Project acronym	B4B
Project full name	Brains for Building's Energy Systems
Grant No	MOOI32004
Project duration	May 1, 2021 – December 31, 2025

Use case Sensing360

Applying new low-cost sensors for multi-sensing with a focus on the potential of HVAC fault detection by small optical vibration sensors.

Research and evaluation for low-cost vibration sensors on the HVAC for early fault detection.

Authors	Eric van Genuchten
Work package(s)	1
Results	2
Due Date	Dec 2025
Deliverable Status	Final

SENSING360

SUMMARY

Within the B4B project, Sensing360 has specifically contributed to the goal of improving energy inefficiency in climate control systems by detecting faults that lead to more than 25% energy waste in buildings.

Specifically, participation in B4B has led to significant steps towards testing low-cost optical vibration sensors as fault indicated for the Heating, Ventilation and Air Conditioning (HVAC) systems as their energy usage is the major contribution to the total energy consumption of a building. With these sensors it was able to detect the characteristics of different faulty operating conditions and therefore predict failure upfront and indicate non optimal operation of a HVAC with data analysis, and a start of implementation of machine learning algorithms for automatic fault detection based on vibration spectra and experience from other industries with rotating equipment.

During the project, analysis was made of the different sensors used and which data is available to do failure prediction, this work was mainly executed by the Technical University of Eindhoven. With this data and failure data from the field, the faults where identified, rank on occurrence and severity related to energy waste. With this input, 5 different sensors position of the vibration sensors were identified, and sensors have been installed and a measurement campaign of 6 months has been executed with two periods (summer and winter) of on purpose trigger faulty operation of the HVAC at one of the projects living labs: the Kropman building in Breda.

The instrumented parts of the HVAC are:

1. Fan (rotating)
2. Cooling unit (static)
3. Warmtewiel (slowly rotating)
4. Heating coil valve (static)
5. Cool air flow channel (static)

The extensive analysis of the results shows clear vibration signals for the different conditions of the fan and one can distinguish between fans, bearings, motor and other mechanical components. This result is relevant, since then most of the crucial efficiency and energy waste losses can be identified with low-cost optical vibration sensors. The other parts of the HVAC show no to very little vibration signals, there cannot be any difference between noise and events, therefore as identified as not working due to different reasons, but the main reason that there is not sufficient energy in the system, so either being static or to slow rotating ("warmtewiel"). This asks for more expensive structural monitoring, instead of more cost-effective vibration monitoring. As the goal was to focus on low-cost, therefore in the scope of this project there has not been performed more research on this.

The main conclusion is that the fan can be monitored very precisely with basic vibration monitoring, while the other parts need more enhanced methods. From market and HVAC failure analysis by different partners in the project and the ~75% of the energy loss can be contributed to the HVAC not functioning properly and from that 60+% is due to fan failures, confirming how crucial it is to develop a monitoring system for this specific part.

The analysis indicates that dedicated sensors is for fans in HVAC systems have a potential business case and the technology does allow for early detection of 95% of the failures and that can be used to the complete the total 4S3F framework for building management.

The next steps of the project include further development of the data and potentially look into the part of the HVAC which needs more complex sensoring, therefore first the business case need to be built with relevant partners like Kropman. This would the first step; build the more detailed business and extend this with pilots with companies doing building and maintenance management. Initial discussions are already planned, so it can be considered as

TABLE OF CONTENT

1 INTRODUCTION

1.1 Why vibration monitoring in HVAC systems?

Within the Brain4Building MOOI project, early detection of technical failures is essential for improving building performance, reducing operational costs, and increasing occupant comfort. Among all building systems, Heating, Ventilation and Air Conditioning (HVAC) installations represent one of the most critical components to monitor. They are responsible for most of a building's energy consumption, operate continuously under varying conditions, and contain multiple interdependent subsystems (such as chillers, air handling units, pumps, and sensors) that are prone to gradual degradation.

Failures in HVAC systems often develop slowly and remain unnoticed until they cause significant performance loss, comfort issues, or unplanned downtime. By the time these faults become visible, energy waste or occupant complaints may already be substantial. For this reason, the project focuses on developing data-driven monitoring methods capable of recognizing subtle patterns of deviation and predicting failures before they escalate.

Focusing on HVAC systems allows us to demonstrate the value of predictive maintenance in a domain with rich sensor data, measurable performance indicators, and high impact on sustainability goals. Early-stage fault detection not only reduces maintenance costs but also contributes to more stable operation, improved indoor climate, and lower CO_2 emissions. This aligns directly with the broader ambition of Brain4Building: enabling smarter, self-learning buildings that proactively maintain their own performance.

Vibrations in HVAC components—such as fans, ducts, motors, dampers, and structural connections—can indicate imbalance, stopping, wear, loose fastenings, or resonance phenomena. By detecting vibration patterns early, maintenance costs can be reduced, failures can be prevented, and energy efficiency can be improved.

Within the Brains for Building project, the focus was on monitoring vibration behaviour in HVAC installation and linking this to predictive or condition-based maintenance. The choice for vibration monitoring was motivated by the facts that:

- vibrations often precede mechanical failure;
- they directly reflect changes in mechanical performance;
- measuring vibrations is relatively easy to integrate with existing systems;
- vibration monitoring supports condition-based maintenance rather than scheduled maintenance.

Sensing360's contribution is centred on using fibre-optic sensors to capture vibration patterns in HVAC equipment and evaluate their suitability for predictive maintenance, in cooperation with Kropman and Eindhoven University of Technology (TU/e). Together the relevant part of the HVAC has been analysed to monitor based on criticality, occurrence of failures and accessibility.

In the report first the use technology is explained, then the rationale to monitor the HVAC and its specific components. From that the experiments and measurements are described to then conclude the analysis of the results and conclusions.

2 TECHNOLOGY – VIBRATION AND OPTICAL SENSORS

2.1 Vibration basics

Vibration monitoring is one of the most widely used techniques for detecting mechanical faults in rotating equipment such as fans, pumps, and compressors in general and in project scope of HVAC systems. The principle is rooted in classical mechanics: when a mechanical component begins to wear, loosen, or become unbalanced, it introduces additional forces into the system. These forces manifest as vibrations, which can be measured, trended, and analysed to identify emerging failures at an early stage.

At the most fundamental level, vibration sensors measure acceleration, velocity, or displacement of a component's motion. Acceleration is particularly informative because, from Newton's second law,

$$F = ma,$$

where $F$is the force transmitted through the structure, $m$is the mass, and $a$is the measured acceleration. Any change in vibration acceleration therefore reflects a change in the forces acting on the machine. Because mechanical degradation increases the dynamic forces in specific parts of the system, increases in acceleration directly indicate that more energy is being injected into the structure.

These raw vibration signals contain many overlapping motion components. To diagnose specific mechanical issues, the time-domain signal is transformed into the frequency domain—typically using a Fast Fourier Transform (FFT). In this spectrum, the vibration energy is distributed across frequencies, and peaks emerge at frequencies associated with particular machine behaviors or failure modes. Examples include:

- Rotational frequency (1× RPM): imbalance
- 2×, 3×, ... harmonics: misalignment or mechanical looseness
- Bearing characteristic frequencies: inner/outer race defects, cage faults
- Blade-passing frequency: fan or impeller problems

A higher peak at a given frequency means that more vibrational energy is present at that frequency. This is significant because energy concentration in the spectrum corresponds to a specific forcing mechanism. As a component deteriorates, the forces it generates become more periodic and stronger, causing the associated frequency peaks to increase in amplitude.

By trending these peak amplitudes over time, it becomes possible to detect subtle changes long before a failure becomes operationally noticeable. A small but steady rise in energy around a bearing characteristic frequency, for example, is a reliable indicator of early bearing wear. This approach allows maintenance teams to pinpoint the underlying issue and plan interventions proactively rather than reactively as seen in the P-F diagram in Figure 1.

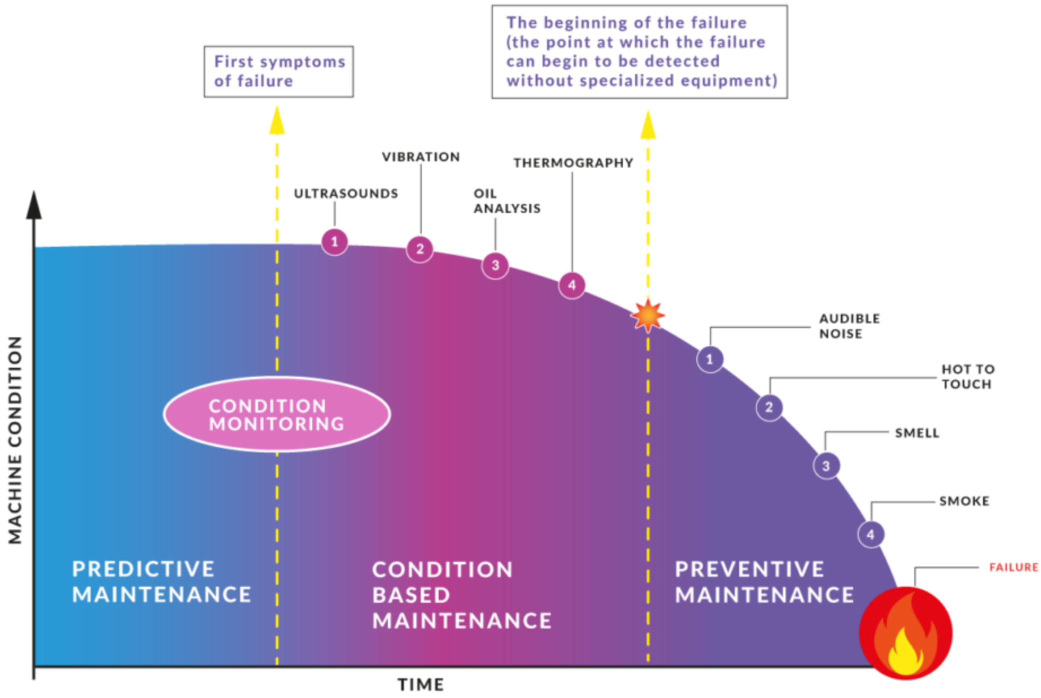

Figure 1: P-F curve, probability -failure diagram summarizing different methods for failure predcition of rotating equipment.

Different application show different vibration chacteristics, as speeds, sizes and failure differ in Figure 2 a general overview of which frequencies are relevant for which applications, which lead to the choice of the sensors and acquisition devices.

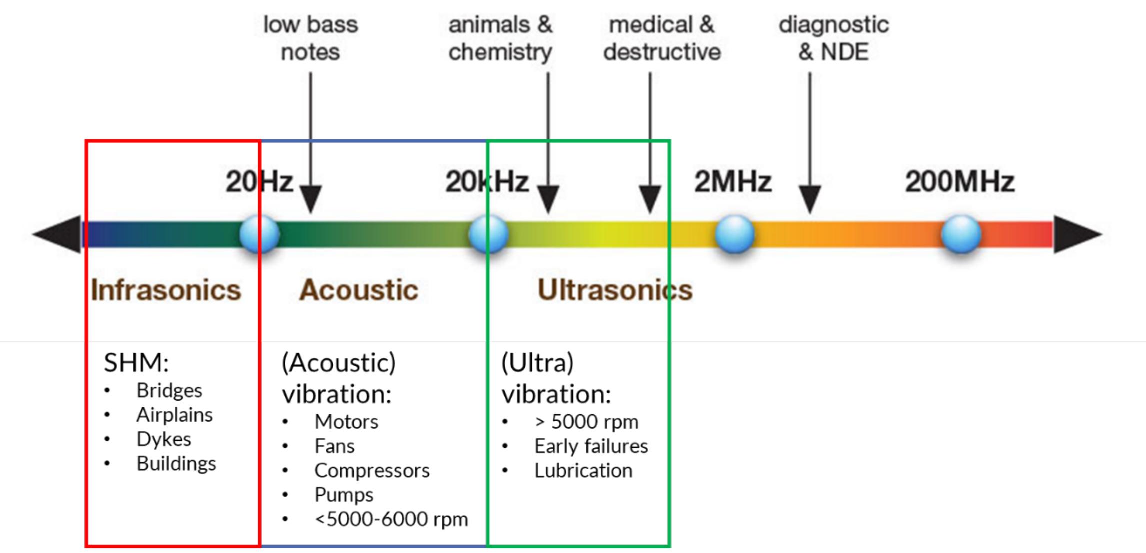

Figure 2: Relevant frequencies to analyse for different application, ranging from structural monitoring till turbo machinery. In the scope of B4B the range is from 0,5 kHz - 5 kKz

Thus, vibration monitoring provides a physics-based, data-driven method to identify mechanical faults by connecting measured motion (acceleration or displacement) to force, energy distribution, and their manifestation in the frequency domain.

2.2 Optical sensors – Fibre Bragg Gratings (FBG)

Sensing360 uses Fibre Bragg Grating (FBG) technology: measurement by light only.

Working Principle of Fiber Bragg Grating Sensors

Fiber Bragg Grating (FBG) sensors are optical sensors created by inscribing periodic variations in the refractive index along the core of an optical fiber. These microscopic index modulations act as a wavelength-selective mirror. When broadband light is sent through the fiber, the grating reflects a narrow wavelength—called the Bragg wavelength—while all other wavelengths pass through.

The Bragg wavelength is defined by:

$$\lambda_B = 2n_{\text{eff}}\Lambda$$

where:

- λ_B= Bragg wavelength,
- n_{eff}= effective refractive index of the fiber core,
- Λ= grating period.

This principle is schematically shown in Figure 3 at the bottom of this page.

Any change in strain or temperature alters either the refractive index or the spacing Λ, shifting the Bragg wavelength. FBG sensors therefore convert mechanical deformation, vibration, or thermal changes directly into measurable wavelength shifts. Because wavelength is an absolute physical quantity, measurements are highly stable over time and not subject to the typical electronic drift or noise seen in conventional electromechanical sensors.

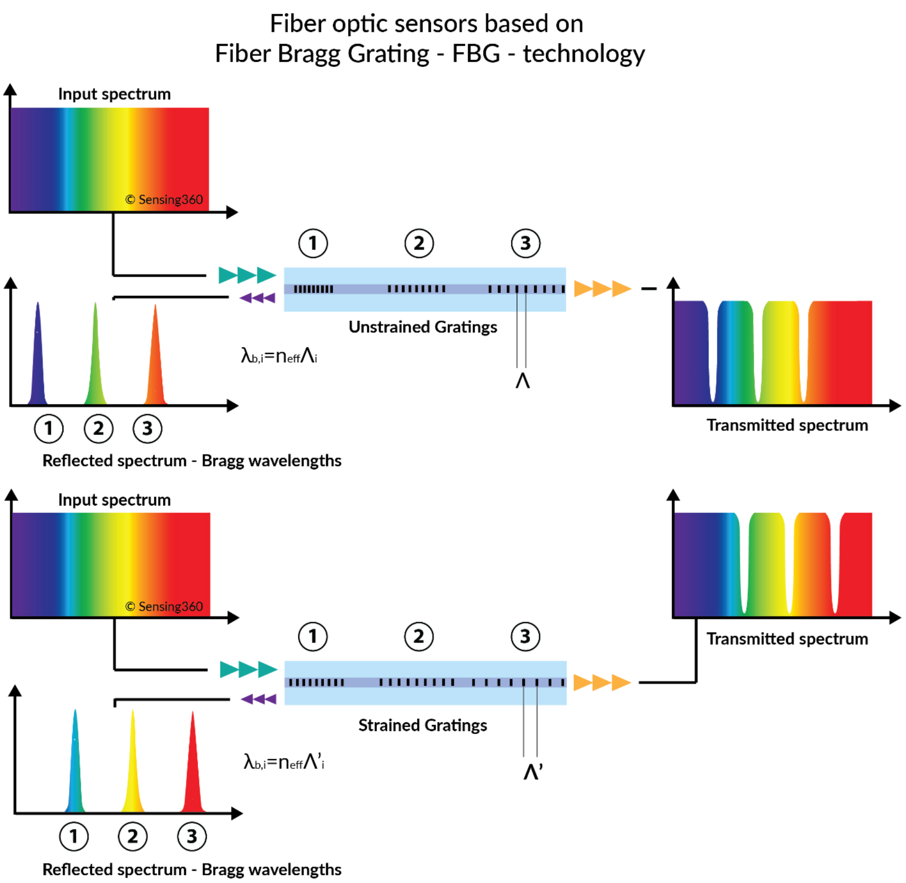

Figure 3: Sensing principle of Fiber Bragg Gratings (FBG) sensors

FBG Sensing for Vibration and Structural Monitoring in HVAC

FBG sensors are sensitive to both static and dynamic strain. Vibrations in rotating machinery—such as fans, pumps, and motors—induce micro-strains in the fiber when it is bonded to the housing, bracket, or bearing support. These micro-strains modulate the Bragg wavelength at the same frequency as the mechanical vibration.

By interrogating the fiber at high sampling rates (kHz range), the system can reconstruct:

- vibration amplitude,
- vibration frequency content (e.g., via FFT),
- long-term strain and structural deflection trends,
- temperature effects.

This makes FBG sensors suitable for detecting imbalance, misalignment, bearing wear, loose components, and thermal overstress in equipment.

Key Advantages of FBG Sensors

- Immune to Electromagnetic Interference (EMI)

HVAC environments often include large motors, variable-frequency drives, and high-current wiring that can create noise for electronic sensors. FBGs use purely optical signals—no electricity at the sensing point—making them completely immune to EMI and ideal for noisy mechanical rooms.

- Multiplexing: Many sensors on a single siber

One fiber can contain dozens of gratings written at different Bragg wavelengths. These "multiple sensors on one line" drastically reduce cabling, installation complexity, and failure points. For large HVAC installations—multiple fans, AHUs, dampers, piping supports—multiplexing is a major economic advantage.

- High temperature and harsh environment tolerance

FBG sensors are resistant to: moisture, dust, oils, chemicals, extreme temperatures. They maintain accuracy even where conventional sensors suffer drift, corrosion, or electrical degradation.

- Longevity and stability

Optical fibers do not corrode and do not require recalibration because the measurement is based on wavelength—a stable quantity unaffected by electronics aging.

- Very Small, Lightweight, and Non-Intrusive

FBGs can be bonded directly to equipment with adhesives or embedded in composites or mounts. They add negligible mass and do not alter machine dynamics—important for accurate vibration measurement.

- Capability for Both Strain and Temperature Measurement

With dual-grating or temperature-compensated setups, you can isolate:

- strain-induced vibration signals,
- thermal loads affecting HVAC efficiency or component aging.

One technology serves two monitoring purposes simultaneously.

Why FBG Sensors Are Cost-Effective for HVAC Monitoring

Although the interrogator (optical readout unit) can be more expensive than a simple accelerometer, the total system cost for large-scale deployments is often significantly lower. The cost-effectiveness arises from several factors: Multiplexing reduces wiring and installation costs, traditional vibration monitoring requires:

- one cable per sensor,
- multiple channels of data acquisition hardware,
- extensive labor for routing cables.

FBG sensors allow 10–30 sensing points on one single fiber, minimizing installation time and material cost. In large AHUs, long duct runs, or distributed mechanical rooms, this advantage becomes substantial.

Furthermore optical sensors are durable in harsh HVAC environments, as standard accelerometers may fail or drift when exposed to condensation, vibration-induced cable damage, electrical noise, and high temperatures near motors. Compared to FBGs have no such limitations, reducing sensor replacement and downtime.

With the above described above this technology is suitability for predictive maintenance monitoring in HVAC sysems. FBG sensors offer the level of precision needed to detect small changes in system behaviour—ideal for early fault detection. Because they capture high-resolution strain and vibration information, they enable identification of:

- rising harmonic peaks (misalignment or looseness),
- specific bearing frequencies (early bearing defects),
- structural resonance changes (fatigue or cracking),
- thermal overload patterns.

Combined with machine learning or physics-informed models, FBG data improves failure prediction accuracy and reliability, supporting the goals of the Brain4Building project for smarter, self-monitoring HVAC systems.

3 DRIVE HVAC – PREDICTIVE TECHNOLOGY

In the last chapters the advantages and technology have been explain and linked to why to use it, in this chapter the component positioning of the sensors is discussed. This is done together with project partners, TU/e, TuD and Kropman and based on the extensive analysis during the project. This analysis is done within the project based on AHU analysis faults to calculate energy deviation. Based on the maintenance work orders 11255 orders from 1822 non-residential buildings over 5 years. This data shows that fan issues account for ~65-70% for the energy impact in the heating season, shown in figure.

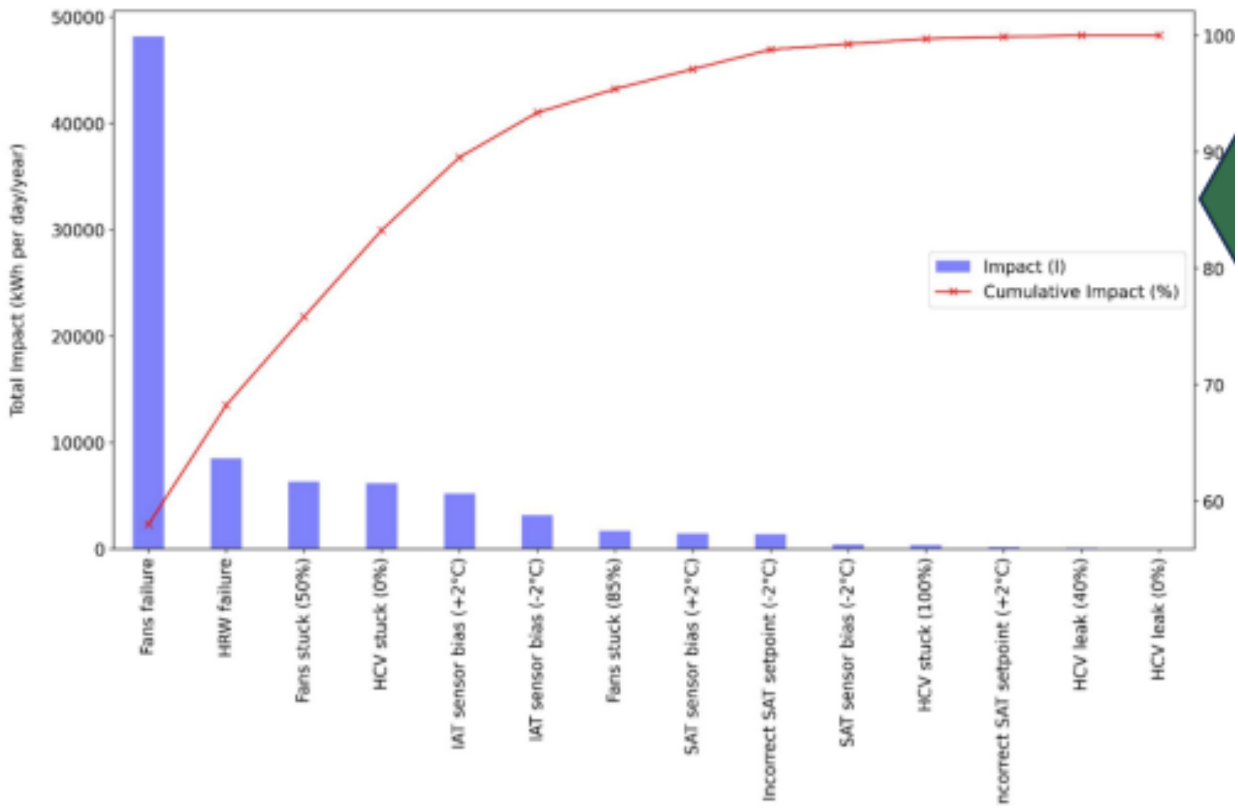

Figure 4:Total energy loss impact of the different HVAC components based on the 5000 maintenance orders for the heating season.

The same analysis is done for the cooling season, see Figure 5, where the fan even more accounts for a major part of energy loss (80-85%). Indicating that from the components of the fan is the crucial part to monitoring, directly or indirectly.

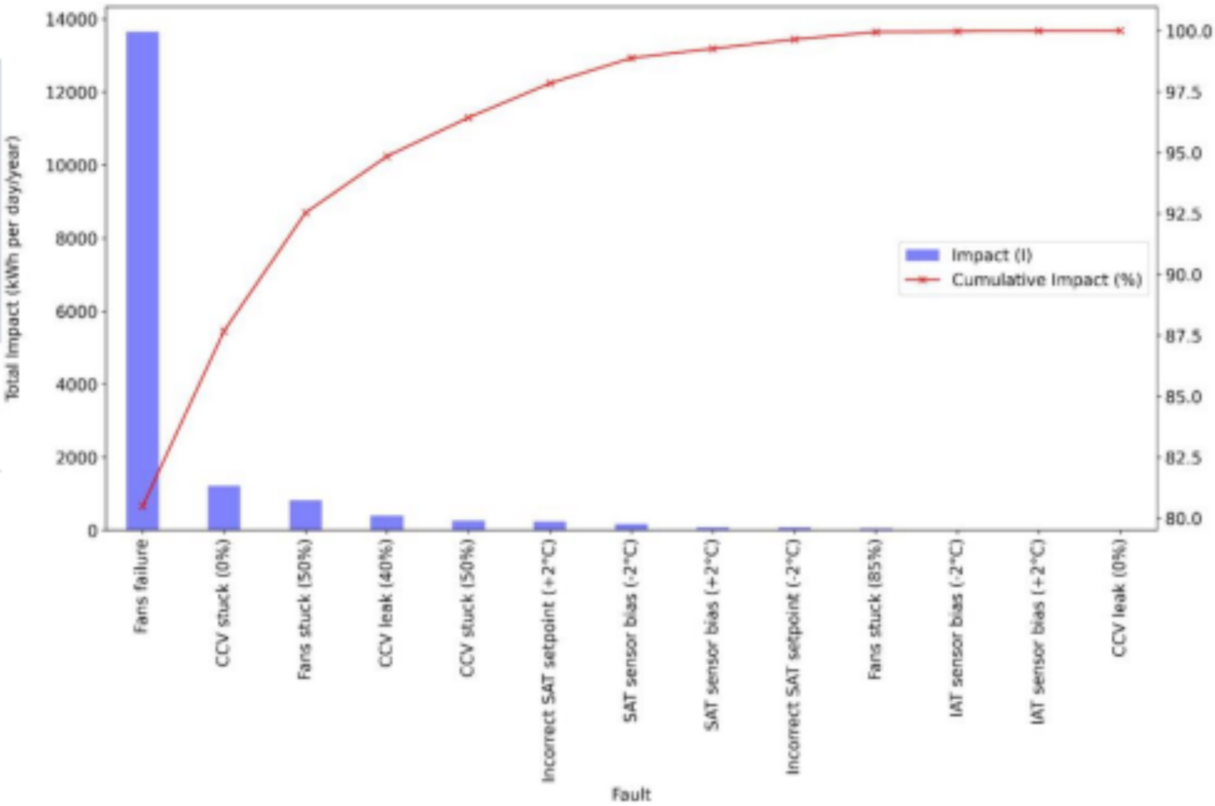

Figure 5: Total energy loss impact of the different HVAC components based on 5000 maintenance orders for the cooling season.

With the data of energy indicating the most logical position, during this project more position have been identified from technical perspective, they are listed below.

Fan (Rotating Component)

The fan assembly—consisting of the motor, shaft, bearings, and impeller—is one of the most failure-prone parts of an HVAC system on occurrence. Mechanical degradation in rotating equipment produces highly characteristic vibration signatures that are ideally suited for FBG-based strain and vibration monitoring.

Reasons for selecting the fan:

- Early detection of imbalance: Dust buildup, impeller deformation, or mass imbalance causes increased vibration at 1× rotational speed.
- Monitoring bearing health: Defects in bearings generate elevated responses at specific bearing frequencies and their harmonics.
- Misalignment detection: Shaft or coupling misalignment manifests as high 2× or 3× harmonics.
- Loose mounting or structural fatigue: Increasing vibration energy near structural resonances indicates degradation.

FBG sensors bonded to the fan housing or bearing support can detect micro-strain changes with sensitivity, enabling early-stage predictive maintenance and preventing unplanned downtime.

Cooling Unit (Static Heat Exchange Component)

Although cooling coils and their surrounding structure do not rotate, they are subject to thermal cycling, pressure fluctuations, and mechanical loading from airflow and mounting stresses. Failures often develop slowly and remain unnoticed until a major malfunction occurs.

Reasons for selecting the cooling unit:

- Thermal expansion monitoring: Repeated heating and cooling cycles can induce structural strain, loosening brackets or causing small cracks in the coil frame.
- Detecting structural deformation: Coil bending or sagging due to aging or fouling alters static strain patterns
- Identifying abnormal pressure or flow conditions: Blocked or fouled coils change the strain distribution, which can serve as an indirect indicator of performance reduction.
- Monitoring the condition of supporting structures: Fatigue or weakening of mounting frames can lead to vibrations or instability.

Heat Recovery Wheel (Warmtewiel – Slowly Rotating)

The thermal wheel rotates at a low speed, but its rotational stability and integrity are critical for energy recovery performance. Failures here tend to be subtle and slow developing, making them ideal for optical monitoring.

Reasons for selecting the warmtewiel:

- Detecting rotational irregularities: Warped or unbalanced wheels introduce low-frequency mechanical strain variations.
- Monitoring bearing and belt condition: The wheel uses bearings and sometimes belts that degrade over time, causing periodic vibration signatures even at low RPM.
- Identifying fouling or uneven mass distribution: Dirt accumulation on one side of the wheel leads to asymmetric loading, detectable as repeating strain peaks.
- Ensuring proper alignment and structural stability: Misalignment can reduce efficiency and increase mechanical stress.

Heating Coil Valve (Static Component with Actuation)

The heating valve itself is static, but it performs dynamic actuation that affects system behavior and introduces mechanical and thermal effects into nearby structures.

Reasons for selecting the heating coil valve:

- Monitoring valve actuation quality: Wear in the actuator or stem friction changes the strain profile during opening/closing movements.
- Detecting blockage or partial obstruction: Abnormal pressure buildup can be inferred from changes in structural strain.
- Ensuring proper thermal expansion behavior: Repeated heating can introduce stress concentrations around connection points.
- Identifying early mechanical degradation: Loose mounting hardware, degraded seals, or actuator fatigue can be detected.

Cool Air Flow Channel (Static Structural Component)

The airflow channel or ductwork is subject to aerodynamic forces, thermal gradients, mounting stresses, and mechanical wear over time. Even though it is static, it plays a central role in distributing conditioned air.

Reasons for selecting the airflow channel:

- Monitoring structural deformation or fatigue: Large ducts experience pressure cycles that can cause flexing or long-term material fatigue.
- Detecting abnormal airflow or blockages: Changes in airflow patterns introduce different pressure-induced strain signatures.
- Identifying loose panels or supports: Vibration or rattling caused by loose mounts or degraded isolation can be detected through strain changes.
- Measuring the influence of connected vibrating components: Fans or motors transmit vibration into the duct structure, which can be monitored as a secondary indicator.

This installation provides information on the *health of the overall AHU structure* and its interaction with rotating equipment.

4 EXPERIMENTS AT LIVING LAB OF KROPMAN

In the last chapter the components to install on the HVAC have been identified:

1. Fan (rotating)
2. Cooling unit (static)
3. Warmtewiel (slowly rotating)
4. Heating coil valve (static)
5. Cool air flow channel (static)

In this project the living lab of Kropman gave the opportunity to start a measure campaign of a year for both the cooling and heating season. The Objective of the experiments are to evaluate the applicability of FBG sensors for vibration monitoring on selected HVAC components in a real building.

Figure 6: Installation images of the FBG sensors on the heating coil valve and acquisition device in the electronic cabinet.

The logging data was logged at 2,5 kHz on all components and for at least six months with different faulty conditions. The data was logged for 1 minute and then every 5 minutes continuously and remotely offloaded. The data acquisition was not integrated into the smart building software from Kropman, but standalone connected to the internet. The measurement plan was is listed in Figure 7 on the next page.

Cooling Season Experiments	
Date	**Fault Experiment**
04/07/2023	Indoor Air Temperature sensor bias
05/07/2023	No Fault
06/07/2023	Fan Stuck 30%
07/07/2023	No Fault
08/07/2023	Weekend
09/07/2023	Weekend
10/07/2023	Supply Air Temperature sensor bias
17/07/2023	Fan Stuck 50%
18/07/2023	No Fault
19/07/2023	No Fault
20/07/2023	No Fault
21/07/2023	No Fault
22/07/2023	Weekend
01/08/2023	No Fault
02/08/2023	No Fault
03/08/2023	No Fault
04/08/2023	No Fault
05/08/2023	Weekend
06/08/2023	Weekend
07/08/2023	No Fault
08/08/2023	No Fault
09/08/2023	No Fault
15/08/2023	**08:23 - 11:02** :- Heat Recovery Wheel Stuck (30%) & Cooling Coil Valves Stuck (30%) **11:02 - 13:03** :- Heat Recovery Wheel Stuck (30%) & Cooling Coil Valves Stuck (70%) **13:03 - 16:05** :- Heat Recovery Wheel Stuck (30%) & Fan Stuck (70%)
16/08/2023	**08:15 - 11:32** :- Fan Stuck (70%) & Heat recovery Wheel Stuck (70%) **11:32 - 16:08** :- Heat recovery Wheel Stuck (70%) & Cooling Coil Valves stuck (70%)
17/08/2023	No Fault
05/09/2023	No Fault
06/09/2023	Heat Recovery Wheel Failure
07/09/2023	Heat Recovery Wheel Stuck
08/09/2023	Unstable Cooling Coil Valve Control
09/09/2023	Weekend
10/09/2023	Weekend
11/09/2023	No Fault

Heating Season Experiments	
Date	**Fault Experiment**
10/03/2023	Supply Water Temperature Bias
17/03/2023	Heating Coil Valve Stuck (75%)
18/03/2023	Weekend
19/03/2023	Weekend
20/03/2023	Unstable Heating Coil valve
21/03/2023	No Fault
22/03/2023	Heat Recovery Wheel Failure
23/03/2023	No Fault
24/03/2023	No Fault
25/03/2023	Weekend
26/03/2023	Weekend
27/03/2023	Heat Recovery Wheel Stuck (50%)
28/03/2023	Fan Stuck (65%)
29/03/2023	No Fault
30/03/2023	No Fault
31/03/2023	No Fault
01/04/2023	Weekend
02/04/2023	Weekend
03/04/2023	No Fault

Figure 7: Measurement plan of vibration sensors of the HVAC

5 RESULTS

In this chapter the results are described and conclusion are made regarding the scope, value and what is possible from detection perspective.

5.1 Initial sensor data quality check

The first check, do we see sufficient deformation to perform vibration analysis on. For that an analysis has been made to determine if the data is valuable indicated in Table 1: signal quality for vibration analysis for different HVAC components

Table 1: signal quality for vibration analysis for different HVAC components

#	Component	Data	Details
1	Fan	Yes	Clear signal and frequencies visible one correct locations
2	Cooling unit	No	No signal, to limited displacement
3	Warmtewiel	No	Bearing not assessable without major HVAC adjustments
4	Heating coil valve	No	To limited energy, open/close cannot
5	Cool air flow channel	No	To low frequency and energy to see frequencies apart from the noise

From this analysis the conclusion is that from the HVAC and identified part, only the fan is relevant to focus on with vibration analysis. This matches with the relevant of the fan for the energy use, therefore this focus is still on the component response for the main energy loss in building or air handling unit.

5.2 Failure detection with vibration

In Figure 8 the frequency plot from the fan is shown, here the clear peak is visible and explainable, enabling tracking of these peaks resulting into the possibility to predict failures. The orange arrow at the graph is located at 16 Hz which is related to the rotation speed, indicating that the measurement is of high quality.

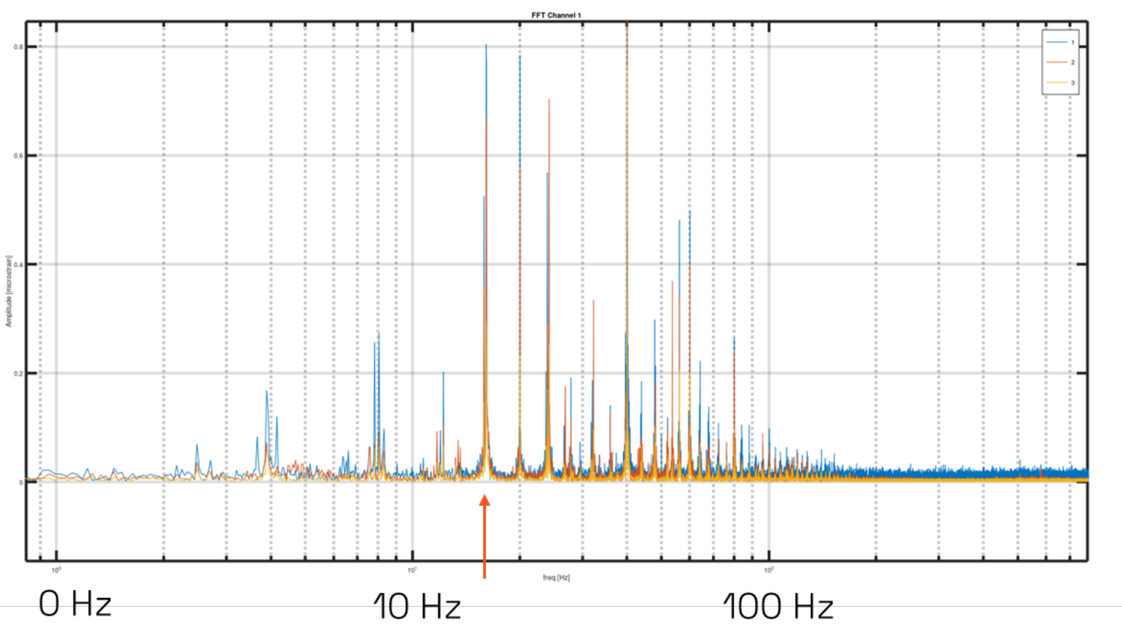

Figure 8: Frequency spectrum of the fan on the HVAC monitored. The orange arrow gives the main peak; 16 Hz, which relates to the rotation speed of 200 RPM, which is correct according to the fan specification.

Then looking at the fan in more detail the analysis focusses on “normal” behaviour and faulty behaviour, during the testing different error were introduced see Figure 7. Now we specifically zoom in to a heatmap plot of the data; where one places the frequency spectra next to each other in the sequence of time and example of the fan for three days is shown in Figure 9.

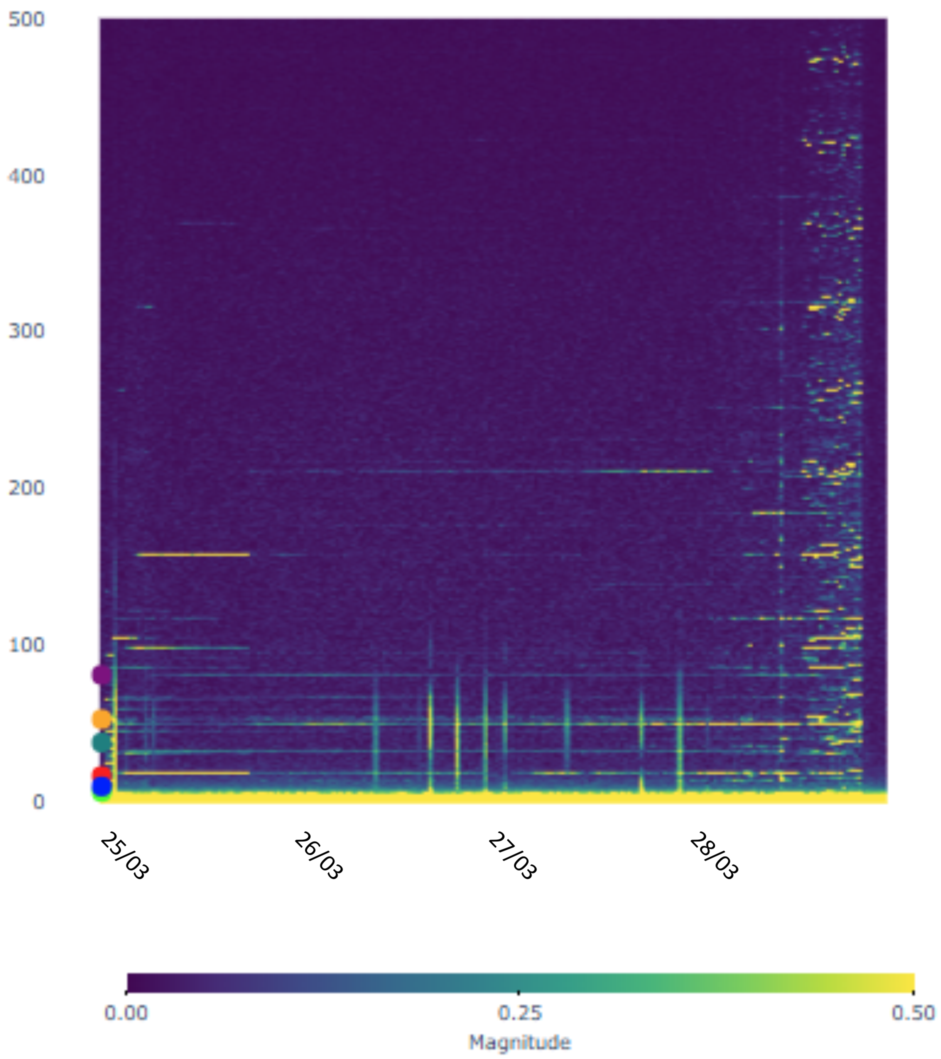

Figure 9: Heatmap of the frequency data placed in time, on the x axis dates are shown, on the vertical axis the frequencies and the colour indicate the magnitude of the spectra.

The horizontal lines a the one which are most relevant, then the HVAC running conditions are shown in

26/03/2023	Weekend
27/03/2023	Heat Recovery Wheel Stuck (50%)
28/03/2023	Fan Stuck (65%)

Figure 10: Test condition related to figure 9.

It is clearly shown that on the 28th of March when the fan is “stuck” the vibration rise and that is clear indicator that there is an fault and well detectable.

To get more grip on what is failing and how long before it fails, more detailed analysis is done on the exact spectra and the visible frequencies. This to pinpoint the failure and indicate what to do and within what time frame. In the next paragraph this is described.

5.3 Individual components analysis

In this paragraph the exact peak position are analysed and which effects are visible:

RPM prediction

Nominal conditions: 2023-08-03 14:04:52 - 2023-08-03 15:45:10
Fault conditions: 2023-08-15 13:06:37 - 2023-08-15 16:01:59 and 2023-08-16 09:12:20 - 2023-08-16 11:32:40

Using FFT both in nominal conditions and fault conditions it is possible to:

1. Predict nominal fan RPM.
2. Predict the number of blades of the fan
3. Predict the fault

Based on one it is seen **Error! Reference source not found.** that the first fan harmonic lies at 4.067Hz, multiplying it by 60 we get 244 RPM[1].

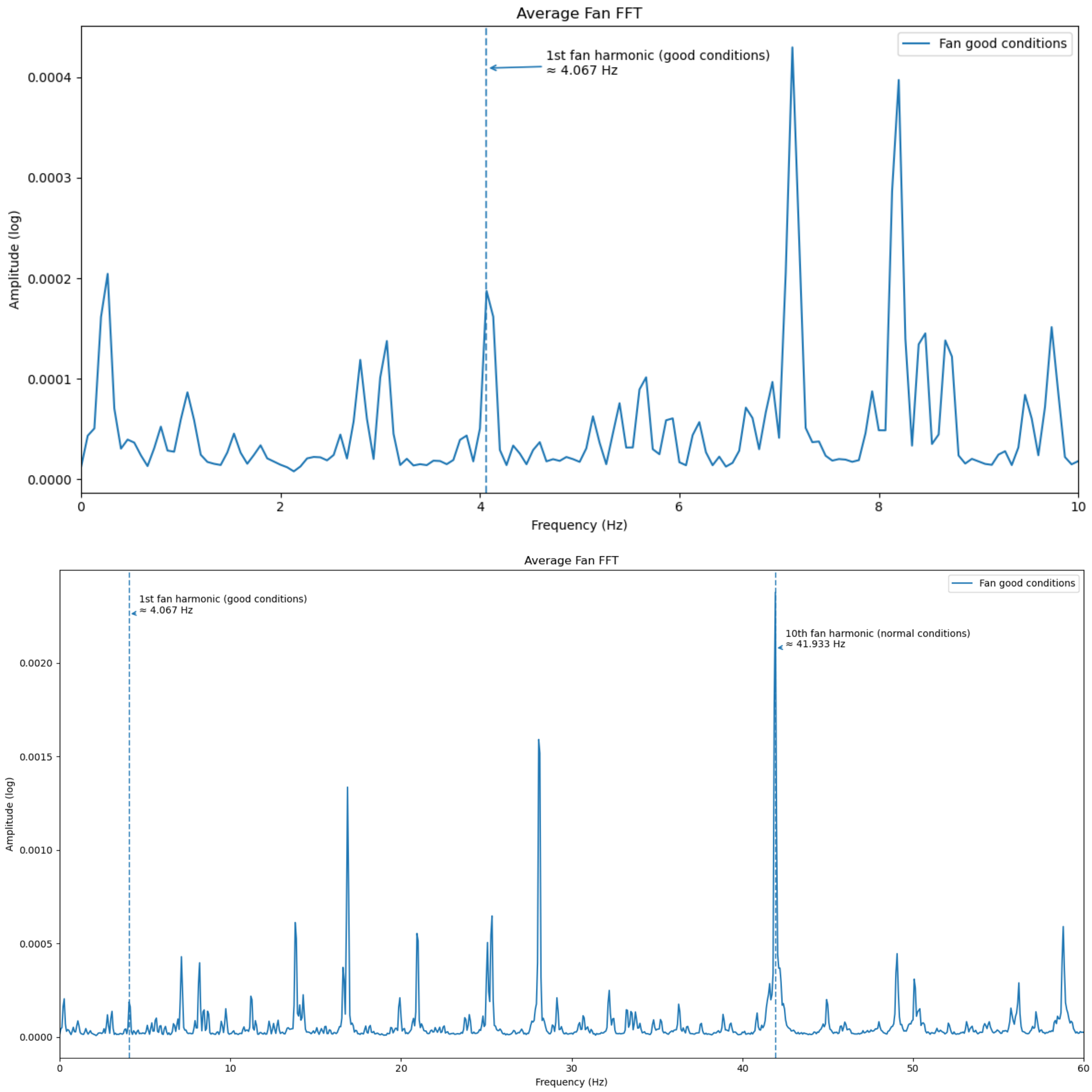

Figure 11: Detailed frequency analysis and different errors indicated in the graphs

[1] It should be more as it is possible to see another peak at 4.133Hz which is due low FFT resolution. Therefore, the RPM is within [244:248] ± 4 RPM

Based on data where the fault in a fan was reported. It is possible to predict both RPM and the fault itself as seen in Figure 12. The RPM dropped from 244 to 212. Overall energy content at almost every fan frequency harmonic for faulty conditions has increased compared to good conditions (see Figure 12).

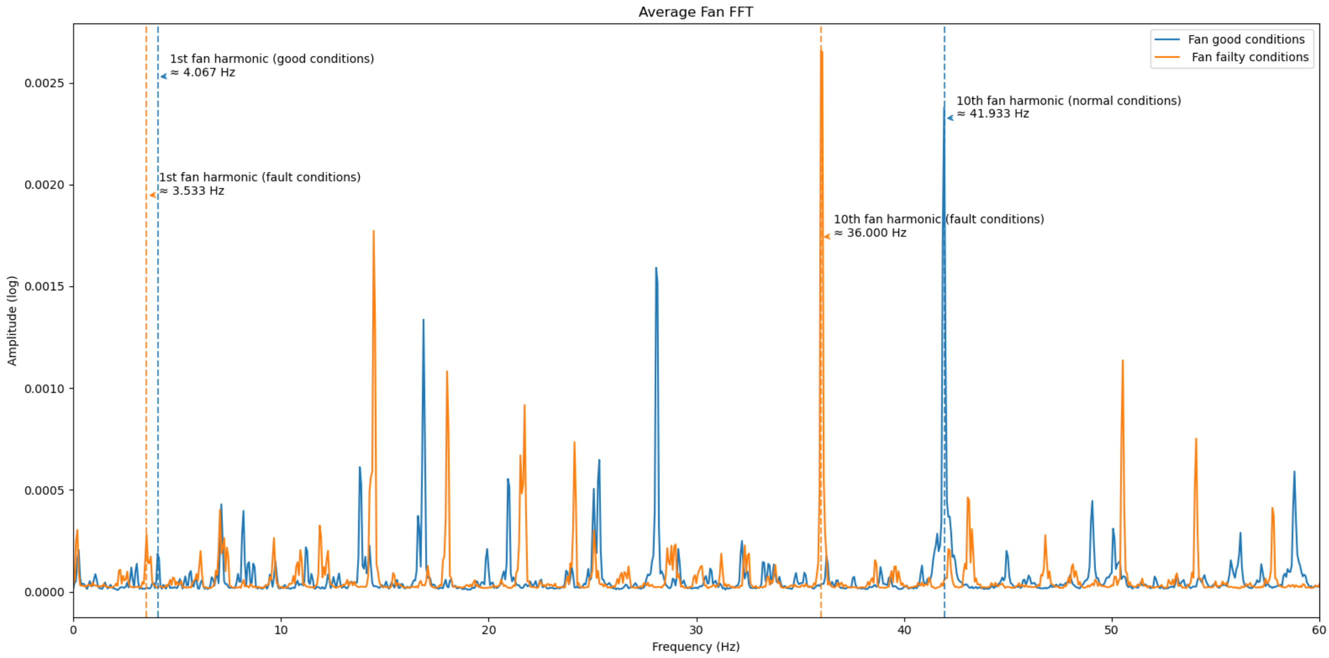

Figure 12: Frequency analysis for faulty and good running conditions and the observations indicated in the graph.

Based on the analysis fail failures can be detected and disguised between the different failures like: stuck, fans, bearing, motor, etc...

Table 2: Distinguish between good and fault running conditions to be used as monitoring level indicators.

Harmonic	Amplitude	
	Good	Fault
1	0.000187	**0.000281**
2	0.000397	**0.000402**
3	8.78E-05	**0.000205**
4	0.000617	**0.001772**
5	0.000554	**0.001083**
6	0.000505	**0.000917**
7	**0.001591**	0.000735
8	**0.000249**	0.000233
9	0.000176	**0.000228**
10	0.002378	**0.002657**

5.4 HVAC failure detection with vibration sensing

In this final sub chapter, the results of all analysis is summarized in for all faulty running conditions, these are summarized in Table 3: Overview of test fault condition and detection conclusion

Table 3: Overview of test fault condition and detection conclusion

#	Fault measurable via the fan	Detactable
1	Unstable heating valve	No
2	Fan stuck	Yes
3	Supply air	No
4	Recovery wheel stuck	Yes
5	Cooling valve stuck	No
6	Unstable cooling valve	No
7	Supply temperature issues	No

From the research done in the scope of this project, one can conclude the main finding: fans and recovery wheel can be reliably measured using FBG vibration sensors; the detectable faults are accounting for 80-90% of the energy loss by not optimized HVAC systems, see chapter 3.

Other elements showed lower vibration levels and required adapted sensor strategies. The cost is feasible: < €50 per sensing point for scalable implementations appears achievable.

Then further development needed: optimized mounting methods, improved spectral analysis for low-amplitude vibration, integration into building monitoring platforms. Therefore, the recommendation proceeds with next-phase pilots on multiple fan systems and integrate vibration data with predictive maintenance models.

6 CONCLUSION

The Sensing360 contribution within the Brains for Buildings (B4B) MOOI project demonstrates that low-cost optical vibration sensing has clear and practical value for fault detection in HVAC systems, particularly for the components responsible for the majority of energy losses. The measurement campaign at the Kropman living lab validated both the technical viability and the predictive capability of Fibre Bragg Grating (FBG) sensors for monitoring HVAC machinery.

The results clearly show that the fan is the dominant source of meaningful vibration information and therefore the most suitable target for low-cost predictive monitoring. The fan produced distinct vibration signatures, strong harmonic structures, and clear differences between healthy and faulty operating conditions. These signals enabled detection of multiple fault types, including stuck conditions, bearing-related issues, and RPM deviations. This aligns with earlier fault occurrence data showing that fans account for 60–85% of HVAC-related energy losses, depending on the season

In contrast, the other monitored components—cooling coil, heating valve, airflow channel, and heat recovery wheel—showed insufficient vibration energy or structural accessibility issues to extract reliable diagnostic information with low-cost vibration sensing. As summarized in the results table, these components produced signals too weak to separate from noise, or required installation positions not feasible without major HVAC adjustment

This confirms that vibration-based fault detection is highly effective for rotating components but less suitable for static or slow-moving parts unless more advanced sensing strategies are applied.

Overall, the project provides evidence that FBG vibration monitoring enables early detection of approximately 95% of fan-related faults, meeting the objective of improving energy performance through early detection of deviations. The technology is scalable, robust, low-maintenance, and cost-effective, with sensor costs below €50 per sensing point in mass implementation.

The findings validate that fan monitoring is both technically feasible and economically justified and should be considered a cornerstone for predictive maintenance strategies in HVAC systems.

7 RECOMMENDATIONS

Proceed with large-scale pilot deployments focused on fan monitoring:

Given the strong diagnostic performance on the fan and its significant energy impact, the next step is a multi-site demonstration with HVAC service partners such as Kropman. This will enable validation under diverse building types, operating conditions, and climates, and will support refinement of detection thresholds and long-term stability.

Integrate vibration data into predictive maintenance and smart-building platforms:

To unlock full value, the FBG sensor data must be fused with building management systems (BMS), operating logs, and contextual data (temperatures, airflow, valve positions). Integration will enable automated alerts, machine-learning-based diagnostics, and adaptive maintenance planning, completing the 4S3F framework referenced in the project context.

Expand spectral and machine-learning analysis to enhance early warning capability:

The report shows that harmonic tracking and energy changes correlate strongly with fault development. Next steps include:

- automated feature extraction across harmonics,
- anomaly detection algorithms,
- model training on expanded datasets,
- integration of physics-informed models for RPM, blade count, and bearing frequencies.
  This will support more accurate fault classification and remaining-useful-life estimation.

Build a detailed business case with partners:

With fan monitoring contributing to reducing 60–85% of HVAC-related energy losses, a clear business case emerges for scaling the technology. Recommendations include:

- quantifying payback periods,
- evaluating service-based models,
- assessing the impact on maintenance workflows,
- creating a roadmap for commercialization with industry stakeholders.
  Initial discussions with partners already underway should be formalized into structured feasibility studies.