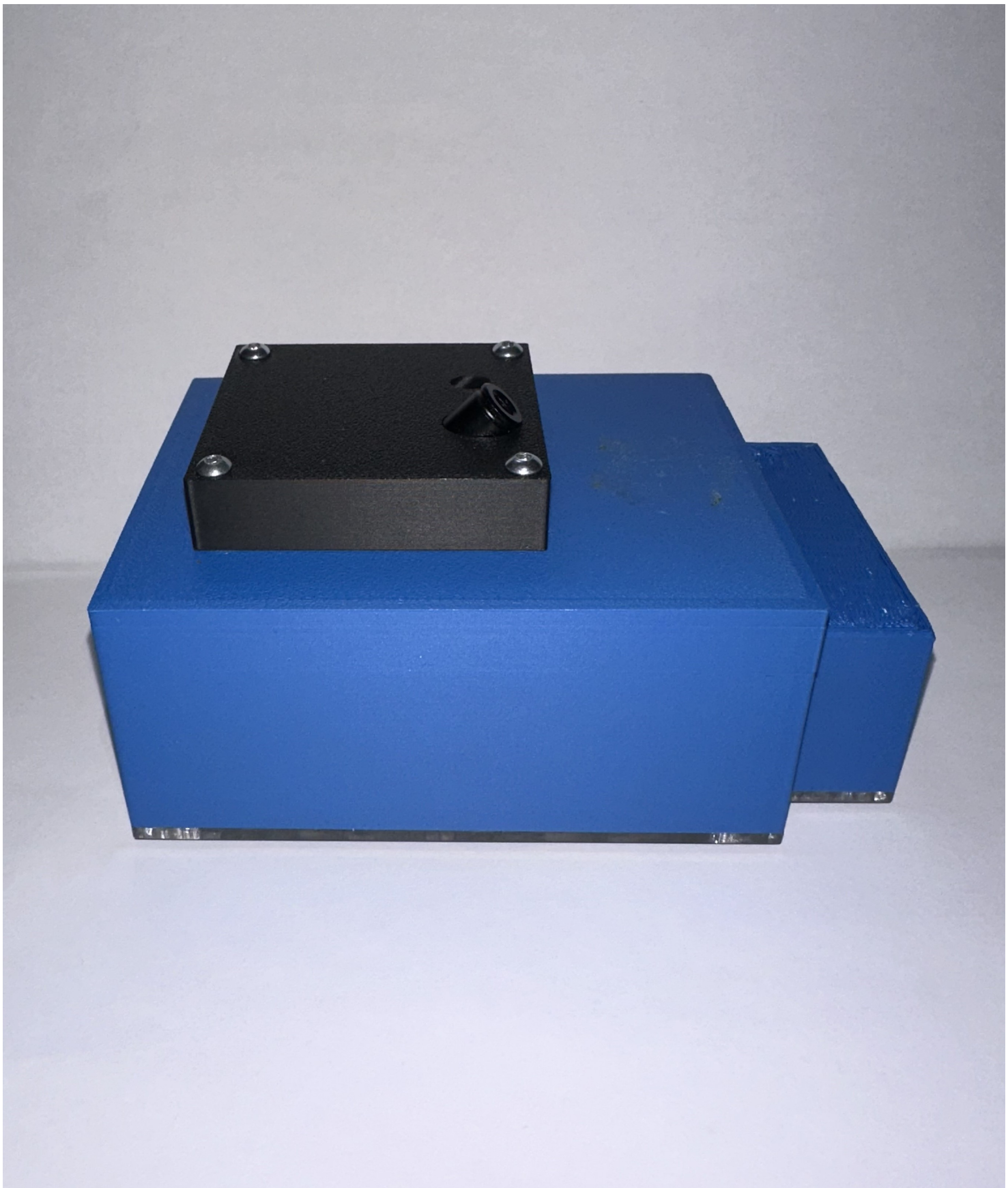

Figure B.3: Rear view of the NKT_Tool highlighting the mounted sensor housing and the robust 3D-printed main casing.

Appendix C

Result_Graphs

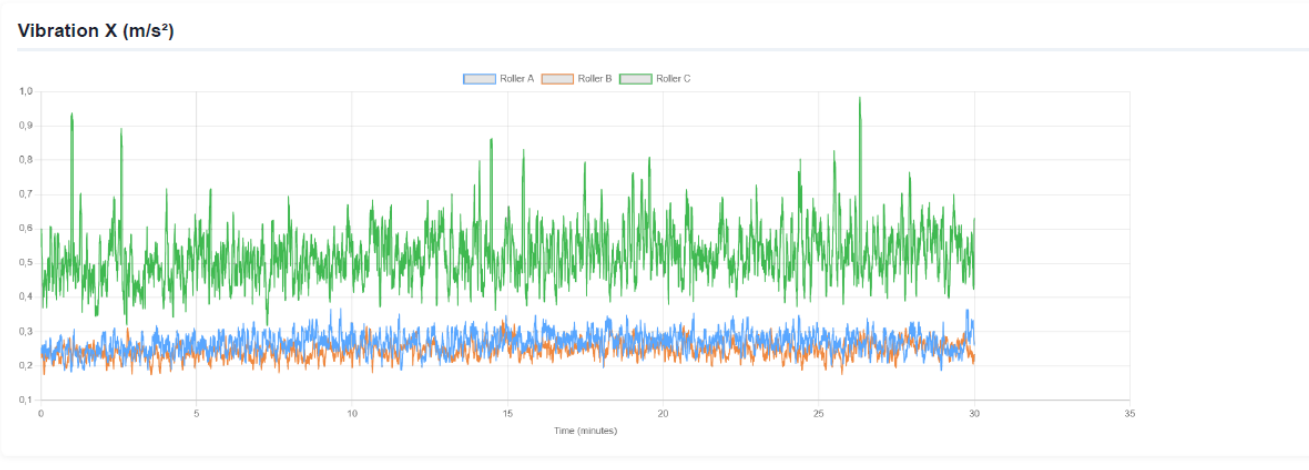

Figure C.1: Vibration data for X-axis with 3.4kg load.

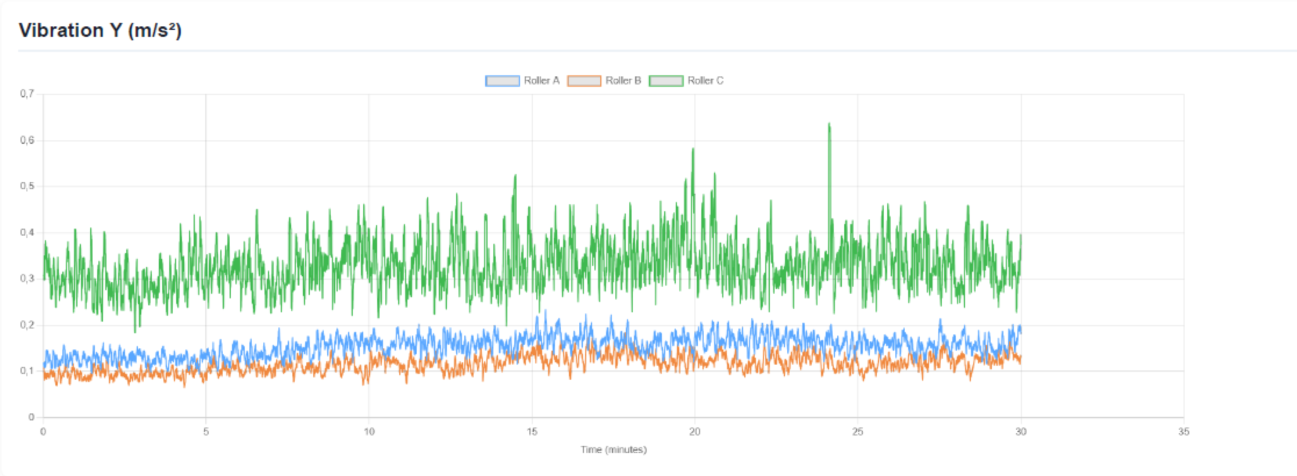

Figure C.2: Vibration data for Y-axis with 3.4kg load.

Figure C.3: Vibration data for Z-axis with 3.4kg load.

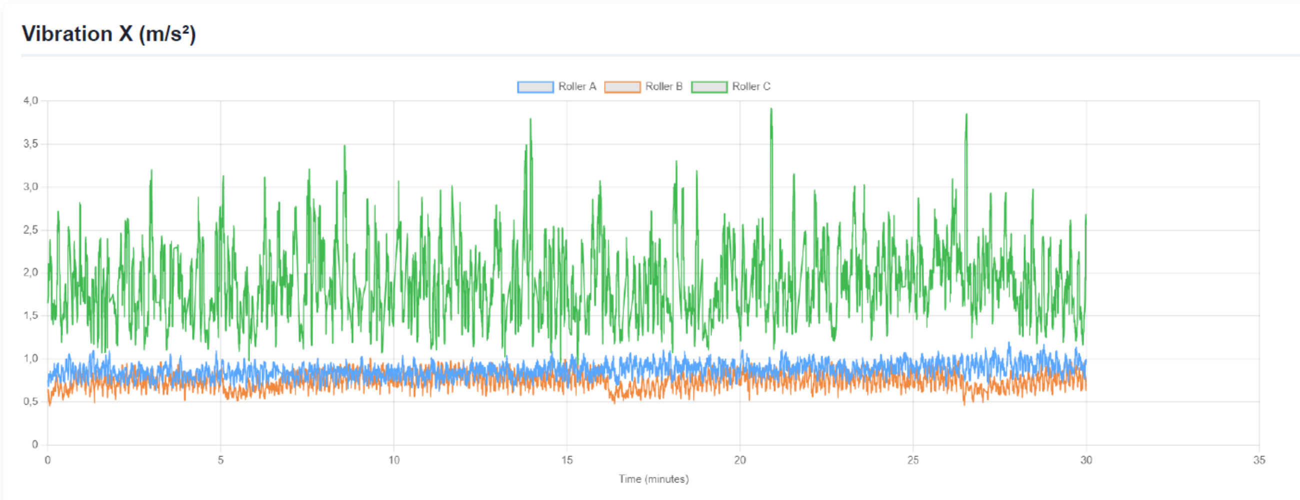

Figure C.4: Vibration data for X-axis with 18.2 kg load.

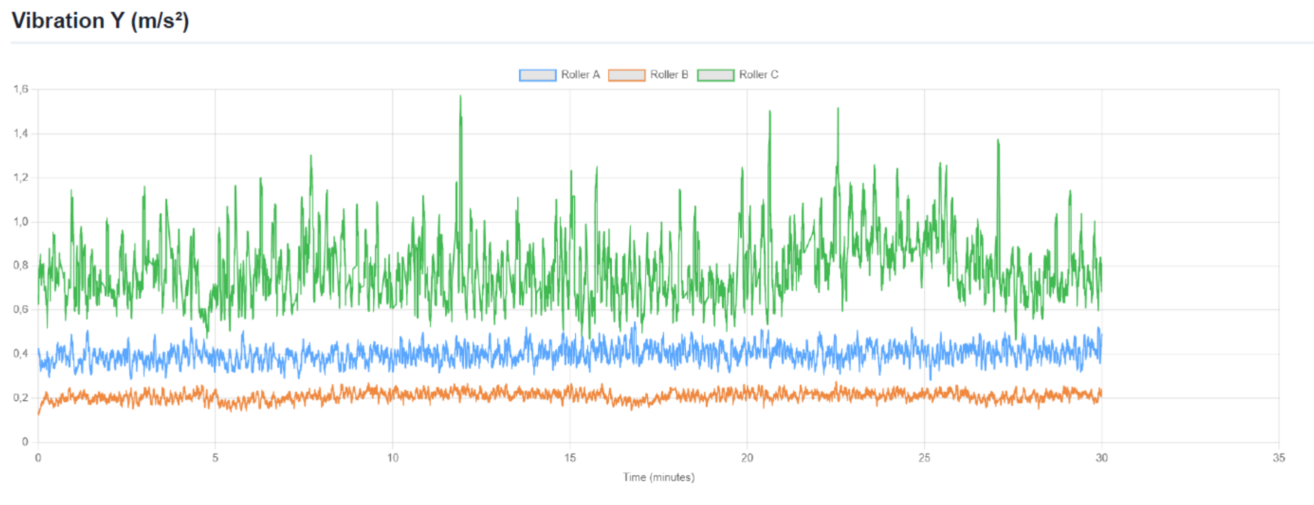

Figure C.5: Vibration data for Y-axis with 18.2 kg load.

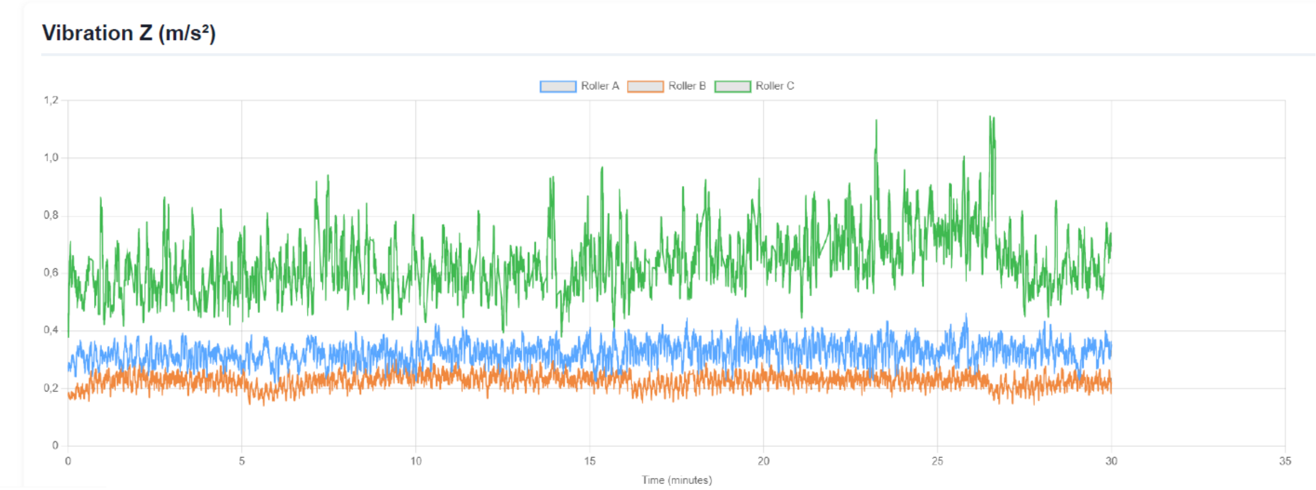

Figure C.6: Vibration data for Z-axis with 18.2 kg load.

Figure C.7: Vibration data for X-axis with 30.8 kg load.

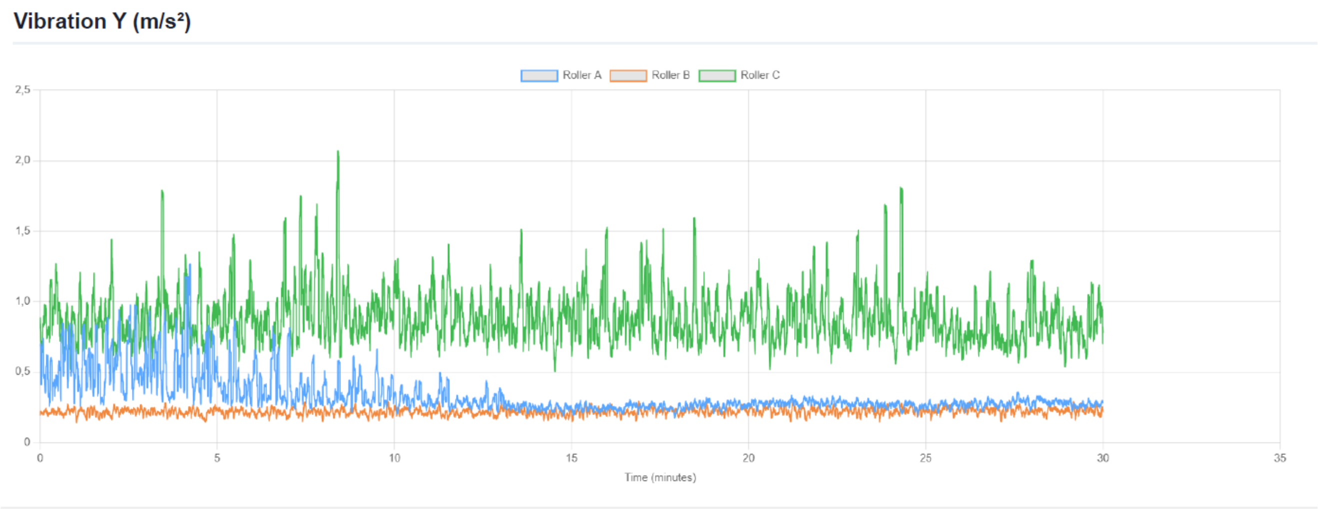

Figure C.8: Vibration data for Y-axis with 30.8 kg load.

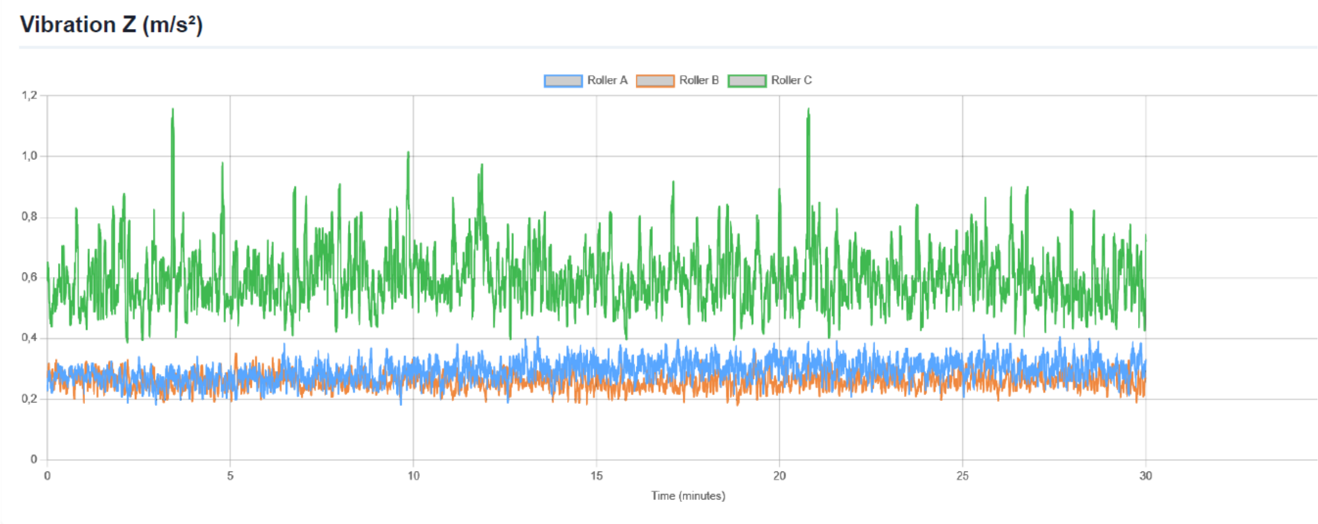

Figure C.9: Vibration data for Z-axis with 30.8 kg load.

Figure C.10: Vibration data for X-axis with 44.7 kg load.

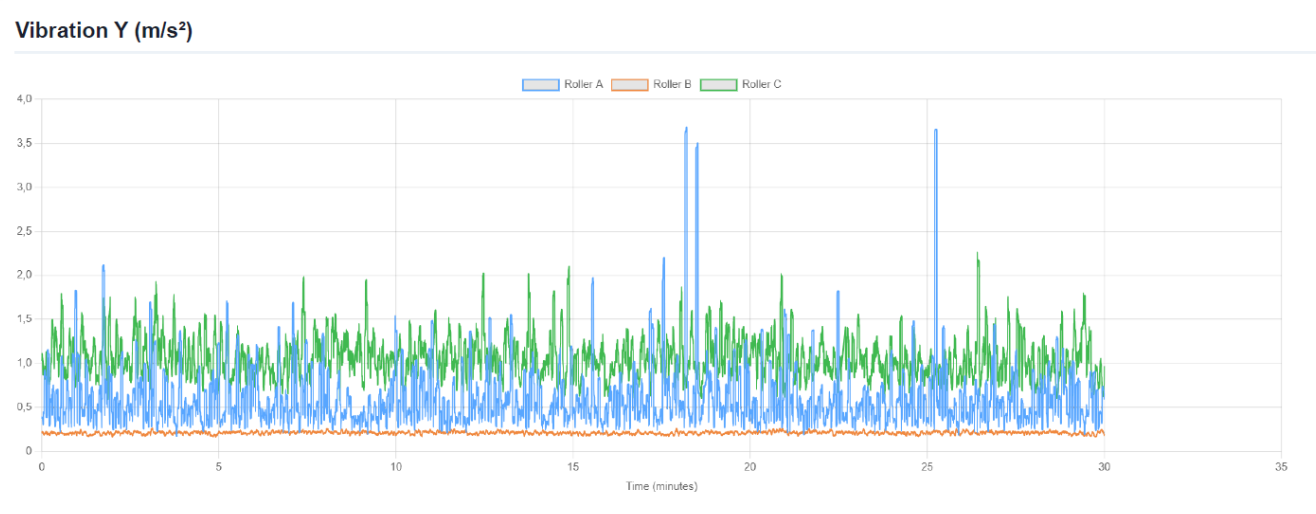

Figure C.11: Vibration data for Y-axis with 44.7 kg load.

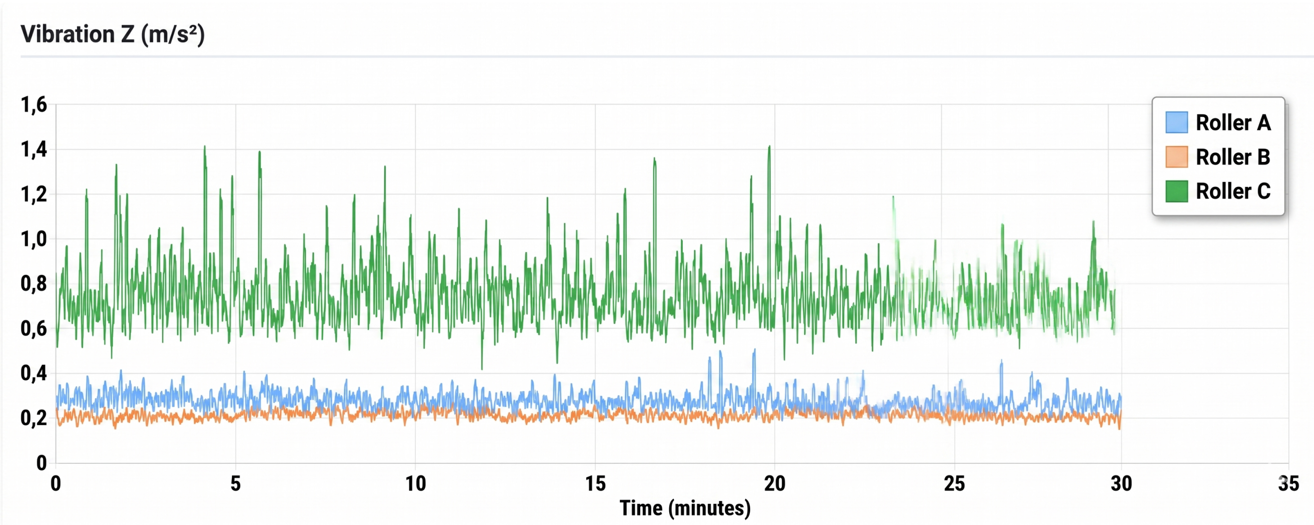

Figure C.12: Vibration data for Z-axis with 44.7 kg load.

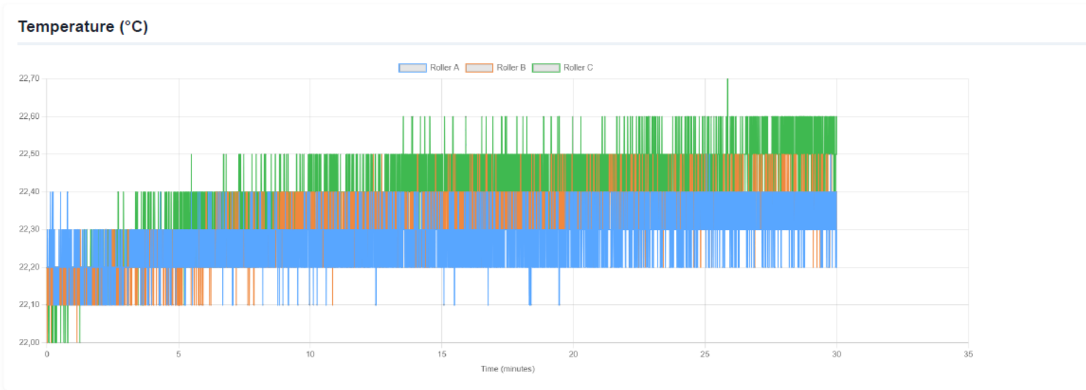

Figure C.13: Temperature trends over 30 minutes for Roller A, B, and C with a 3.4kg load.

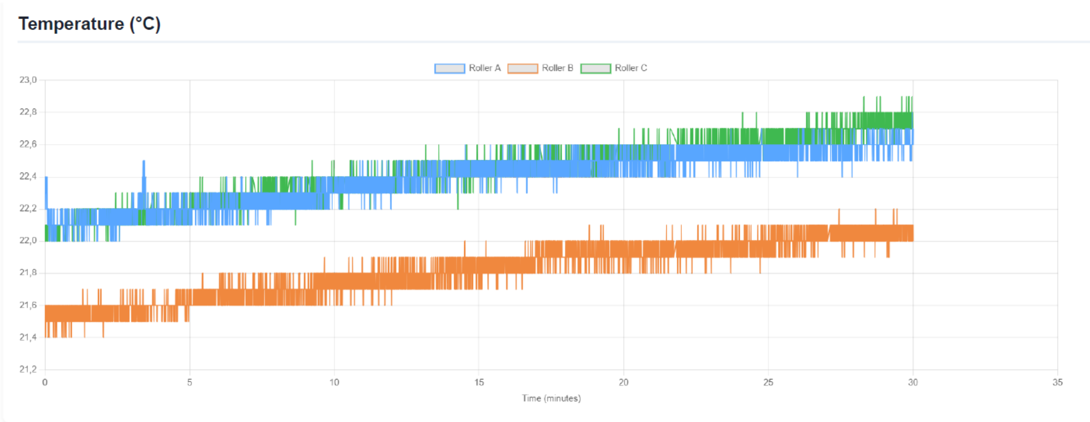

Figure C.14: Temperature trends over 30 minutes for Roller A, B, and C with a 18.2kg load.

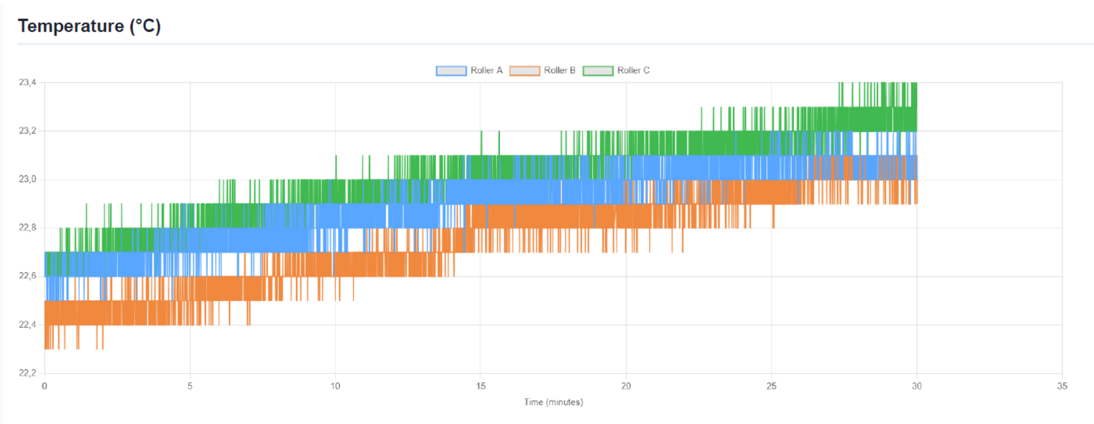

Figure C.15: Temperature trends over 30 minutes for Roller A, B, and C with a 30.8kg load.

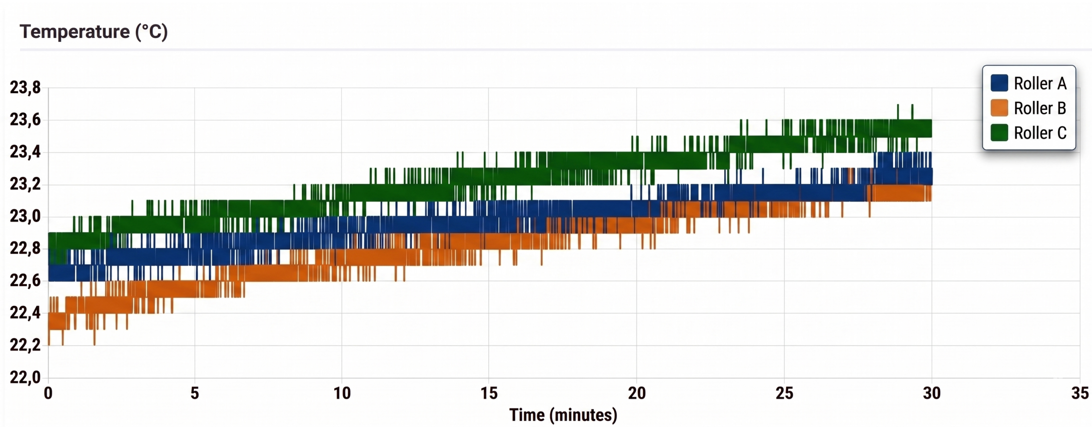

Figure C.16: Temperature trends over 30 minutes for Roller A, B, and C with a 44.7kg load.

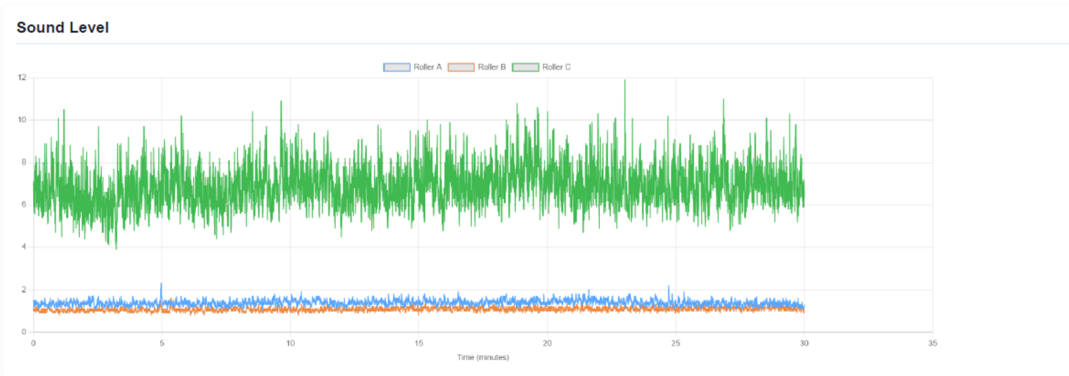

Figure C.17: Sound level measurements over a 30-minute period for Roller A, B, and C with a 3.4kg load.

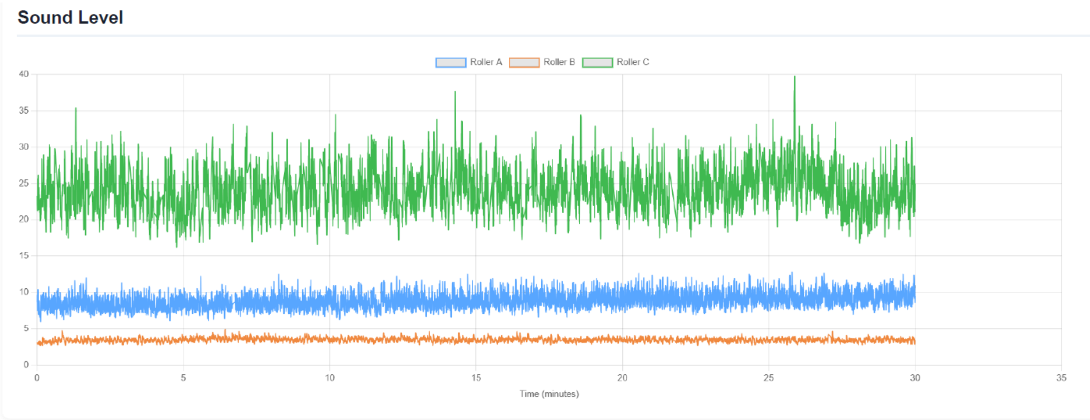

Figure C.18: Sound level measurements over a 30-minute period for Roller A, B, and C with a 18.2kg load.

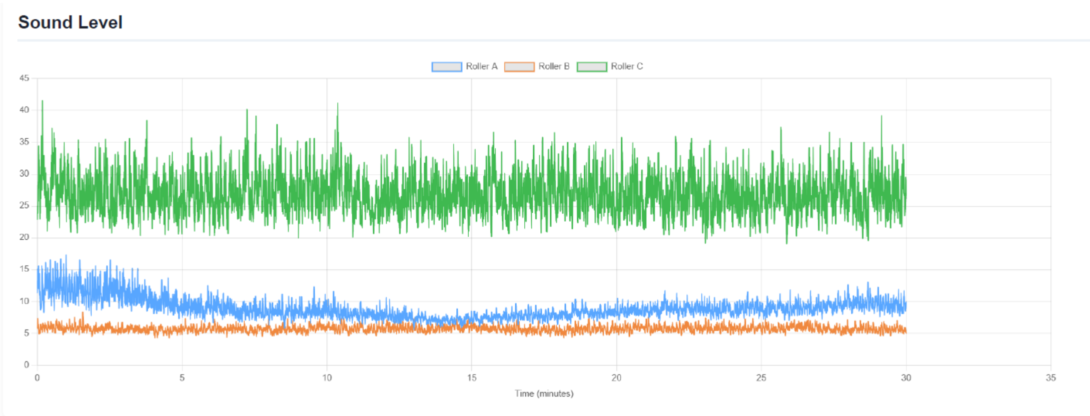

Figure C.19: Sound level measurements over a 30-minute period for Roller A, B, and C with a 30.8kg load.

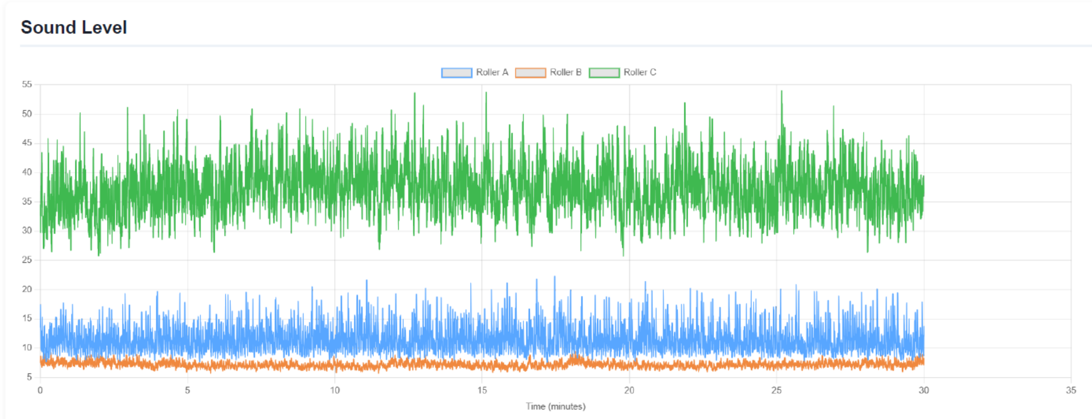

Figure C.20: Sound level measurements over a 30-minute period for Roller A, B, and C with a 44.7kg load.