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Integrating Reliability-Centered Maintenance with Building Information Modelling to enhance the efficiency of multi-component systems

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Preface

This graduation project was the result of a deep interest in exploring methods to optimize maintenance strategies and process. My experience as part of the onsite team overseeing the construction, commissioning, and operation of a wastewater treatment plant sparked my curiosity about improving process efficiency and ensuring system reliability. I strongly believe that optimization is not always a matter of complexity but rather a systematic approach combined with dedication.

I am extremely grateful that I was able to complete my master’s at Eindhoven University of Technology. The two years I spent were rather challenging on a personal level and required significant commitment but as I reflect on it, the knowledge and skills offered were worth it.

I would like to express my gratitude to Dr. Pieter Pauwels for encouraging me to do my best and for always introducing his students to innovative technologies. My sincere thanks also go to Dr. Ekaterina Petrova for her guidance and encouragement throughout this project, as well as to Dr. Zaharah Buksh for her valuable support. I am especially thankful to Jan-Fokko Haan for the insightful discussions and the support he has shown.

Finally, I would like to extend my deepest appreciation to my family for their solid faith in me, which has been a constant source of strength throughout this journey. To them I say, “*without you, I would never have got to the stage of writing this preface*.”

Nemat Hemza,
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Summary

Buildings typically have a lifespan of 30 to 50 years, during which the operation and maintenance phase plays a crucial role in ensuring asset reliability and meeting the needs of occupants and users. This phase generates vast amounts of data, often stored in siloed systems and databases, limiting its accessibility and usability. Moreover, while maintenance is the predominant activity that ensures building services efficiency, current practices are predominantly reactive, failing to support the highest standards of reliability and performance. The reliance on fragmented, unstructured data and traditional methods creates uncertainty and resistance to adopting innovative strategies such as condition-based maintenance. This also hinders efforts to enhance the overall efficiency of maintenance processes. Although the design phase is shorter than the operation phase, it offers a valuable tool in the form of Building Information Modelling (BIM). BIM process fosters collaboration among stakeholders and ensures that project information is reliable, accessible, and available across all building phases and case studies. However, the potential of maintenance processes to benefit from a BIM model and process requires an exploration of the practical value and methods of integration.

This research aims to address these challenges through three established objectives. First, it seeks to define a systematic approach for optimizing maintenance, using the Reliability-Centered Maintenance (RCM) framework. Multi-component systems benefit from this approach as it intends to assign proactive strategies to critical components and maintains a dynamic iterative analysis, through the age exploration phase. Second, the research identifies the information requirements necessary for maintenance personnel to effectively decide on strategies, schedule activities, and execute tasks. This lays the foundation for determining which maintenance data should be integrated. Finally, the research demonstrates the concept of integration through the development of a web-based user interface. This interface provides maintenance teams with an innovative tool to improve decision-making and operational efficiency.

This research employs two primary methods: Reliability-Centered Maintenance (RCM) and Systems Engineering, both of which are demonstrated through a case study of an office building's Air Handling Unit (AHU). The methodologies rely on both quantitative and qualitative data, which were collected and thoroughly processed. Quantitative data included Piping and Instrumentation Diagram (P&ID), a BIM model for AHU representation, historical work orders to investigate maintenance history, and dynamic sensor data for optimizing maintenance intervals. Qualitative data were gathered through informal discussions and semi-structured interviews with maintenance personnel. These interviews also facilitated the evaluation and validation of the research findings.

The RCM methodology consists of three sub-processes that include identifying the system, analysis, and optimization. To identify the system, set spatial boundaries, recognizing its primary function, and breaking it down into components. Each component's role within the system is described to establish its importance to overall operations. The analysis process examines each component individually to identify potential failure modes, their causes, and their effects on the system's functionality. The Failure Mode Effect Analysis (FMEA) of five key AHU components: the damper, filter, heat recovery wheel, heating coil, and fan was produced. Although the identified failures are not severe enough to cause a complete system breakdown, they significantly increase energy consumption, explaining the current maintenance strategy of annual inspections.

This FMEA is further assessed through a criticality assessment using the parameters of severity, occurrence, and detectability. The optimization phase focuses on deciding on the most appropriate maintenance strategy to ensure component reliability. Maintenance strategies—ranging from run-to-failure and corrective to preventive and condition-based maintenance—are selected based on the outcomes of the criticality assessment. Since RCM is a dynamic process, the maintenance interval is continually refined through age exploration phase. As an example, filter replacement was analyzed

using data from the differential pressure transmitter, resulting in a recommendation for a 10-month replacement interval based on the most recent maintenance cycle.

Systems Engineering was used to investigate the integration by ensuring that the platform meets stakeholder requirements. During the concept development phase, feedback from stakeholders established the needs that can be supported through a BIM-based platform and the development of a use case diagram that illustrates the interactions between the platform and its users. Subsequently, a comprehensive list of functional and non-functional requirements was established to ensure the platform meets both operational and performance criteria. The concept development phase concluded in the design of a scalable and flexible system architecture. This architecture leverages existing data sources, introduces new microservices, and connects to the user interface via an API.

To design the platform, the initial step involved identifying the necessary information requirements. A literature review provided a list of properties required for maintenance of mechanical systems. This list was further enhanced with insights from the RCM process, which introduced parameters previously overlooked in integration research. These properties were validated and assessed through the interviews with maintenance personnel to ensure their practical relevance and applicability.

For the development of the prototype, an existing Application Programming Interface (API) was utilized and enriched with additional functionalities. The API in its original form included features such as 3D model visualization, viewing dynamic sensor data within a space, and querying RDF files for metadata. To demonstrate the concept of this research, the interface was enhanced to allow users to extract detailed component information, enable coloring components based on their assigned maintenance strategy, view associated tasks, and search the FMECA. Furthermore, the study proposes additional integrations with Enterprise Resource Planning (ERP) systems to access historical work orders, and with Building Management Systems (BMS) to detect faults, as well as incorporate user feedback and complaints.

The research also emphasizes the importance of using Industry Foundation Classes (IFC) standards and explores the application of other standard ontologies to further enhance the semantic representation of components. However, no single ontology fully captures the RCM process or effectively links failures to their respective components.

This research started with an objective to optimize maintenance strategies and process which is successfully achieved through analysis of multi-component system requirements for optimal maintenance and stakeholder needs for a web-based platform that integrates a BIM model with maintenance information. The platform concept fosters a data-driven approach to decision-making and incorporates occupant feedback. By combining expert knowledge through RCM with dynamic data, the research lays the foundation for a hybrid and efficient maintenance approach. Although not all functionalities of the platform were fully developed, the proof-of-concept validates the feasibility of this integration and opens opportunities for future research and development.

Abstract

In an era where people spend most of their time indoors, interest in the architecture, engineering and construction of intelligent, sustainable, and healthy buildings becomes increasingly vital. However, the operation and maintenance of such buildings remains undervalued, particularly due to challenges in fragmented and unstructured data. For example, in building installations reactive maintenance strategies like run-to-failure and corrective maintenance predominate over more effective approaches such as condition-based maintenance. This research sets the grounds through a systematic approach to discuss optimizing maintenance and subsequently structure data in an integrated web-based platform.

By applying RCM, multi-component systems can benefit from a methodical analysis of critical components requiring maintenance. The implementation on a case study AHU evaluated failure causes and their effects on the system, followed by criticality assessments that was driven by expert knowledge. The results offer practical insights on RCM implementation and expectations for facility management

This research proceeds to employ a systems engineering approach to develop a platform that integrates the results of RCM with a BIM model. Semi-structured interviews with maintenance managers were conducted to establish platform requirements. Key functionalities such as querying element properties, searching failure modes, and viewing maintenance strategies have been developed. Additional functions, including automated integration with maintenance management systems and fault reporting by users, are proposed for future development. The platform leverages Brick Ontology to link dynamic sensor data to specific building spaces and incorporates the SSN and SOSA ontologies to further detail failure and alarm representation.

In essence, by offering a systematic approach to optimizing the maintenance of an AHU and visualizing the results within a BIM-based platform, this work contributes to predictive maintenance, enhanced energy efficiency, and improved indoor air quality, aligning with the broader goals of intelligent, sustainable and healthy building management.

List of Abbreviations

AHU	Air-Handling Unit
API	Application Programming Interface
ASHRAE	American Society of Heating, Refrigerating & Air-Conditioning Engineers
BIM	Building Information Modelling
BMS	Building Management System
CMMS	Computerized Maintenance Management System
ERP	Enterprise Resource Planning
FMEA	Failure Mode, Effect Analysis
FMECA	Failure Mode, Effect, Criticality Analysis
HVAC	Heating, Ventilation, Air-Conditioning
IDM	Information Delivery Manual
IDS	Information Delivery Specification
IFC	Industry Foundation Classes
IoT	Internet of Things
LOD	Level of Detail
LOIN	Level of Information Need
MEP	Mechanical, Electrical, Plumbing
O&M	Operation & Maintenance
P&ID	Piping & Instrumentation Diagram
RDF	Resource Description Framework
RCM	Reliability-Centered Maintenance
SOSA	Sensor, Observation, Sample & Actuator
SSN	Semantic Sensor Network

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1.Introduction

During the life cycle of a building, maintenance of multi-component systems within building services constitutes a basic need for safe and efficient operation, to sustain the value of assets and satisfy users' demands. The prevalent maintenance strategies consist of scheduled component replacement, periodic inspection, and the run-to-failure approach followed by repair or replacement. These strategies are not optimal and often result in excessive or insufficient maintenance (Zhao et al., 2022) which translates to increased cost and lower operational reliability.

Reliability-Centered Maintenance (RCM) is a structured analytical process designed to optimize maintenance strategies by evaluating the functions and potential failure modes of individual components. This method allows for the systematic selection of appropriate maintenance actions, enhancing both operational efficiency and safety while minimizing costs (Geisbush & Ariaratnam, 2022). In building management, RCM is particularly valuable for multi-component systems, such as air-handling units (AHUs), which are integral to the performance of Heating, Ventilation, and Air Conditioning (HVAC) systems. Given that people spend 80-90% of their time indoors (Duffield & Bunn, 2023), maintaining an efficient AHU is critical to ensuring optimal indoor air quality, which directly influences occupant health and comfort. Effective maintenance of AHUs also reduces energy consumption and operational expenses, which is especially significant in large-scale facilities.

While an optimal maintenance process is crucial, its successful implementation depends on ensuring that information is reliable, systematically structured to improve interpretability, and readily available to all stakeholders. In the design phase, the emergence of Building Information Modelling (BIM) has demonstrated significant value in fostering a collaborative process where stakeholders can access and share information within a 3D building model. The BIM process has shown to improve coordination and communication among stakeholders (Petrova & Pauwels, 2018). These benefits are further supported by standardization efforts, such as the adoption of Industry Foundation Classes (IFC), which provide a standardized descriptions for built assets, and ISO 19650, which establishes concepts and principles for information management within the BIM process.

Therefore, the rapid evolution in digitalization necessitates the re-examination of the maintenance process and its requirements. In fact, to implement RCM and transition from the predominantly reactive strategies to promoting data-driven predictive maintenance the adoption of appropriate digital tools is necessary. In this context, a concept emerges where maintenance management can leverage both the BIM process and model to enhance efficiency across all stages of maintenance—from decision-making to scheduling and execution.

1.1 Problem Definition

Despite the availability of numerous maintenance management systems, the maintenance process remains far from efficient. Maintenance personnel often operate in silos, relying on document-based information that fails to provide a comprehensive view of the asset. For planning and scheduling, various commercially available Computerized Maintenance Management Systems (CMMS) are widely used such as McMain and Timely (Capterra, 2024). However, these systems are predominantly static in nature and their use is to enable reactive and preventive maintenance but lack the ability to support predictive maintenance. Furthermore, data input, structuring, and organization within CMMS are manual processes, depending greatly on personnel's engagement and interpretation.

Moreover, Building Management Systems (BMS) like Priva and Schneider are employed to monitor and control building systems. BMS facilitates predictive maintenance through sensor data monitoring, however, they generally lack detailed information about components, focusing primarily on displaying dynamic readings. Additionally, there are other maintenance software with specialized functions - for example O-Prognosis is used for asset condition inspections and creating long-term maintenance plans (Plandatis, n.d.) - yet the functionalities of these software are often limited to specific scopes within the maintenance process. Consequently, the large quantity of maintenance software solutions, each claiming to offer superior features, makes it challenging to assess their effectiveness in addressing the comprehensive needs of maintenance. As a result, service companies often rely on a combination of software tools to meet the diverse demands of stakeholders.

Therefore, maintenance personnel often operate within isolated software systems, relying solely on the data available within these systems, supplemented by scattered information that they must independently collect and manage. This decentralized approach significantly hinders collaboration, rendering it both inefficient and time-consuming.

Moreover, when applying RCM to optimize the maintenance strategy, it is essential to recognize the need for both static and dynamic information. Static information is required to identify the system and its components, while dynamic information is necessary to evaluate failures and iteratively refine the maintenance plan. Existing maintenance management systems and the limited integration between them are insufficient to fully address these requirements. Given that the BIM process has proven to encourage a collaborative environment in the design phase and the model is considered to be a valuable data source for the operational phase of a building (Naghshbandi, 2016), its use for visualizing and integrating with RCM presents a potential solution to these challenges worthy of investigation.

However, it is important to clarify the scope of "integration" as used in this research. The integration proposed here does not involve embedding maintenance functionalities directly within a specific BIM model or software. Instead, this study explores integration on a broader scale, aiming to develop a unified, centralized platform that is vendor-neutral. This platform would connect outputs from various maintenance management systems, enabling personnel who may not be using or have the expertise in those specific systems to see relevant information. The IFC model serves as the backbone to map components to these outputs, functioning as a static visual representation of the asset while being linked it to dynamic maintenance data.

The focus of this research is not to expand the BIM model or process but to use it within an integrated platform aimed at enhancing maintenance operations and supporting RCM implementation. Additionally, the information contained within the BIM model can be significantly enriched when adapted with maintenance-specific purposes in mind, further supporting the effectiveness of the proposed integration. This approach seeks to provide maintenance personnel with a centralized, data-driven platform that improves decision-making, as well as maintenance planning and execution.

1.2 Objectives and Research Question

The primary objectives of this research are meant to address key challenges in achieving effective maintenance management to enhance the efficiency of mechanical equipment. These objectives aim to investigate RCM process as a systematic approach for selecting optimal maintenance strategies. Furthermore, by identifying the information requirements necessary to enhance decision-making and ensure the efficient planning and execution of maintenance activities, means of integrating and interacting with this information can be investigated.

These objectives give rise to the following main research question:

How can Reliability-Centered Maintenance be integrated with Building Information Modelling to optimize maintenance strategies for multi-component systems and enhance the process efficiency?

To address this question, the research will focus on a specific case study, an AHU in an office building, which is central to HVAC system performance. Nevertheless, the scope of this research extends beyond AHUs, aiming to develop a structured framework and methodology that can be applied universally to any multi-component system within a facility, whether in residential or industrial settings.

To address the main research question, the following sub-questions arise and will be thoroughly explored:

Q1. How can the appropriate maintenance strategy be selected, considering a multi-component system within a building, its role, components, and BIM representation?

Q2. What are the information requirements necessary to include in a BIM platform to enhance the efficiency for maintenance selection and execution considering an AHU within an HVAC system?

Q3. How can the RCM documents, maintenance information and BIM model be integrated allowing a user to interact with them to enhance the efficiency of maintenance process?

1.3 Method

The research question was investigated through four phases. The first phase involved a review of literature to establish theoretical foundation. This was followed by the development of a framework for RCM and a concept for data integration. In the third phase, the framework was applied to the AHU for practical validation, and finally, a prototype was designed to demonstrate and validate the proposed integration concept.

The literature review examines studies on the application of RCM across various industries, the maintenance practices for HVAC systems, and the latest advancements in the integration of BIM with maintenance management and the wide Operation & Maintenance (O&M) phase. This review provides the foundational knowledge necessary for an understanding of the current state of research and highlights the critical gaps that this study seeks to address.

The thorough analysis of the reviewed literature establishes the development of an RCM framework. This framework, applied and validated through a case study of a typical AHU in an office building, can be used for maintenance decision-making in systems with multiple components. The output of this phase, that is the Failure Mode, Effect Criticality Analysis (FMECA) and maintenance plan derived from experts' knowledge, can be adapted to AHU with similar components or extended to account to accommodate additional components.

To examine the needs of the maintenance personnel and process, this research incorporates a design cycle dedicated to developing an interface for maintenance management. The design process begins with concept development, focusing on defining the functional requirements and specifying the critical information to be integrated in the interface, including the outputs of the RCM analysis. This interface is flexible and can be employed for different buildings and systems provided that the data modelling is adhered to.

1.4 Reading Guide

The remainder of this graduation report is organized into the following series of chapters:

Chapter Two presents a comprehensive literature review, establishing the theoretical foundation and contextual background for the research. This chapter examines existing studies on RCM, HVAC system maintenance, and the integration of BIM with O&M phase with an emphasis on maintenance activities of mechanical and electrical equipment.

Chapter Three details the research methodology. This chapter is divided into five sections. The first section delves into the development of a generic RCM framework, built upon insights from the literature. The second section focuses on how principles of systems engineering are used to assess the needs for maintenance management. Next the case study and the assessment of collected data is described, whereas the fifth section lays out the principles for the platform development.

Chapter Four discusses the implementation phase and presents the outcomes of applying the RCM framework to the case study of an AHU. This chapter details the essential information requirements for effective maintenance management and concludes with a detailed description of the platform's functionalities.

Chapter Five reviews the testing and validation phase where the interface is evaluated for its effectiveness and its ability to meet stakeholders' needs in supporting maintenance activities.

Chapter Six concludes the graduation report by providing an overview of the results through concise answers to the research sub-questions. It also highlights the scientific and societal contributions of the research, discusses key findings and addresses the limitations of the research, offering suggestions for future research.

2. Background Research

This chapter is organized into four sections. The first three sections clarify key terminologies and establish definitions for the primary topics of the research: maintenance, HVAC Systems and BIM. The final section provides a systematic literature review of papers studies exploring the integration of maintenance and BIM.

2.1 Maintenance Strategies

Maintenance is a critical responsibility for facility managers, essential to ensuring that building systems remain functional, efficient, and safe throughout their operational lifespan. Specifically, mechanical, electrical and plumbing (MEP) systems induce most of the maintenance-related activities in a building that account for 50% of the total life cycle cost in a large and complex building (Kwon, et al., 2019). Therefore, the adoption of effective maintenance strategies is crucial in reducing operational costs and extending the longevity of MEP systems.

This study investigates the maintenance of multi-components systems focusing on mechanical components through the application of RCM. However, before exploring RCM, it is necessary to establish a unified definition for commonly used maintenance strategies, as the same terms are frequently interpreted differently across the literature. Accordingly, this section distinguishes between two primary categories of maintenance: reactive and proactive, as illustrated in *Figure 1*. Following this, the principles of RCM are investigated, and its practical application is introduced. The literature review in Section 2.1.3 examines notable case studies demonstrating the successful implementation of RCM.

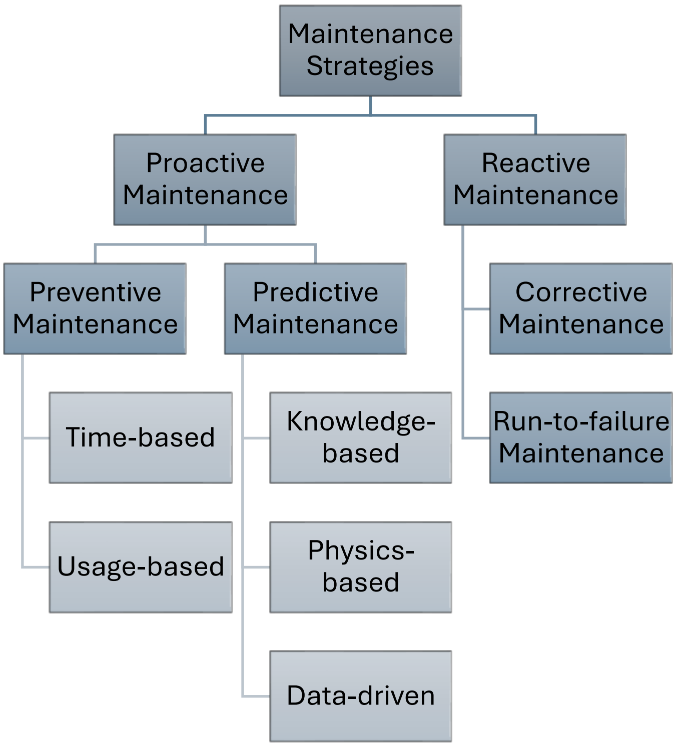


Figure 1: Maintenance Strategies

2.1.1 Reactive Maintenance

Reactive maintenance is the oldest and most recognized form of managing failures in MEP equipment. Generally, reactive maintenance is associated with a run-to-failure strategy, where the equipment is operated until it reaches a functional failure point and is subsequently repaired or replaced to restore operational condition. While often not perceived as a formal strategy, RM is an accepted and sometimes desired approach, as will be discussed later in this research.

The primary advantage of RM is its simplicity in execution and the minimal interference of maintenance personnel which can reduce operational costs (Sullivan et al., 2010). However, as a holistic strategy on its own it contradicts the fundamental goals of asset reliability management. Asset reliability management aims to ensure the continuous availability of assets resulting in high operational efficiency (ASHRAE, 2019). In reactive maintenance, since repairs are only initiated after a failure occurs, there is a delay before the equipment is operational again. This delay may be lengthened due to factors such as delayed response time, unavailability of spare parts or extensive repairs that were not visible and may necessitate replacement of the entire unit (Gullati, 2020). Consequently, the simplicity of reactive maintenance is counteracted by operational inefficiency, cost uncertainties, and reliability risks.

Corrective maintenance is often regarded as a form of reactive maintenance that can be differentiated from the run-to-failure approach. It involves restoring the system to as-new condition often through scheduled overhauls at predetermined intervals in an asset's lifespan. Although these overhauls are planned, they do not qualify as proactive maintenance because they address existing problems that have not yet led to complete functional failure (Gullati, 2020). Thus, while corrective maintenance is more structured than run-to-failure maintenance, it remains reactive by nature.

2.1.2 Preventive Maintenance

Preventive maintenance is a form of proactive maintenance aimed at preventing failure through systematic maintenance tasks. It involves scheduled tasks, for instance component replacement, irrespective of their condition at the time, as well as replacing service items like filters, oils and belts, and the lubrication of moving parts (Gullati, 2020).

Preventive maintenance has two major methods of implementation. It can be based on either calendar schedule so periodic maintenance tasks - performed seasonally, yearly, monthly, or weekly - or age dependent. In age dependent preventive maintenance, asset runtime is considered, and the schedule is based on operating hours (Zhao et al., 2022). As a result, a comprehensive maintenance plan is developed, requiring full engagement from the maintenance team (Sullivan et al., 2010).

The advantages of preventive maintenance include ensuring durability, reliability, efficiency, and safety of the assets (ASHRAE, 2019). Moreover, with the presence of a scheduled maintenance plan, managers can identify the spare parts required, appoint specialized personnel and estimate budgets accurately. However, failures may still occur between maintenance activities as there is no continuous monitoring of the asset’s condition. Additionally, since preventive maintenance heavily relies on manufacturer specifications, it can easily result in either insufficient maintenance or over-maintenance (Zhao et al., 2022).

To support maintenance scheduling, commercially available Computerized Maintenance Management Systems (CMMS) offer various functions such as mapping equipment with specific maintenance needs, automating procedures by fixing the scheduling of work orders (Eisner, 2022). These systems are particularly valuable for tracking the maintenance history of assets, allowing managers to gain deeper insights and a comprehensive understanding of asset performance. A well-maintained log containing but not limited to inspection reports on asset condition can significantly enhance maintenance planning and present opportunities for optimization transitioning away from a fixed, rigid preventive maintenance plan.

2.2.2 Predictive Maintenance

Predictive maintenance is the second form of proactive maintenance examined in this research. Often used interchangeably with condition-based maintenance. Predictive maintenance involves taking remedial action only when an adverse condition is detected in the operational state of the equipment. This can be achieved through periodic inspections, continuous monitoring, or a combination of both (ASHRAE, 2019). Continuous monitoring may consist of sensors readings, vibrations analysis, or energy consumption monitoring. Thus, predictive maintenance relies on the continuous production, processing, and analysis of dynamic data, thereby reducing costs of parts and labor (Sullivan et al., 2010).

Predictive maintenance offers numerous advantages, making it a widely researched and advocated strategy. Its primary basis is to keep the machinery in functional condition and extend its life expectancy by preventing early failure and costly shutdowns. In contrast to preventive maintenance, predictive maintenance reduces unnecessary maintenance actions and overuse of resources, effectively avoiding over-maintenance (Gullati, 2020). Studies indicate that industrial surveys have observed a 25-30% reduction in maintenance costs and a 70-75% decrease in equipment breakdowns through predictive maintenance implementation (Sullivan et al., 2010).

However, the complexity of predictive maintenance presents difficulties for its implementation. Unlike preventive maintenance, which largely involves routine planning, budgeting and resource allocation, predictive maintenance requires an initial investment in advanced monitoring technology and personnel training (Gullati, 2020) to ensure effective use of these technologies. As predictive maintenance relies on dynamic data analysis to identify early signs of impending failure, enabling timely intervention before critical issues arise, it is only logical to explore the possibility of Building Management Systems (BMS) in facilitating the monitoring and analysis process of predictive maintenance. BMS monitor integrated sensors and other monitoring devices installed on assets, continuously collecting real-time performance data (Holbert, 2024), which can then be analyzed to assess asset conditions. BMS is often synonymous with Building Automation System (BAS) because in addition to monitoring, the system has the capability to control building’s mechanical and electrical equipment.

Predictive maintenance methodologies are essentially divided into three approaches: physical model-based, knowledge-based and data-driven (Zonta et al., 2020). Physical model-based approaches rely on physics or mathematical modelling, knowledge-based approaches utilize knowledge gained from studying similar equipment whereas data-driven models are based on statistics or pattern recognition. It is important to note that hybrid methods, which combine two or more approaches, are most utilized (Zonta et al., 2020) to enhance the reliability of results as each method has its own inaccuracies and limitations.

Despite the use of numerous advanced technological tools to assist predictive maintenance such as Internet of Things, Big Data, Digital Twin, Artificial Intelligence and Machine Learning to name a few (Achouch et al., 2022), several challenges persist. The first significant challenge, as mentioned earlier, is the high initial cost and the need to familiarize personnel with predictive maintenance technologies and practices. Additionally, data reliability can be an issue, as sensors may fail or produce insufficient data. Finally, integrating, modelling, and updating predictive models within various management systems presents a further challenge.

2.2.3 Reliability-Centered Maintenance

The term Reliability-Centered Maintenance (RCM) first emerged in aviation through a documentation initiative by United Airlines (Nowlan & Heap, 1978) and was subsequently adopted by the defense industry (Love, 1987). RCM is a dynamic process aimed at enhancing the reliability, efficiency, and availability of assets while lowering operational costs. Despite its adaptability to evolving technologies, the core objective of RCM has remained consistent. This foundational approach has proven so effective that it is now widely implemented across various industries (Geisbush & Ariaratnam, 2022).

RCM is fundamentally a decision analysis framework that employs “a structured, systematic blend of experience, judgment, and operational data/information to identify and analyze which type of maintenance task is both applicable and effective for each significant item as it relates to a particular type of equipment” (Nowlan & Heap, 1978). Initially, RCM in aviation marked a shift from RM to proactive maintenance strategies, specifically within the preventive maintenance classification. Recent studies have leveraged RCM to optimize preventive maintenance intervals, with the goal of reducing maintenance costs (Okwuobi et al., 2018; Patil et al., 2022). Patil et al. (2022) report that implementing RCM in a steam boiler system reduced annual maintenance costs by 20.32%. Furthermore, Okwuobi et al. (2018) advocate for installing early failure-detection technologies, as the initial investment is often quickly recouped through significant gains in reliability and availability.

RCM differentiates between two types of failure: functional and potential (Nowlan & Heap, 1978). An asset that experiences functional failure is unable to meet its specified performance standards. However, a potential failure is indicated by observable changes in condition that signal an impending functional failure. Accurately identifying these types of failures requires a comprehensive understanding of each asset’s functions.

Figure 2 shows the basic steps for RCM as per first implementations specifically in the weapon industry (Love, 1987). It is important to highlight that a fundamental step in the RCM process is Failure, Modes Effects Analysis (FMEA). Love (1987) introduces a refined Failure, Modes Effects and Criticality Analysis (FMECA) incorporating criticality, a key factor that drives the final decision logic. FMECA is a bottom-up approach that identifies failure at component level, investigates the cause and effect of each failure on the system and assesses its criticality in terms of safety and operation. In its initial stages, the RCM was designed to select between four maintenance strategies: scheduled inspection, scheduled replacement, redesign or intensive inspection to items with hidden function (Love, 1987; Nowlan & Heap, 1978).

Figure 2: Basic RCM Steps adapted from (Love, 1987)

Geisbush and Ariaratnam (2022) identify sixteen industries that have adopted RCM approaches, with facility maintenance among them; however, RCM has yet to be widely implemented in the facility management sector. Nevertheless, it is hypothesized that RCM may demonstrate positive impacts on operational efficiency, process quality, and user comfort.

The implementation of RCM mandates following a process of predefined steps with the specific data required at various steps. For example, in applying RCM to radial gates, reliability engineers collected various essential documents and data, including “design specifications and drawings, as-built drawings, inspection reports, past work orders, and the equipment manufacturer’s operation and maintenance (O&M) manuals” (Geisbush & Ariaratnam, 2022). Additionally for RCM application on reciprocating compressor system, Liang et al. (2012) report that necessary data to assess maintenance intervals can be retrieved from product manufacturers, from knowledge of similar products, existing fault statistic data, judgment of domain experts or based on model quantitative analysis. Thus, successful implementation relies on a combination of expert knowledge and comprehensive maintenance data related to the asset.

In summary, while the core objectives and principles of RCM have remained consistent since its inception nearly 60 years ago, the methods and practices of implementation varied across industries and continue to evolve. Consequently, the adoption of predictive maintenance is essential, facilitated by leveraging dynamic data and machine learning algorithms.

2.2 Heating, Ventilation and Air Conditioning Systems

This section is divided into three sub-sections. The first sub-section provides an overview of what constitutes a HVAC System, then shifts the focus to the AHU which is the center of interest for the research. The second sub-section examines the critical functions of the AHU, highlighting its importance in building operations and its role in ensuring indoor air quality, a key factor in human well-being. The final sub-section addresses the maintenance of the systems, with an emphasis on fault detection and its implications for system reliability and performance.

2.2.1 Composition of System

Heating, ventilating and air conditioning (HVAC) Systems are designed to meet user’s thermal comfort and play a major role in ensuring acceptable indoor air quality which is essential for a safe and healthy indoor environment. These systems regulate critical parameters, including temperature, humidity, air motion, air quality, radiant energy, and pressure within a space (ASHRAE, 2020). The design of an HVAC system can be as complex as the building it serves, requiring careful consideration of various factors. Two key considerations are minimizing energy consumption and reducing maintenance costs (ASHRAE, 2020).

HVAC systems range from simple, single-function units to complex, integrated systems, depending on the building's requirements and the purpose of the installation. Generally, an HVAC system consists of the following components (Seyam, 2018):

Primary Equipment:

- Heating equipment; includes steam boilers and hot water boilers.
- Cooling equipment; includes water chillers or refrigerants from refrigerator process.
- Air delivery equipment; includes centrifugal fans, axial fans, and plug or plenum fan.

Air distribution:

- Terminal Units: Grilles and diffusers, fan-powered terminal, air volume terminal, all-air induction terminal, air-water induction terminal.
- Ductworks: Ducts delivering air-conditioned air to desired space.

Piping:

- System piping, used to deliver refrigerant, hot water, cooled water, steam, gas, and condensate from HVAC components.
- Delivery piping used to distribute refrigerant, hot water, cooled water, steam, gas, and condensate to HVAC units.

Design considerations also include space requirements, such as dedicated rooms for equipment, adequate space for ducts and piping, and accessibility for maintenance. Sensors are integrated to monitor system performance and efficiency, ensuring that HVAC systems achieve their primary functions of maintaining thermal comfort and indoor air quality for occupants and processes.

Figure 3 presents a BIM model which includes a basic HVAC system, with key components labeled for clarity. The heating equipment is housed in a dedicated room, while the AHU occupies its own separate space, both interconnected through a network of system and delivery piping. For simplicity and clarity of *Figure 3*, the ductwork network has been omitted. It is also important to note that the illustrated office building will serve as the case study for further analysis in subsequent sections.

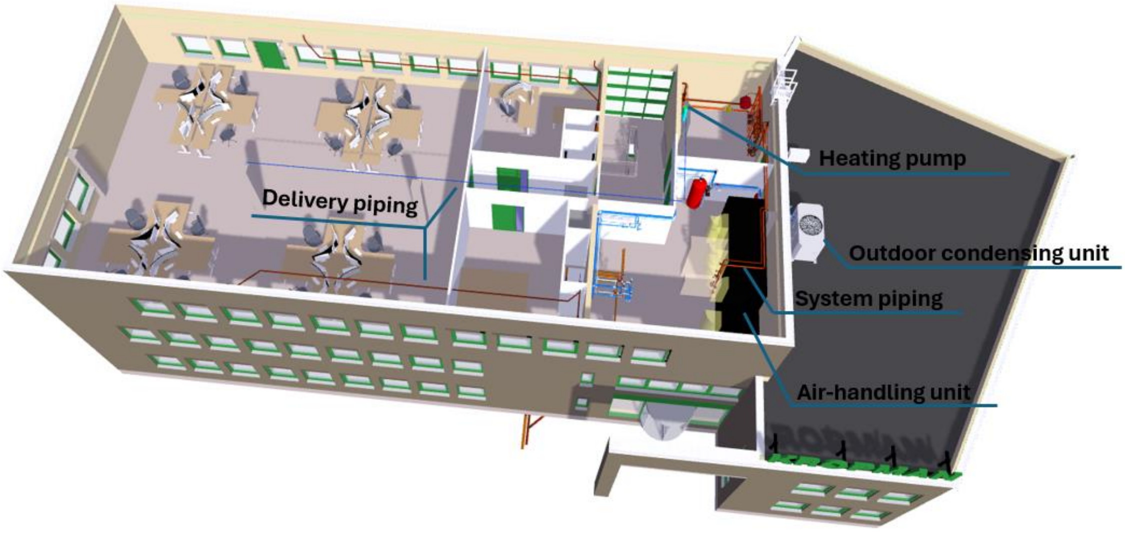


Figure 3 BIM model showing HVAC System, Breda office building

The AHU is a vital component of an HVAC system, responsible for supplying fresh, treated air to improve indoor air quality. Like HVAC systems, AHUs vary in complexity depending on their functions and the number of zones they serve. They can be designed for single or multiple zones and can operate as single-duct or dual-duct systems. Additionally, AHUs can function as either constant air volume (CAV) systems, which deliver a fixed airflow rate, or variable air volume (VAV) systems, which adjust airflow based on demand (ASHRAE, 2020).

Main components in AHU designs include air filters, heating and cooling coils, dampers, fans, actuators and sensors. Additionally, the unit may contain humidifiers and heat recovery devices (ASHRAE, 2020) that make it more energy efficient. Complex units also include noise and vibration control. A crucial design consideration is the integration of AHUs with the BMS or BAS, which manages various systems within a building. BMS integration is essential for optimizing AHU operation and ensuring efficient building performance

2.2.2 Indoor Air Quality

Indoor air quality is assessed through parameters such as temperature, humidity, airflow, and cleanliness (Asem, et al., 2022). Indoor air quality significantly impacts building occupants, influencing productivity, contributing to microbial contamination in poor conditions, and facilitating the spread of airborne infections (Asem, et al., 2022). As a result, continuous monitoring and regular maintenance of HVAC systems are essential to ensure their optimal performance.

Indoor air quality has gained increasing attention as people spend more time indoors. A comprehensive literature review by Mannan and Al-Ghamdi (2021) highlights research conducted over the past 20 years, examining indoor air quality in residential and commercial buildings worldwide. Studies focus on various parameters, including volatile organic compounds (VOCs), particulate matter (PM), carbon dioxide (CO_2), and carbon monoxide (CO), with particular attention to schools and offices. The overarching goal is to ensure compliance with indoor air quality guidelines established by regulatory bodies such as the World Health Organization, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), as well as the Danish Society of Indoor Climate.

Some occupants report symptoms associated with sick building syndrome when spending time in certain buildings. Although the exact causes remain uncertain, Joshi (2008) identifies inadequate ventilation, contamination from indoor and outdoor sources, and improper humidity levels as potential contributors. Preventive measures include designing HVAC systems in accordance with ASHRAE recommendations and ensuring their routine maintenance (Joshi, 2008).

2.2.3 Maintenance of System

As with other MEP equipment, HVAC suppliers recommend regular maintenance to be performed to guarantee maximum efficiency and lengthen life expectancy. Maintenance tasks range from replacing dirty filters to inspecting for leakage and verifying correct electrical flow.

The reliability and efficiency of an HVAC system are closely tied to its maintenance practices, with user satisfaction serving as a key measure of its effectiveness. Proper maintenance is therefore essential to fulfilling the system's intended purpose. Au-Yong et al. (2014) examined the relationship between maintenance characteristics and occupant satisfaction. Their survey of maintenance personnel revealed that the top three factors influencing user satisfaction are the skill and knowledge of the manager, the skill and knowledge of workers, and the response to failures and downtime. Both managerial and worker’s skills can be improved through comprehensive data availability and clear system understanding.

Es-Sakali et al. (2022) provide a detailed overview of predictive maintenance algorithms, categorizing them into knowledge-based, model-based, and data-driven approaches. The authors argue that relying on a single model is insufficient; instead, hybrid approaches that combine these methodologies are more effective. By integrating data-driven methods with knowledge- and model-based techniques, hybrid models can overcome common challenges such as incomplete or low-quality data. Thus, this research adopts a hybrid approach by integrating both dynamic data with expert knowledge through FMECA. By leveraging both data-driven insights and domain expertise, this method aims to enhance decision-making, ensuring more effective maintenance strategies and system reliability.

A final important topic is fault detection, diagnosis, and prognosis in HVAC systems, which is essential for identifying failures, understanding their causes, and ultimately optimizing maintenance. Yang et al. (2018) emphasize the importance of prognostic modelling and propose a FMEA framework for HVAC systems. FMEA systematically identifies component faults, their causes, and their effects on the overall system, making it a valuable tool for failure prognosis. Moreover, the study highlights challenges in data collection, such as data scarcity and unreliability.

Recent advancements in machine learning have significantly contributed to fault detection, diagnosis and prognosis automation. According to Singh et al. (2022) and Matetic et al. (2023), supervised techniques like Support Vector Machines (SVM) and Artificial Neural Networks (ANN) are widely applied, along with unsupervised methods like Principal Component Analysis (PCA) in HVAC application. It is worth noting that, these data-driven models often lack domain-specific knowledge and depend heavily on large, high-quality datasets (Singh et al., 2022; Matetic et al., 2023). To address these limitations, Matetic et al. (2023) advocate for a hybrid approach: a workflow where simpler HVAC systems can be managed with physics-based and rule-based methods, while complex systems with rich sensory and building information benefit from a combination of data-driven and knowledge-based techniques.

2.3 Building Information Modelling

This section is structured into four sub-sections. The first provides a definition of BIM as employed within this research. By defining BIM, the study emphasizes the significance of both the process and the resultant model, highlighting the enhanced collaboration it facilitates as well as the improved data availability and accessibility it offers. The second sub-section addresses the model's data availability in greater depth, specifically focusing on aspects such as levels of detail, development, and information need. The third sub-section shifts the focus from model-specific details to fostering collaboration through the adoption of standardized file formats, particularly the Industry Foundation Classes (IFC). The final sub-section explores other semantic representations, examining their potential to enrich the semantic content of building models.

2.3.1 The Definition of Building Information Modelling

Building Information Modelling (BIM) is subject to varied interpretations regarding its definition. Some interpretations focus primarily on the end product—the Building Information Model itself—while others emphasize building information management, describing it as a process that facilitates collaboration among stakeholders and ensures data availability and accessibility throughout the entire lifecycle of a building.

BIM represents a revolutionary digitalization approach first envisioned by Eastman in 1974 as a "Building Description System." He suggested the use of computer-based models instead of traditional drawings, with an emphasis on a database-oriented design. Since its inception, BIM has grown significantly, becoming widely adopted in the architecture, engineering, and construction sectors.

When BIM is viewed primarily as a model, it often includes references to additional dimensions such as 4D, 5D, 6D, and 7D, which represent time, cost, facility management, and more. In reality, both the model as an end product and the collaborative process are critical. For the model to achieve its intended objectives, collaboration must be established and encouraged from the start.

The European Council of Engineers Chambers describes BIM as "a cooperative working method that comprehensively captures and administers information relevant to the lifecycle of a building, allowing transparent communication and information transfer among all persons involved in the process."

The definition of BIM adopted in this research aligns with the view that BIM, as a digital representation of a building or civil infrastructure asset, can be extended to form the basis of a comprehensive database of all assets and facilitate the exchange of information in a unified and digital manner (Eastman et al., 2011). This study also adopts Borrmann et al.'s (2018) rationale, which describes BIM "as a comprehensive digital representation of a built facility with significant information depth," particularly valuable because it includes "information about the installed devices, including maintenance cycles and warranty conditions."

Thus, BIM ideally embodies a dynamic, comprehensive process that begins with project design, evolves through construction and commissioning, and continues to grow in the operation and maintenance phases. In Europe, for example, BIM became mandatory for project design of all centrally procured government projects in the UK in 2016 and similarly in Finland in 2017 (Borrmann et al., 2018).

However, despite BIM's advancements, two significant challenges remain, which this research discusses and elaborates on. The first challenge is that although BIM is typically used as a "historical database of the existing building" (Naghshbandi, 2016) during the O&M phase, it is often not updated with data relevant to ongoing operations.

The second challenge is the degree of BIM implementation, which varies significantly across sectors and project types (European Commission, 2019). For instance, surveys indicate that in France, BIM usage is 58% in commercial buildings (offices, retail, hotels) but only 19% in both infrastructure and single-family residential buildings. Similarly, in Germany, BIM adoption is 59% in commercial buildings, 22% in single-family residential projects, and 16% in infrastructure. Proficiency in BIM usage also varies by sector; in Germany and France, the proficiency range is relatively narrow (58-68% and 50-80%, respectively), whereas in the UK, proficiency ranges widely—from 8% for ceilings to 62% for steel components.

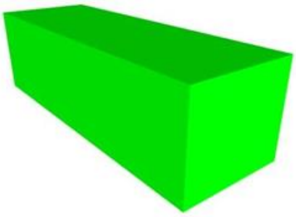
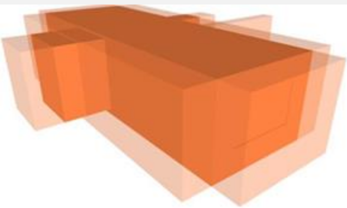
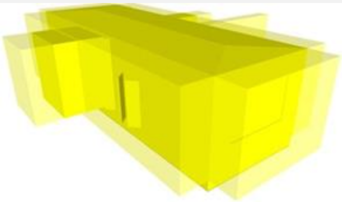
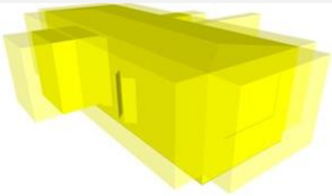
2.3.2 Levels of Detail, Development, Information Need

Having discussed the value and definition of BIM, it is essential to examine the model produced as a final product, which represents the building using an object-oriented design that integrates both information and 3D visualization. The modelling detail of these objects can vary significantly. For instance, an AHU might be represented as a simple cube, which is considered a low level of detail. However as more geometric details are added, the model becomes increasingly representative of the real-world object, resulting in a higher level of detail. This visual representation is further enriched with semantic information attached to the object. Thus, originally level of detail refers solely to the granularity or visual precision of the model. However, the most widely acknowledge and used metric in BIM is the Level of Development (LOD), which encompasses not only visual detail but also the reliability and usability of the model (BIMForum, 2023).

Although essential in BIM, LOD specifications vary widely and lack uniform descriptions, which can lead to different interpretations among practitioners and inconsistencies arising from misunderstandings (Abualdenien & Borrmann, 2022). Abualdenien and Borrmann (2022) conducted a comparative study of 58 LOD guidelines. They found that most standards used in the US derive from the AIA and BIMForum specifications, while countries like the Netherlands, Italy, Switzerland, and Belgium also use these specifications as a foundational basis. The authors concluded that specification recognize that as objects progress through higher LODs, the model becomes more reliable with increasing detail over the project's lifecycle. *Table 1* shows a cooling system as represented by AIA and BIMForum documentation (2023) where description of the LOD 350 entitles the model to provide precise information on the actual size, spacing, location, and connection of components, as well as floor and penetration elements and necessary access clearances

Moreover, each LOD encompasses semantic and geometric information, commonly referred to as "level of information" and "level of geometry" (Abualdenien & Borrmann, 2022). Notably, some important differences exist between specifications, such as defining LOD at a building level rather than an element level, or mapping LOD to project design phases instead of individual elements, which is often more practical. Ultimately, Abualdenien and Borrmann (2022) suggest that LOD should be assessed against specific use-case requirements, rather than solely defining it as a progressive refinement throughout the design phase.

Table 1: LOD levels according to BIMForum (2023)

LOD 100	**LOD 200**	**LOD 300**
Symbolic or generic representation	Generic and graphical representation	Graphical design
Conceptual	Approximate geometry	Sufficiently developed / Precise geometry
		
LOD 350	**LOD 400**	**LOD 500**
Graphical design and fully measurable	Detailed design	As-constructed, Field verified
Construction-level	Fabrication, assembly and installation	Same as LOD400 but with attached accuracy level
		

The Level of Information Need (LOIN) represents a more recent approach to defining information requirements within BIM. LOIN is tailored to specific actors and use cases, meaning it is defined "for specific exchange scenarios - accordingly, it needs to have a purpose, actors, and project milestone assigned as metadata" (Abualdenien & Borrmann, 2022). As shown in the *Figure 4*, LOD represents a refinement process, whereas LOIN does not build incrementally on previous levels and is possible to include multiple building elements. ISO 19650 defines LOIN as "the quality, quantity, and granularity of information," with the recent ISO 7817-1:2024 standard, providing the core concepts and principles of LOIN. The objective of this standard is to establish a consistent framework for specifying information needs and deliverables across BIM projects.

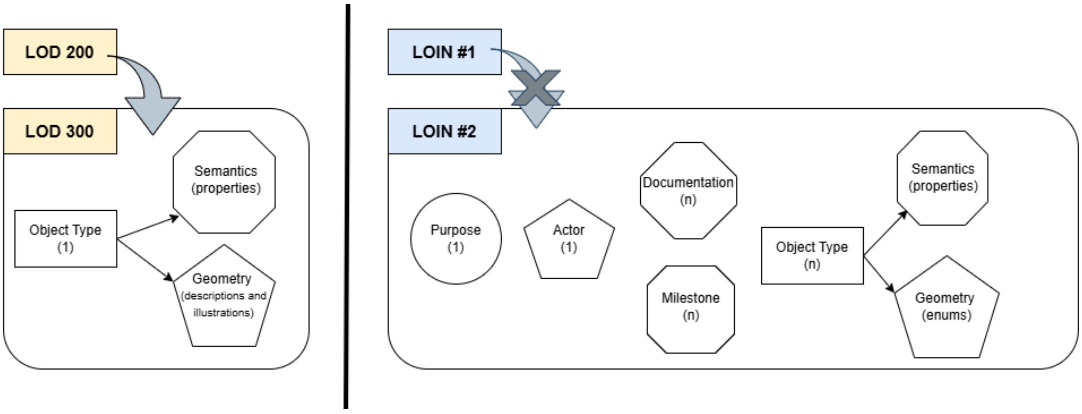


Figure 4: LOIN adapted from (Abualdenien & Borrmann, 2022)

It is important to note that while the construction phase relies heavily on the geometric accuracy of these objects, the operations and maintenance (O&M) phase also requires comprehensive documentation to support its activities. Building services, however, remain under-represented compared to structural or architectural elements, as they are often considered less critical for the design and construction phases. Consequently, the topics explored in this research are still in the early stages of study and have not yet been solidified into widely recognized standards

2.3.3 Industry Foundation Classes

The Industry Foundation Classes (IFC) standard was developed by buildingSMART and became ISO-certified in 2013. Its objective is to facilitate interoperability across disciplines and platforms through an open, standardized data model.

The IFC schema specifications are regularly reviewed and updated to address gaps in representation, with the latest official version being IFC4.3.2.0 (buildingSmart, n.d.). The adoption of this standard reinforces the understanding that BIM is not confined to a specific commercial design software or a single model file.

IFC objects are organized in a spatial representation, with attached attributes, properties, and relationships. For example, an *IfcBuilding* is contained within an *IfcSite* and may include elements such as *IfcBuildingStorey* and *IfcSpace*. This representation is essential for tracking spatial relationships within the model. However, while this structure is evident at the geographical level, it is not reflected within building services. For instance, there is no relationship in IFC that mandates an *IfcFilter* be contained within an AHU or any unit. In effect, specific multi-component systems like an AHU or HVAC do not exist as unified IFC objects; instead, components are represented as independent objects, as illustrated in *Figure 5*.

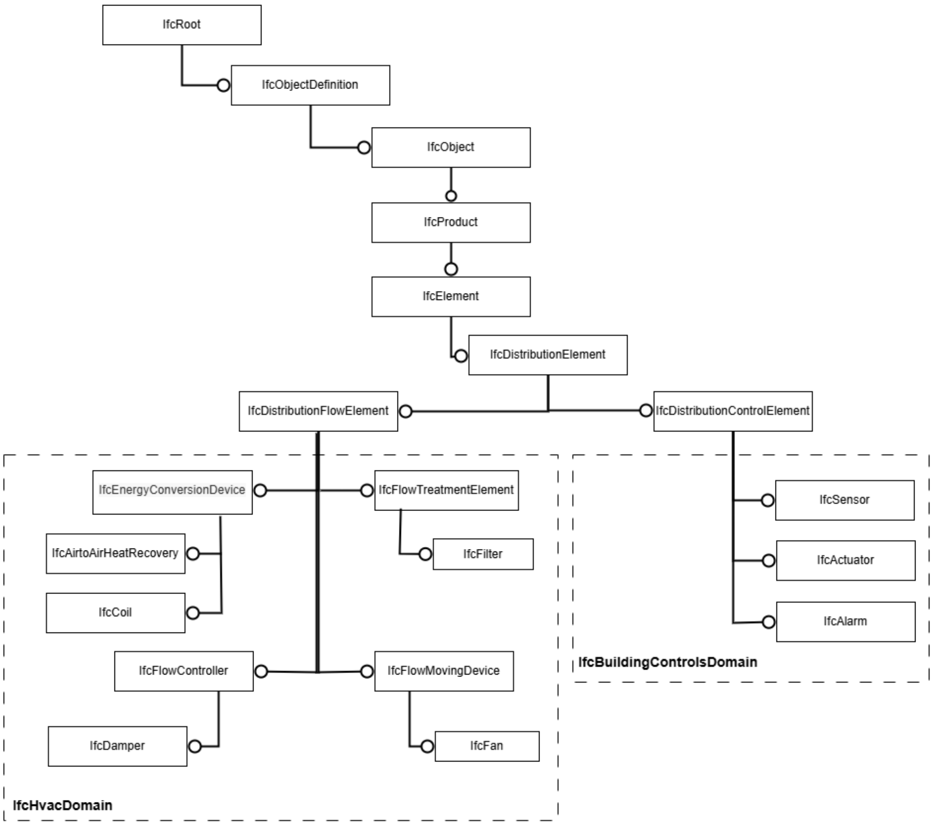


Figure 5:IFC representations of HVAC's components as per IFC4.3.2.0

2.3.4 BIM Process Standardization

Having established that BIM is not merely a model but rather a comprehensive process aimed at ensuring smooth collaboration among stakeholders throughout the entire lifecycle of a building, it is essential to review BIM from a process-oriented perspective. This process requires establishing both the appropriate mode of communication and a common language to ensure consistency and clarity among all participants.

The ISO 19650 series of standards plays a crucial role in establishing a framework for collaborative information management in buildings and civil engineering works. Its objective is to prescribe structured processes for effective information creation, exchange, and use throughout a project's lifecycle. ISO 19650 defines a systematic approach, encompassing key activities that management should undertake to achieve efficient information management. This is translated into Employer's Information Requirements (EIR), a BIM Execution Plan (BEP), ultimately leading to the development of a Master Information Delivery Plan (MIDP).

Part 3 of ISO 19650 focuses on the operational phase of built assets, specifying the use of an Asset Information Model (AIM), which is not limited to graphical elements but includes both non-graphical and documentation. The AIM serves as a dynamic repository of information that facilitates maintenance and asset management. In effect all the activities across the lifecycle are enabled by a Common Data Environment (CDE), a central virtual repository where processes for collecting, managing, and disseminating information are carried out, it can be viewed as both a solution and a workflow (Klaudia, 2024). This CDE ensures that all stakeholders have access to accurate and current information, thereby enhancing collaborative decision-making.

An earlier approach to structuring the BIM process is conveyed by standards developed by buildingSMART, such as ISO 29481:2010, commonly referred to as the Information Delivery Manual (IDM). IDM preceded ISO 19650 and was designed to provide a methodology that specifies what information needs to be communicated and in which phase throughout a project. IDMs are not software-specific but are used as a basis for successful implementation of software solutions (buildingSMART, 2010). An IDM typically includes a comprehensive description of project processes as well as the flow of Exchange Requirements (ER) within those processes. As such, IDMs aim to capture the required level of information need for a project, presented in a format that is comprehensible to stakeholders.

In contrast, Information Delivery Specification (IDS) is a computer-interpretable document, generally represented as an XML file, which defines specific information requirements for object modelling. IDS focuses on how data elements such as objects, classifications, properties, values, and units must be delivered and exchanged in BIM processes (van Berlo et al., 2023). This detailed specification allows for automated compliance checking, facilitating the validation of IFC files against the IDS.

Thus, while IDM provides a human-readable overview of information requirements and processes, IDS serves as a structured, machine-readable format that ensures compliance and accuracy in data exchange, enhancing the overall consistency and reliability of BIM projects.

The process outlined in *Figure 6* shows the role of IDS in creating, validating, and enriching building information in a BIM process. The client is responsible to create an IDS, which is then sent to the modeller. The modeller verifies software capabilities, creates data, and enriches it using buildingSMART Data Dictionary (bSDD). The modeller then exports the IFC with the IDS setting, and any validation issues are exported in BCF (BIM Collaboration Format). Finally, the IFC is sent back to the client, who validates the data against the IDS.

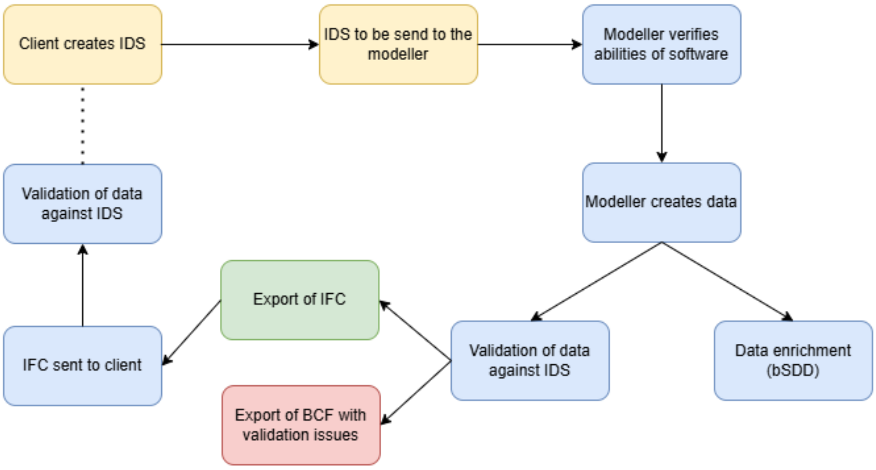


Figure 6: Process of Validating IFC against IDS as adapted from buildingSMART

2.3.5 Semantic Representations

IfcOWL translates the IFC schema into the Web Ontology Language (OWL), which is designed to enable machine-readable representations of terms and the relationships between them (W3C, 2009). It is a formal semantic language that adheres to the Resource Description Framework (RDF), where data is represented as triples, consisting of a subject, predicate, and object. The predicate functions as the relationship linking the subject to the object. By using RDF triples to describe elements, a machine-readable knowledge graph can be constructed, capable of representing the characteristics of elements within a searchable structure.

However, establishing a standard data structure alone is insufficient; a formalized terminology for naming elements and defining their relationships is essential. "A common ontology defines the vocabulary with which queries and assertions are exchanged among agents" (Gruber, 1993). Ontologies are domain-specific and operate at varying levels.

The Building Ontology Topology (BOT) was developed as an extensible ontology for defining relationships within the building domain. BOT introduces essential classes, including *bot:Building*, *bot:Element*, *bot:Interface*, *bot:Site*, *bot:Space*, *bot:Storey*, and *bot:Zone*, along with properties to establish spatial and structural relationships among these entities. BOT is, essentially, a minimal OWL DL ontology, a sublanguage of OWL (Rasmussen et al., 2021).

Another ontology, Brick, is an "extensible dictionary of terms and concepts in and around buildings" (Brick, n.d.), capable of defining relationships and adaptable within existing databases. The current stable version, Brick v1.4 includes *brick:Entity*, which is subdivided into four classes**:** *brick:Collection*, *brick:Equipment*, *brick:Measurable*, and *brick:Point*. For example, using Brick ontology a *brick:HVAC_System* can explicitly be defined as a *brick:System* and assigned specific properties. Additionally, within *brick:Equipment*, a comprehensive list of devices represents building services and installations.

Other ontologies, such as the Semantic Sensor Network (SSN) ontology, use a "lightweight but self-contained core ontology" called Sensor, Observation, Sample, and Actuator (SOSA), which links sensors, observations, actuators, and samples. SOSA was developed as a simpler, more accessible vocabulary compared to the SSN ontology, which is more detailed and provides a framework for describing sensor networks, their capabilities, functions, deployments, and relationships within systems (Haller, et al., 2017).

MIMOSA is an open standard relevant to maintenance management, focusing on two primary standards: OSA-CBM (Open System Architecture for Condition-Based Maintenance) and OSA-EAI (Enterprise Application Integration). OSA-CBM emphasizes components such as sensors, diagnostics, prognostics, and maintenance actions, while OSA-EAI provides definitions for integrating data across maintenance and asset management systems (MIMOSA, n.d.). Although MIMOSA does not provide a formalized ontology, it offers a structured data model that can be integrated with other ontologies to enhance interoperability.

2.4 Integration of BIM and maintenance

This systematic literature review was conducted based on aspects adopted from the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure a comprehensive and transparent examination of existing research. The review aims to explore the current state of integrating maintenance management with BIM, focusing specifically on the use of maintenance management systems (CMMS, BMS), maintenance information visualization, and recent innovative integration attempts. Articles were sourced primarily from Scopus, with a validation cross-check through Web of Science. *Tables 2 and 3* show the Query String used. The validation check resulted in 108 documents which were all included in the initial search. The inclusion criteria were restricted to articles published in English from 2018 onwards. Papers related to specific infrastructures such as pavements, roads, bridges, railways, and historical heritage were excluded to maintain the focus on MEP maintenance. Initially, to pick a starting date for the research, the search was set from 2008. As can be seen from *Figure 7*, the year 2018 has a noticeable surge in publications and thus, I decided to review papers from 2018. The papers were exported to excel with title, author, year of publication, abstract in order to easily filter through title and abstract. The initial search yielded 177 papers, which were narrowed down to 156 after removing duplicates. Further filtering by title reduced the amount to 69 papers, followed by abstract screening, which resulted in 60 papers. Finally, 54 papers were selected based on a thorough review of their introductions. The selected papers were categorized into four groups: 1. Process and Information Management 2. Integration of BIM and CMMS 3. Integration of BIM and BMS and 4. Further integrations of BIM and maintenance.

Table 2: Scopus query string, inclusion and exclusion criteria

SEARCH PLATFORM	SCOPUS
QUERY STRING	TITLE ("BIM" OR "Building Information Modelling" OR "Building Information Model" AND "maintenance") AND PUBYEAR > 2018 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (LANGUAGE , "English"))
ADDITIONAL EXCLUSION CRITERIA	All papers that relate to specific infrastructures, such as pavements, roads, bridges, railways, and historical heritage. Papers that were not available online.
INCLUSION CRITERIA	Conference papers, articles, reviews and conference reviews were included Only English papers were included

Table 3: Web of science query string and inclusion criteria

SEARCH PLATFORM	WEB OF SCIENCE
QUERY STRING	TI=("BIM" OR "Building Information Modelling" OR "Building Information Model") AND TI= "maintenance"
REFINED BY:	PUBLICATION YEARS: 2018 OR 2019 OR 2020 OR 2021 OR 2022 OR 2023 OR 2024 LANGUAGES: ENGLISH

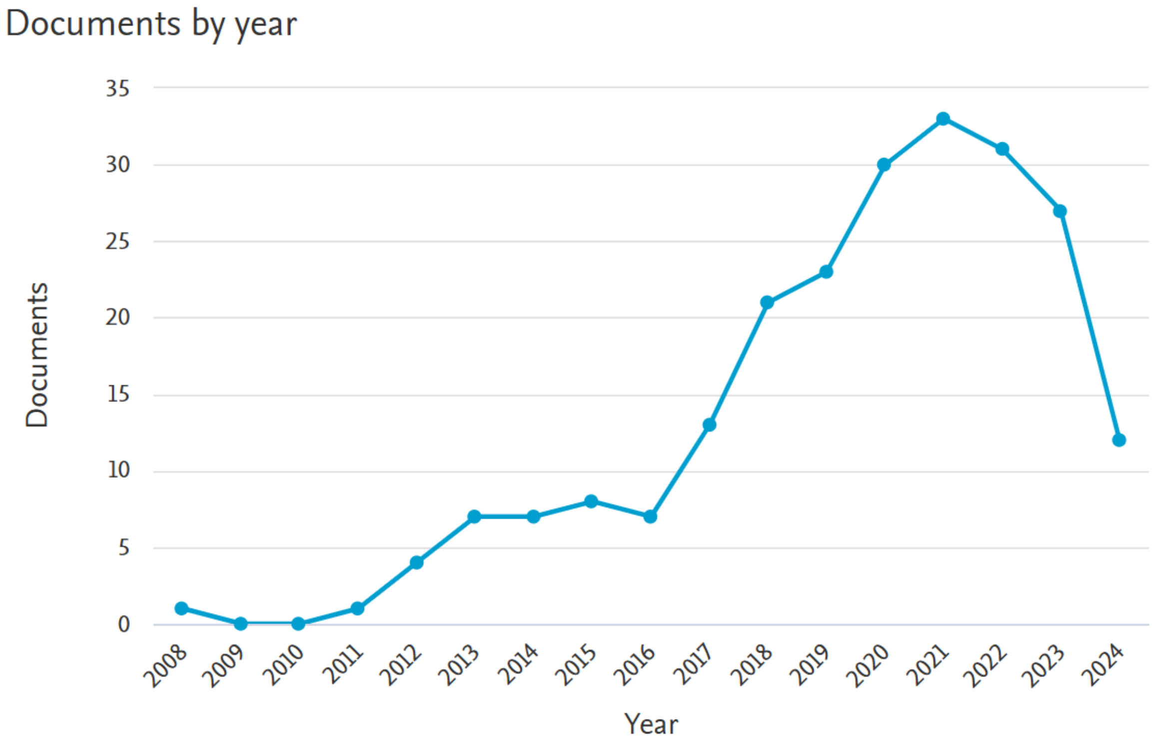


Figure 7: Research papers in SCOPUS based on research string, dated 20/06/2024

Systematic literature reviews between the years 2018-2024 typically fall into three categories: those with a broad scope examining papers on the holistic phase of operation management (Gao & Pishdad-Bozorgi, 2019), (Abideen et al., 2022), (Goretti & Kaming, 2023), those investigating the evolution of digital twins as a method integrating BIM and O&M (Coupry et al., 2021), (Lu et al. , 2022), and those focusing on specific industries such as facility management of Green Buildings (Cao et al., 2022) and maintenance in the manufacturing industry (Alvanchi et al., 2021). Moreover, recent bibliometric analyses identify China, the U.S and the U.K as the leading countries in publishing research about this topic (Goretti & Kaming, 2023), (Abideen et al., 2022), (Cao et al., 2022).

Studies highlight maintenance and repair as fundamental activity that can benefit from the 3D visualization capabilities of BIM (Gao & Pishdad-Bozorgi, 2019), (Cao et al., 2022). However, for effective implementation, this visualization must integrate information from facility management systems like BAS and CMMS (Gao & Pishdad-Bozorgi, 2019). The most researched topic, for attaining this integration, is information management (Abideen et al., 2022) which includes identifying information requirements, suggesting methods for accessing and handling data and conceptualizing the integration of fault detection and diagnosis with BIM. Subsequent research areas are technological advancement and maintenance (Abideen et al., 2022). Researchers have employed various research methods, including case studies, programming techniques and experts' interviews being top three researching methods (Abideen et al., 2022), to explore the advancement of this integration. A major goal of emerging BIM-O&M systems is to reduce dependency on experts (Gao & Pishdad-Bozorgi, 2019). Thus, these research methods are chosen to acquire expert knowledge and incorporate it into the systems.

Through their literature review, Alvanchi et al. (2021) derive a list of BIM capabilities that have the potential to resolve and improve challenges in O&M. These capabilities are classified into four beneficial characteristics: object-oriented and 3D visualization of BIM model, the collaborative environment between stakeholders, the interoperability of software that is generated and space management. Despite efforts to leverage these capabilities, researchers continue to face limitations related to current technology, information aspects, organizational management and lack or inadequacy of current standards (Lu et al. , 2022). To overcome these limitations Lu et al. (2022) advocates the use of a Digital Twin rather than expanding BIM to a multi-dimensional model of 7D (Goretti & Kaming, 2023) that incorporates facility management information. Digital Twins are created with a defined scope and possess "the capacities of integrating various data resources" (Goretti & Kaming, 2023) as well as incorporating advanced technologies such as augmented reality, mixed reality and virtual reality (Coupry et al., 2021).

All in all, the previous literature reviews had various objectives: analyzing O&M in general or listing benefits and challenges of BIM, but only partially addressing maintenance, much less MEP equipment. This validates the need for a more specific systematic review of this subject to provide deeper insights as a foundation for this research.

2.4.2 Process and Information Management

The efficiency of the maintenance process is crucial for timely execution. Galiano-Garrigos and Andujar-Montoya (2018) uses Alicante University as a case study, presenting the process from reporting a fault incident to repairing it and ensuring user satisfaction. The study concludes that the current process is inefficient with time and resources being wasted and being prone to human error due to extensive manual search for information. Similarly, Guzman and Ulloa (2020) study the workflow of maintaining 172 HVAC systems in an aquatic system. The traditional process involves scheduling preventive maintenance, contacting a maintenance subcontractor that performs the appropriate tasks and provides paper-based documentation and reports to be filed in a physical or digital database.

On the other hand, for BIM to be effectively incorporated into the maintenance process, the model must contain sufficient information relevant to the needs of O&M personnel. Therefore, it is important to consider their information requirements to introduce them early in the design process. In this context, Chung et al. (2019) and Benn and Stoy (2023) trace a recommended process identifying phases of information hand over. Chung et al. (2019) bases the information on COBie's 18 data sheets, dividing it according to project phases: early design, detailed design and O&M. The information is further linked to process tasks identified from literature review and surveys. COBie spreadsheets include information on building assets and are used for data exchange between BIM and facility management systems. However, the nature of a spreadsheet does not effectively address challenges related to data exchange, manual data extraction and input, or efficient data management.

Heaton et al. (2019) claims that by neglecting the O&M phase during the design phase, BIM models generally generate little value for facility management activities as they lack the information required by operating managers. They propose the use of Information Delivery Manuals as a standard process-based methodology for early engagement of maintenance (Heaton et al., 2019). Additionally, Sadeghi et al. (2019) suggests that COBie and LOD schema need to be consulted for correctly capturing and retrieving O&M information.

In an attempt to examine the information compatibility between 238 IFC files belonging to 15 buildings with their respective information in the CMMS, Halmetoja and Lepkova, (2022) use a case study of Finnish property-owning company that is speculated to be leading in digitalization. In terms of content, the IFC files lacked a percentage of components that were reported in CMMS such as fans, pumps, replaceable filters. The main discrepancy between objects representation is that often in BIM designers use "a packed object in an IFC file" (Halmetoja & Lepkova, 2022) whereas for maintenance planning individual components are scheduled for maintenance. Therefore, there is a divergence between the two software in data entry which makes locating and recognizing equipment difficult because of the different naming conventions used.

Heaton et al. (2019) establishes an asset classification hierarchy to be included within the BIM software, starting from functional output of the asset, going to system it belongs to. The functional output is chosen as chief classification because it is easily recognized by diverse stakeholders and highlights the significance of the system's function.

Benn and Stoy, (2023) investigates information requirements based on expert interviews with facility managers. Although the case study involves elevators, the authors conclude that most information is static data generic to all asset management. The authors suggest incorporating the requirements such as Exchange Information Requirements (EIR), detailing who needs what information. Although relevant, the study is limited by the small sample size of experts, with only three participants, two of which have merely 3 and 6 years of experience.

While identifying information requirements is crucial, presenting it is equally important, Ali et al., (2021) concentrates on developing a maintenance BIM model for mobile application. The methodology consists of focus groups and a case study for validation. A theoretical framework was developed, critical information to be added identified and the model validated through a series of expert meetings. The simplified BIM model includes asset information, location, specification, manufacturer, statutory, condition and cost information.

Therefore, previous studies have researched specific maintenance information requirements, as well as revising and optimizing the process for adopting BIM in O&M phase. Researchers emphasize the necessity of classifying assets differently for the O&M compared to the design phase, partially addressing deficiencies in information caused by the isolated phases.

2.4.3 Integration of BIM and CMMS

Beyond defining the process and information requirements, academics delved into finding methods of integration between O&M software and BIM. Condotta and Scanagatta, (2023) presents research performed based stakeholders' requests to develop an API that populates CMMS with BIM information. The authors emphasize the importance of a common taxonomy as a database structure between the various CMMS to be able to map with IFC models. This taxonomy automates matching CMMS spatial and maintenance objects - such as Building complex, Building, Floor, Room, Objects and Elements - to IFC representations, namely *IfcSite*, *IfcBuilding*, *IfcBuildingStorey*, *IfcSpace* and specialized Ifcs (e.g. furniture, HVAC). Data import should be based on IFC *GlobalId*, enabling linkage and updates between the two databases.

In another study, Chen et al. (2018) demonstrate IFC entities and attributes that for the integration of work orders with BIM, proposing extensions such as *IfcMaintenancePlan*, *IfcInspection*, *IfcMaintenanceTask*, *IfcMainteanceRequestEvent* and *IfcMaintenancSchedule* with attributes to match attributes of CMMS system. Thus, integrating Work orders with BIM is beneficial for planning, such as choosing the optimal path for workers (Chen et al., 2018) or prioritizing work orders (Kamal et al., 2021). Kamal et al. (2021) proposes a framework of three modules: databases integration, work order prioritization using case-based reasoning and a simulation with a user interface. The study suggests the presence of a standard structure for WOs which is easily identified and analyzed. However, this is rarely the case as work orders are usually unstructured and unsystematic. Sobhkhiz and El-Diraby, (2023) presents a method using unsupervised machine learning to generate semantic networks from unstructured data aiming to transfer valuable information from the non-standardized work orders to BIM objects.

In an effort to investigate current practices of maintenance management in Industrialized Building Systems in Malaysia, Ismail (2021) conducts interviews with eight maintenance contractors. The goal of the study is to analyze the problems faced as well as the use of ICT and emerging technology in maintenance management. The findings highlight that BIM technology use is limited, and a new system is conceptualized to integrate BIM, aiming at improving maintenance efficiency and knowledge management (Ismail, 2021). In a successive paper, (Ismail, 2021) presents the validation of the system through evaluation questionnaires. The model developed as an information database with the goal to aid in the decision-making process and critical defect diagnosis was evaluated in terms of effectiveness, practicality and usability. In both papers by (Ismail, 2021), the integration is addressed in terms of benefits, but the practical aspects of the integration method and system development are not described analytically. Additionally, there is no citation of any other paper that explains system development.

Researchers agree that integrating BIM and CMMS fundamentally enhances building performance among other benefits Dewi et al., (2020) and Riza et al., (2020) attempt to quantify this benefit numerically. They initially define building performance through four variables: safety, comfort, convenience and health for buildings' users (Dewi et al., 2020), (Riza et al., 2020). Consequently, optimizing maintenance of mechanical and electrical equipment is theorized to positively affect these parameters. To validate this hypothesis, Dewi et al., (2020) and Riza et al., (2020) employ an identical research approach with Riza et al., (2020) focusing on mechanical components and Dewi et al., (2020) on electrical components. The first step involves developing a component system breakdown and validating it with experts. The second step integrates the BIM model into a web-based interface, enabling users to report faults and managers to record maintenance actions. The authors use regression analysis to confirm the dependency of component maintenance on the four variables of building performance.

2.4.4 Integration of BIM and BMS

Zhang et al. (2021) and Fang et al. (2021) study two main challenges in the integration of a BIM model with IoT technology: the file size and the suitable connection for data transmission and reception. To ensure a lightweight model, Zhang et al. (2021) proposes converting the IFC model to glTF for geometric data and using JSON for attribute data. Data transmission is conceptualized to occur through the MQTT protocol, with data acquisition via a Zigbee network. By introducing threshold values, alarm messages can be viewed on the 3D platform to give warnings of unseen abnormalities (Zhang et al., 2021).

On the other hand, Fang et al. (2021) suggests the use of FBX files and a new public protocol to establish a BIM maintenance model with additional virtual reality visualization The proposed framework consists of four layers: raw data at the base, transmitted through the protocol layer, standardized into the decision-making and object management layer, and culminating in the integration and visualization layer incorporating BIM and VR. While this model facilitates field maintenance work, it lacks detailing features that promote predictive maintenance.

Cheng et al. (2020) conceptualizes a framework consisting of an information layer and an application layer with the latter further divided into four modules. The first module handles condition monitoring and fault detection, reading sensor data to identify abnormalities. The second module proposes a condition assessment method, resulting in an index that determines whether components require inspection, repair, or replacement. The third module employs machine learning algorithms and maintenance records to predict future equipment conditions, aiding maintenance planning in the fourth module.

In contrast to Cheng et al. (2020), who does not implement a complete case study with a visualization platform, Fialho et al. (2022) develops a prototype that visualizes the performance status of a lighting system. This prototype was validated for ability requirements such as reporting failures, providing maintenance information, and generating reports, as well as for design requirements. However, the use of commercial software (Autodesk and SmartLab) increased costs and required personnel training, presenting a downside to the research.

2.4.5 Further integrations of BIM and maintenance

Many studies suggest that complementing the use of BIM with Radio-frequency identifiers RFID (Hu et al., 2018) (Kameli et al., 2021) and/or AR (Wang & Piao, 2019) (Chen et al., 2020) (Mamaghani & Noorzai, 2023) (Fang et al., 2021) increases work efficiency and personnel performance.

In a case study on a stadium building, Kameli et al. (2021) used RFID to store component IDs, connecting a BIM database and a FM relational database through a web-based platform. The BIM database contains IFC files whereas the FM database holds information on "maintenance manuals, mechanical information, warranty status, date of inspection, and condition class". On-site personnel can use handheld devices (e.g., laptops, tablets, smartphones) to scan RFID tags and access all relevant information via the platform.

Hu et al. (2018) develops an intelligent management system focused on MEP components. A logic chain is proposed to structure and categorize components within an MEP system and add missing FM information, targeting operation manuals, specifications, and records of location, installation, and vendor-specific data. Although (Hu et al., 2018) and (Kameli et al., 2021) create efficient platforms for on-site access via RFID, they only incorporate static information without provisions for dynamic data from sensors.

Wang and Piao (2019), Chen et al. (2020) and Mamaghani and Noorzai (2023) incorporate augmented reality as extra visualization to facilitate maintenance tasks.

Mamaghani and Noorzai (2023) utilize an air-handling unit as a case study, integrating sensor information from an Arduino with a Revit BIM model and an AR platform. The approach links sensor data to Navisworks BIM model and uses AR to visualize maintenance procedure. The authors proclaim that the proposed approach reduces maintenance time by 37% in a period of six months. Similarly, a BIM model and AR are employed to facilitate the inspection and maintenance of fire safety equipment with an experimental group study to evaluate the efficiency of digitalized extraction of data (Chen et al., 2020).

Wang and Piao (2019) primarily focuses on developing a "facility risk assessment and maintenance system prototype". The first research phase uses FMEA combined with fuzzy logic to prioritize risks and decide on maintenance policy. The second phase involves developing and implementing a system to present the results from the assessment phase, connecting it with the BIM model and subsequently with AR presentation. The system provides a collaborative work environment that visualizes facility maintenance decisions, directions, and records. Although the paper provides explanations on the system's functions, it does not discuss the development process and integration methodology. In contrast, Mohamed et al., (2020) aim to define a "semantically integrated knowledge-based" BIM-FM graph. The proposed method uses scan-to-BIM to produce an AS-is model, linking components with relevant COBie spreadsheets via Autodesk Navisworks to populate the model with FM information. The ultimate goal is an ontological approach, achieved by converting the information into OWL-developed ontology using Protégé software, with possibility of SPARQL queries to be applied to RDF.

2.5 Summary of Background Research

RCM is a practical and flexible methodology that employs both reactive and proactive strategies after a systematic analysis of the system. This analysis involves identifying individual components, their potential failures, assessing their criticality and assigning maintenance strategies accordingly. It has been proven to reduce costs and increase operational efficiency. Despite its widespread adoption, RCM has not been fully standardized, with industries often adapting the process to suit specific operational requirements.

Table 4 provides an overview of the discussed maintenance strategies and their key characteristics.

Table 4: Summary of Maintenance Strategies

STRATEGY NAME	TYPE	APPROACH	ADVANTAGES
RUN-TO-FAILURE	Reactive	Unplanned	Low personnel involvement
CORRECTIVE	Reactive	Planned inspection	Restores to as new condition
PREVENTIVE	Proactive	Scheduled maintenance tasks	Known cost and scheduled tasks
PREDICTIVE OR CONDITION-BASED	Proactive	Monitoring-driven	Tailored to assets needs, limits over-maintenance
RELIABILITY-CENTERED	Optimization process	Systematic, Decision-based	Extends asset reliability, cost-efficient

The application of RCM can benefit facility management, particularly in maintaining critical multi-component assets such as an AHU within a HVAC system. However, the nature of RCM involves continuous refinement of maintenance plans based on system performance. This refinement relies heavily on the availability and accuracy of information, emphasizing the need for data integration and management to fully realize the prospects of RCM. BIM alone, as in model and process, is not the solution to support the employment of RCM. While the model itself can provide a foundation for visualization and information extraction, it is essential to define the required information through LOIN in advance. However, the BIM model in a standard ontology format i.e. IFC can be enhanced with further semantic representations, enabling the incorporation of metadata to address specific information needs. Additionally, BIM process standardization, such as ISO 19650, can guide the integration process to establishing a structured framework.

From the literature review, the integration of maintenance management with BIM is studied through three key topics. First, the static information requirements that need to be defined along with the hand-over time (Chung et al., 2019) and (Benn & Stoy, 2023) must be considered. Along these lines Halmetoja & Lepkova, (2022) researches the suitability of models for maintenance scheduling concluding that there are challenging discrepancies between how components are managed in a maintenance software and modelled in a BIM model. Second, maintenance planning, such as work orders and maintenance history, can be integrated with a BIM model. Notable functions researched are the automated extraction of BIM information to CMMS, (Condotta & Scanagatta, 2023) and work order integration with BIM model (Chen et al., 2018) and (Kamal et al., 2021). Third, the integration of dynamic data, specifically real-time sensor readings is considered. The prevalent method to be followed is the use of a digital twin model, (Lu et al., 2022) and (Goretti & Kaming, 2023), emphasizing the importance of creating a connection between the physical and digital model. Research also studies additional visualization techniques such as augmented reality (Wang & Piao, 2019), (Chen et al., 2020) and Mamaghani & Noorzai (2023).

3 Research Methodology

The methodological approach in this research builds upon and contributes to the existing literature on RCM process for optimizing maintenance and Systems Engineering principles for developing a platform that integrates BIM with maintenance. In essence, the research started with exploration of state-of-the-art through systematic literature, followed by data collection and analysis through a case study. Finally, semi-structured interviews were conducted for the validation of the RCM process results but also for platform development. Systems engineering principles served as foundational elements in the platform's design, incorporating an iterative design cycle with stakeholder engagement. Semi-structured interviews were selected as the primary method for collecting qualitative insights from maintenance experts, with the aim of capturing their professional opinions and field-specific knowledge.

This chapter will further examine the rationale and way of implementation of the research method. Although RCM and systems engineering may initially appear as divergent processes, raising scepticism about their mutual use within a project lifecycle—or, more specifically, within this research—both approaches fundamentally address system needs and reliability. Both processes focus on ensuring the system fulfills its holistic functions, adopt a stakeholder-centric approach, and strive for continuous improvement—whether through the iterative feedback cycle in systems engineering or the age exploration phase in RCM.

Indeed, while RCM and systems engineering are distinct processes, they share a common objective of ensuring system reliability and alignment with intended functional outcomes. Their primary distinction lies in the phases of the system's life cycle in which they are typically applied. The fact that both are interdisciplinary in nature and have broad applicability across various fields makes them a flexible and fitting choice. Moreover, both processes can be oriented toward risk management or cost-benefit analysis; however, these topics are beyond the scope of this research.

Although this research focuses on a basic AHU within an office building, the structured methodologies of both RCM and systems engineering prove even more impactful and prominent in complex installations or industrial applications. The office AHU serves as an accessible and manageable model to demonstrate the core principles of these processes while laying a foundation for broader applications. In reality, while simpler than industrial cases, the case study effectively illustrates how data is analyzed within these processes and how expert feedback is integrated.

This chapter will, first, provide a detailed discussion of RCM and systems engineering, followed by an analysis of the research methods employed, including the case study, data evaluation, and expert interviews. Before proceeding, it is important to clarify the difference in the use of the term "system" as it applies in this research. Within the context of RCM, the term "system" refers specifically to the mechanical equipment under analysis, such as HVAC, AHU, or any other mechanical system being evaluated for maintenance strategies.

In contrast, within the framework of Systems Engineering and concept development, the term "system" refers to the integration of BIM with RCM and maintenance management software and the platform or user interface being designed to enable it. By distinguishing between these contexts, discussions and analyses presented in this thesis are clearer to the reader.

3.1 Reliability-Centered Maintenance Framework

There is no standard that establishes fixed steps for the implementation of Reliability-Centered Maintenance (RCM) planning. The basis of all implementations is the textbook by (Nowlan & Heap,

1978) that first introduced the terminology as well as the entire concept. Approximately a decade later, (Love, 1987) the US Marine Corps documented a simplified five steps as illustrated in *Figure 2*.

As discussed earlier in the literature review, from that moment onward RCM experienced a surge in adoption across different industries. However, although researchers follow similar steps, the process has not been standardized and researchers either choose to combine, omit or slightly alter the process steps, aligning it with their specific operational requirements. Gupta and Mishra (2016) compare the elements in 19 frameworks found in the literature and *Table 5* further investigates more recent studies.

Table 5: Comparison of recent papers on RCM

Paper	Case Study	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9
Okwuobi et al.,2018	glass blowing machine	X	X			X		X		
Catelani et al., 2020	yaw systems in wind turbines		X			X		X		X
Prasetyo & Rosita, 2020	no case		X	X		X		X	X	
Ochella et al., 2021	no case	X	X	X		X	X	X		
Geisbush & Ariaratnam, 2022	radial gates	X	X			X		X		
Patil et al., 2022	steam boiler system		X	X		X	X	X	X	
da Silva et al., 2023	hydroelectric power plant		X			X	X	X	X	

The maintenance of mechanical systems can benefit from a comprehensive framework for RCM with explicit steps to enhance the efficiency of the process and its successful realization. *Figure 8* shows nine steps for the RCM process as can be applied for mechanical maintenance. This section describes each step individually prescribing its importance.

The RCM process typically involves a collaborative team effort as it relies on expert judgment and is extensive to be performed. Although, RCM can be implemented from the first year of operation leveraging existing domain expertise, its accuracy improves with continual iterations as operational data is gathered. This is because each system operates within a unique environment, making direct comparisons with other systems somewhat reliable but not entirely precise. Consequently, the last step of age exploration is performance data-driven and cannot be implemented until a sufficient amount data has been collected.

The framework's primary objective is to ensure both comprehensibility and robustness. To achieve this, the steps are not aggregated but rather distinctly divided to assign equal importance to each.

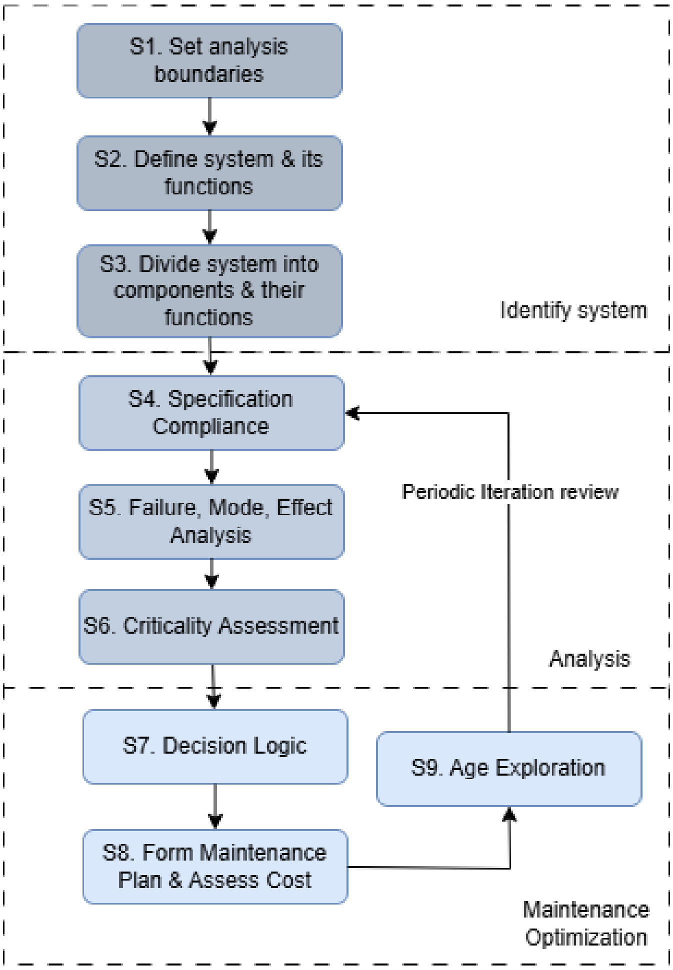


Figure 8: Reliability-Centered Maintenance framework for mechanical systems

3.1.1 Process Description

This section describes the RCM Process as illustrated in the framework, detailing individual steps.

Step 1: Set analysis boundary

The first step of the RCM process is to draw the boundary around the systems to be analyzed. This step is essential for breaking down the analysis into manageable segments or prioritizing areas that are more critical than others. For example, maintaining a specific temperature in a laboratory is crucial for the stability of chemicals. Therefore, when analysing an air conditioning unit, it is more critical to examine the system cooling the laboratory than the canteen. The analysis boundary is not necessarily location-based; it can also examine a process within a production line.

It is necessary to establish the characteristics of the set boundary, its role, users, or any special safety requirements involved. In a fully developed BIM model such information can be extracted and found in the IFC file. Consequently, the analysis can focus on an *IfcBuilding*, an *IfcSpace* or even an *IfcProcess* (if defined), with the attributes and property sets providing detailed descriptions of the region.

Although some studies omit this step, *Table 5*, documenting it in mechanical maintenance is significant as it impacts the results of the analysis. Moreover, this step aids in assessing accessibility, which is a critical maintainability characteristic of the system. By clearly defining the analysis boundary, one can evaluate how accessible the system components are for maintenance activities, which directly influences the ease and efficiency of maintenance operations.

Step 2: Define system and its functions

The mandatory initial step of an RCM process is to describe the system that will be analyzed. This step examines the system as a holistic entity, confined within the previously established boundary. It involves a detailed examination of the role of the system and its expected performance.

A key output of this step can be a functional block diagram. This diagram further divides the system into its intended functions and illustrates the relationships that exist within the system (Siddiqui & Ben-Daya, 2009). The complexity of the results will vary depending on the system in question. For example, a fire sprinkler system has a primary function of releasing water to prevent fire spread whereas a CCTV system has multiple important functions such as monitoring, storing and retrieving video surveillance. Therefore, and given that the principal purpose of RCM is to preserve system's functions to make it more reliable, it is crucial to clearly distinguish and list these functions.

Step 3: Divide system into components and their functions

In this step, the system is divided into subsystems and components, each of which is further defined by its specific function. The RCM analysis is performed at a component level, assessing its function and consequently its failures within the overall operation and intended functions of the system.

A system breakdown structure is produced to visually represent the composition of the system.
This step requires the use of As-built drawings and technical specification about the system to understand its composition and how it functions within the established boundary.

Step 4: Specification Compliance

Although, this step is not present in any of the existing studies, discussions with stakeholders have emphasized its necessity. This brief yet significant step, involves examining the components according to recognized specifications. While it may be partially incorporated into decision logic or criticality assessment, this framework distinguishes a list of standards that needs to be adhered to in an individual step from the start of the analysis.

Adhering to standards is critical in risk management, ensuring that components meet regulatory requirements. For instance, a fire extinguisher system is strictly regulated, and its maintenance frequency is defined in NEN 2559; therefore, this should be incorporated into the maintenance plan.

Step 5: Failure, Mode, Effect Analysis

Failure Mode Effect Analysis (FMEA) is the core of RCM, often integrated with Step 6 and collectively referred to as Failure Mode Effects and Criticality Analysis (FMECA). FMEA or FMECA is a well-established analysis tool across various domains, grounded on early documentations from the U.S. military standards such as Mil-STD-1629 in 1974 but also used in the Apollo program by NASA (Willoughby, 1966). It is defined as a design tool that distinguishes items with highest contribution to system unreliability or otherwise failure. Having divided the system into individual components, FMEA involves listing all possible failure modes of each component. This further entails listing the potential causes of failure and identifying their effects on the overall function of the system. According to the procedure outlined in Mil-STD-1629A, the process of performing FMECA aligns closely with the steps described thus far. This underlines its essential role as the foundational component upon which RCM is built. Moreover, Mil-STD-1629A emphasizes the importance of conducting the analysis early in the initial design process and continually updating it as further insights are acquired through the design phase. However, when a system is generally less critical compared to military applications, the iterative nature of the analysis is less dynamic. A design FMECA may suffice, and iteration is only necessary once maintenance records are gathered during the operational phase.

Step 6: Criticality Assessment

Criticality assessment can be approached through two methods. The first method, which is less computational and more straightforward, involves calculating a Risk Priority Number for each failure. This index is derived from the product of three factors: Severity, Occurrence, and Detection, and serves as an indicator of the criticality of the failure. Mil-STD-1629A outlines a second method that relies on a formula incorporating factors such as failure rate, failure mode ratio, and the probability that failure leads to system failure.

Step 7: Decision Logic

After identifying the most critical components and their effect on the system, the analysis proceeds to a set of questions to decide the optimal maintenance strategy that can be used for each component. It is worth noting that the maintenance strategies must be established at the beginning of this step. Typically, reactive maintenance is assigned to non-significant components whereas proactive maintenance is scheduled for more critical components.

While this step is defined in all studies as the selection of maintenance strategy through decision diagrams or logic tree analysis, it is crucial to recognize that the decision logic is case specific. Furthermore, the method of criticality assessment and the nature of the system significantly contribute to the complexity of the decision logic.

Step 8: Form Maintenance Plan and Assess Cost

This step involves compiling all strategies to form a comprehensive plan for the maintenance of the system. Further optimization can be considered in scheduling activities concurrently to enhance efficiency. Additionally, the formation of a maintenance plan facilitates the creation of a spare parts list and allows for cost assessment. In facilities utilizing specialized CMMS or more general ERP software, the maintenance plan is entered into the software for implementation and automated cost prediction.

Step 9: Age Exploration

Age exploration is introduced as a fundamental step in determining the suitability of maintenance tasks and the most effective time intervals (Nowlan & Heap, 1978). It examines component aging and its lifetime. This final step in RCM leverages innovative techniques to further optimize the procedure ensuring it remains dynamic and adaptive. By focusing on investigating the age of components and optimizing maintenance intervals, various machine learning technologies can be incorporated. When establishing an RCM plan for an existing system, this step precedes Step 8, as relevant data for components is already available and can be analyzed.

Data is extracted from BMS and utilized to develop data-driven algorithms, physics-based methods, or hybrid approaches. These techniques facilitate more precise maintenance scheduling, enhancing the overall efficiency and effectiveness of the RCM plan but also introducing a periodic iteration review loop that feeds back to Step 4.

The RCM process is applicable to systems containing mechanical equipment. The implementation detailed in Section 4.1 provides a further analysis explanation of the steps involved, offering a process that can be adapted and applied to various case studies. Thus, supported with implementation the relevance and utility of the framework across different types of mechanical systems within buildings is ensured.

3.2 Systems Engineering

Systems Engineering is a holistic, interdisciplinary approach to the development, design and management of a system throughout its lifecycle. Kossiakoff et al. (2011) define the role of systems engineering to “guide the engineering of complex systems”. Therefore an effective systems engineering approach establishes the path for all involved disciplines to realize an efficient and economical design. Unlike traditional engineering disciplines that focus on specific technical components, systems engineering addresses the system as a whole, emphasizing the total operation, interaction with with other systems and alignment with the needs of users. System engineering serves as a bridge between various engineering disciplines involved in the design leading the overall design and development process, particulary during the concept development stage.

One of the essential goals of systems engineering is to achieve balance and a high degree of modularity while integrating different functions of the system aiming to make interactions “as simple as possible for efficient manufacture, system integration, test, operational maintenance, reliability, and ease of in - service upgrading.” (Kossiakoff et al., 2011). Modularity is crucial to system engineering, as it enables the allocation of functions to be more efficient and ensures that different system components can operate independently. This modularity not only simplifies system integration and testing but also facilitates easier maintenance and potential upgrades during the system's operational life.

Therefore, systems engineering aims at understanding the broader context, identifying stakeholders requirements, defining system functionalities and overseeing the whole lifecycle. A typical systems engineering process involves requirements analysis, system architecture and design, verification and validation processes as well as lifecycle management. Although the process is systematic, there are several process models - such as linear, V, spiral and waterfall (Kossiakof et al., 2011) – that provide distinct defined steps. This research adopts the overall principles of systems engineering, and concentrates on aspects of the concept development stage.

Concept development represents the foundational step in creating a system that effectively addresses user needs and operational deficiencies. During this step, a balance is investigated between cost, technology and functional requirements, ultimately striving for a system that meets the demands established by stakeholders. Accordiing to Kossiakof et al. (2011), there are three steps in concept development (*Figure 9*). The first step is to establish the need which has been done through the problem definition and the literature review. The second step involves evaluating the required performance for the system determining the level of functionality and performance standards needed to address the identified problem. Finally, the functional requirements, found in Section 3.5, are defined and recorded, creating a comprehensive list of the system's functional specifications that will guide its development.

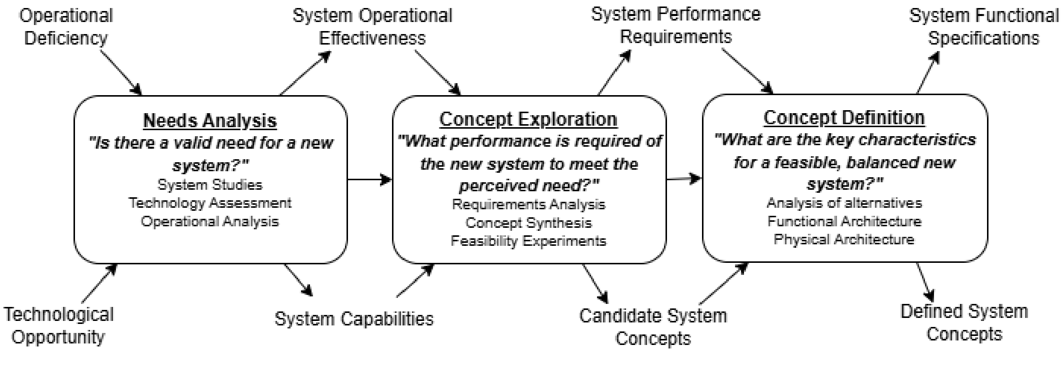


Figure 9: Concept Development Stages as adapted from (Kossiakof et al., 2011)

In this research, the concept definition for the development of a platform that integrates maintenance with BIM is explored. The integration process involves multiple stakeholders, as depicted in *Figure 10*. The primary users of the proposed platform are the maintenance personnel, who will rely on the integrated system to enhance the efficiency of maintenance activities. Although facility users and facility owners must also be considered, their required functionalities are significantly more limited, and they fall within a category of stakeholders who need to be informed because their satisfaction is crucial to the success of integration. Thus, their direct involvement in the platform's initial development is less prominent compared to the maintenance team.

Among the stakeholders, developers hold considerable power over the integration process, as they are responsible for translating the conceptual requirements into a functional platform. For this reason, ensuring the needs of the primary users are well articulated is crucial to guiding the developers effectively. Therefore, to achieve successful implementation of the concept, close collaboration between the primary users and the development team is imperative. This collaboration must be structured with a clear emphasis on aligning the technical development process with the functional requirements and expectations of all stakeholders. By maintaining a continuous feedback loop between users and developers, the platform can be refined iteratively, ensuring that the end product not only meets the technical specifications but also addresses practical user needs effectively.

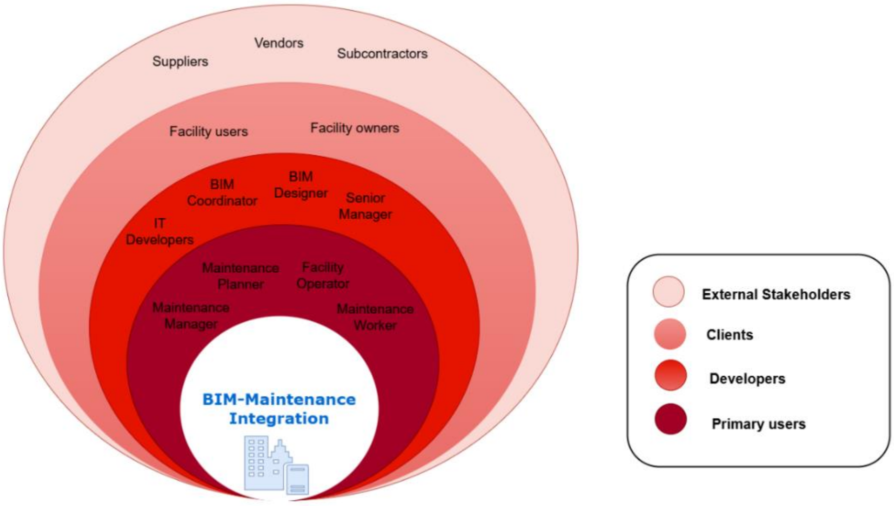


Figure 10: The BIM-Maintenance integration stakeholders' map

3.3 Case Study

A case study was chosen to provide an in-depth exploration of real-world issues and practical implementation of processes. Moreover, it assists in identifying the holistic challenges that are often less evident in theoretical concepts. By focusing on a specific case, detailed insights are gained, findings can be more effectively demonstrated, and the concept becomes more tangible.

The AHU was selected as the case study because of its importance in maintaining acceptable indoor air quality in both commercial and residential buildings, making it a critical component of building mechanical services.

The AHU system is a constant air volume unit with a capacity of 15,000m^3/h installed in a medium-sized office building in Breda. The building itself was constructed in 1993 and underwent renovation in 2009. Meanwhile managers confirm that, apart from the addition of different instruments, regular filter changes, fan replacement and the removal of humidifier, the AHU has not been entirely replaced or significantly damaged. Visually, the AHU appears to be in good condition for its age. Furthermore, the building serves as a live laboratory where continuous experimentation is being performed, such as fault detection and energy performance optimization. This necessitated the addition of various instruments that do not directly contribute to AHU's operation.

The most recent revision of the P&ID, dated 15-03-2024, is presented in *Figure 11.*

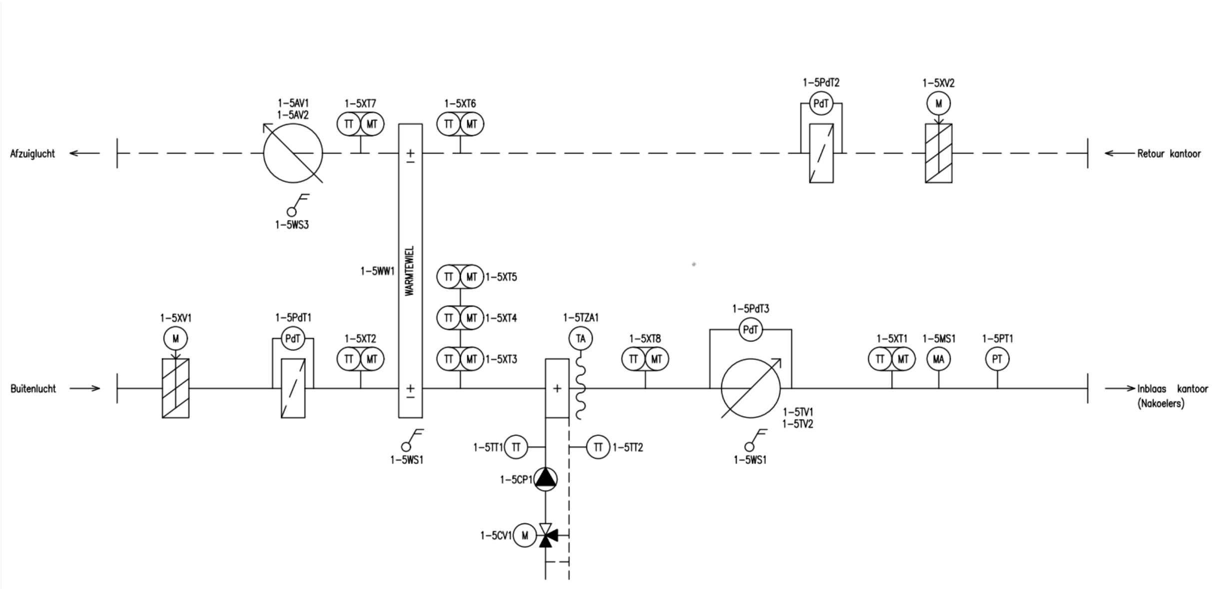


Figure 11: Excerpt of AHU P&ID, 2023 of an office building, Breda

The current maintenance plan for the AHU primarily involves reactive maintenance, supplemented by an annual inspection during which the filters are replaced. The tasks prescribed in the work order can be seen in *Table 6*.

Table 6: Annual maintenance tasks of AHU

Task No.	Task Description
1	Carry out according to work description: Replace filters
2	Clean surface, heat exchanger/boiler, drip tray
3	Check (and repair if necessary): Casing for corrosion and leakage
4	Check (and repair if necessary): Insulation, damage and functionality
5	Report work carried out

This work order is assigned to a maintenance worker and performed during operating hours, requiring the AHU to be turned off for 1½ to 3 hours. According to the maintenance inspection report for the year 2020, the employee was unable to finish the maintenance due to complaints from the office employees as the maintenance took place in January. In contrast, the previous two inspections, performed in mid-March and early April, no complaints were recorded.

Given the vague descriptions of the tasks, it is crucial that the maintenance personnel be experienced and knowledgeable about HVAC systems to successfully inspect and identify any failures. To address these issues and improve the AHU's reliability, the RCM process will be applied, aiming to optimize the maintenance plan.

3.4 Data Collection

Various types of data were identified as necessary to fulfill the research scope. First, the RCM process required insights into the AHU, which were gathered through P&ID drawings and a site visit. The age exploration phase, which focused on the filter, necessitated information regarding its maintenance history, differential pressure readings, and the operating manual. Subsequently, the platform development phase required the use of a Revit model. Additionally, semi-structured interviews were conducted to validate the RCM process and support the concept development and design of the prototype for the integration platform. This section describes the methods used for data collection and processing, as well as the procedures for conducting and evaluating the interviews.

3.4.1 Data Evaluation

Table 7 shows the format of the collected documents and the source of extraction. It was necessary to ensure that all data collected was up to date, such as obtaining the most recent P&ID drawings. This was particularly important, as installations dating back to 1993 are likely to have undergone modifications. Moreover, since the research focused exclusively on the five components of the supply air, it was feasible to visit the AHU room, confirm the drawings, and obtain information regarding the model and serial number of the filters (*Figure 12*). It is worth noting that this procedure for collecting model and serial numbers is standard practice in maintenance planning for mechanical installations.

Table 7: Overview of data collected

Document	Format	Extraction point
P&ID drawings (AHU)	.pdf	Onedrive
Operating manual (filter)	.pdf	Onedrive / Manufacturer's website
Maintenance work orders (AHU)	.pdf	Microsoft Navision
Sensor readings (PdT)	.csv	Insite Reports
Mechanical model	.rvt	Revit central model
Architectural model	.rvt	Revit central model

Figure 12: Photo from supply filter

Maintenance work orders were extracted, with the assistance of a maintenance planner, from Microsoft Dynamics Navision, the Enterprise Resource Planning (ERP) system currently in use. The work orders were filtered and identified based on contract and location identifiers. It is important to note that there is no standardized structure for the details included in these work orders. Additionally, the work orders contained two dates: the order date, when the request was entered into the system, and the execution date, which was intended to be filled in upon completion of the maintenance. Check Appendix A for the layout of the work order discussed. The execution date, if present and not omitted, did not always coincide precisely with the actual maintenance date but was often recorded a day or two afterwards. This discrepancy was easily identifiable by comparing the recorded dates with the differential pressure sensor readings from the respective days. Although this small deviation does not compromise the integrity of the collected data, it underscores the need for improved systems integration.

The quantitative data used in this research consisted of readings from the differential pressure transmitter across the filter. Time-series data was obtained from InsiteSuite, a brand-independent software developed by Kropman to interface with building management systems. InsiteSuite[1] contains a module called InsiteReports, where all data can be downloaded. However, for the specific sensor (1-5PdT1), data was only available starting from 01/08/2022, as all previous data had been marked as deprecated. Thus, the dataset used spans from 01/08/2022 to 02/04/2024, which limits the potential for a comprehensive age analysis of the filter. Further discussion on this limitation is presented in Section 6.4.2 under Limitations and Further Research.

For the BIM model, two Revit models were made available: one architectural and one mechanical. Although the building was constructed some time ago, it was only recently modelled in Revit. Additionally, there are electrical, duct, and plumbing models, but they are not relevant to this research.

3.4.2 Interviews

For the validation of the FMEA and criticality assessment, an interview with the building's technical leader and operation manager was conducted. The interview was guided by the developed FMEA and focused on the failure modes of the five key components of the AHU: damper, filter, heat recovery wheel, heating coil, and fan. Following the validation, the interviewee was provided with the rating scales as defined in *Figure 22*, along with a copy of the FMEA, to rate the severity, occurrence, and detectability of the identified failures. *Table 8* presents the topics and related question type for this interview whereas Appendix A contains the summarized interview as well as the results of the criticality assessment.

Table 8: Topics and Question to validate FMECA

TOPIC:	QUESTION:
COMPONENT FUNCTION	What are the functions of (specific component) in the AHU?
FAILURE MODE & CAUSE	(Specific component) can fail by (failure mode). Do you agree? And what might be the cause of such a failure?
FAILURE EFFECT	If (specific component) fails by (failure mode) in what ways does that affect the AHU?
CRITICALITY ASSESSMENT	Can you rate the severity, occurrence and detectability of (failure mode) of (specific component) following the rating scale you are given?

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[1] https://ivs.kropman.nl/insitereports/

To establish the information and functional requirements of the platform, two interviewees were selected based on their experience and roles within the company. The first interviewee serves as a maintenance manager, primarily responsible for onsite inspection of equipment and the development of long-term maintenance plans. The second interviewee is the head of the remote management department, which is responsible for the remote operation of installations, handling user complaints, and generating work orders for sudden failures. The first part of the interview focused on various aspects of the maintenance process, including the technology used and information management practices. In the second part, specific information requirements were discussed, where interviewees assessed the usefulness of various properties. Finally, the interviewees were presented with the initial version of the prototype, and their feedback was collected to revise the design. *Table 9* presents the topics and related question type for this interview.

Table 9: Topics and Questions to establish integration needs

TOPIC:	QUESTION:
PROCESS	What activities are you (and your team) involved in? Who are the people you primarily collaborate with?
TECHNOLOGY	What software do you use and for what tasks do you use it? Does this software match all the tasks you need to perform, or do you need supporting software/tools?
INFORMATION MANAGEMENT	In what form do you get the information you need and in what form do you share information with the people you collaborate with? How do you ensure that everyone has access to up-to-date reliable information regarding the components and maintenance?
USER INTERFACE PROTOTYPE	What opportunities do you see for BIM to help you with your job? In what ways do you believe it can facilitate your job?

3.5 Maintenance-BIM Integration Development

The functional requirements for the platform, as presented in *Table 10*, have been extracted from interviews conducted with the identified users of the system. These requirements essentially define the expected functionalities necessary for the system to fulfill its intended purpose. On the other hand, *Table 11* presents the non-functional requirements, which specify the system's ability to perform these functions effectively. To facilitate smoother development processes and minimize iterative feedback loops, it is essential that the functional requirements be clearly articulated and unambiguous, while the non-functional requirements must be quantifiable and specific. This approach aligns with the principles of systems engineering, which emphasize rigorous requirement definition to ensure comprehensive system performance and integration.

Table 10: Functional requirements of the system

Id	*Description*	*Priority*
FR1	**User shall be able to navigate 3D model and zoom into spaces**	**High**
FR2	**User shall be able to select components within AHU**	**High**
FR3	**User shall be able to search and view information of AHU/components**	**High**
FR4	**User shall view maintenance history of AHU/components**	**High**
FR5	**User shall search for components by unique id**	**High**
FR6	**User shall be able to navigate FMECA**	**High**

Table 10 continues from previous page

FR7	**User can view system by maintenance strategy**	**Medium**
FR8	**User can view faults generated from BMS or fault detection algorithms**	**Medium**
FR9	**User can view dynamic/live readings of sensors**	**Medium**
FR10	**Building's users can report suspected faults**	**Medium**
FR11	**Maintenance worker has access to fill in maintenance report**	**Medium**

Table 11: Non-functional requirements for the system

Id	***Description***	***Priority***
NFR1	**The 3D model shall load in less than 120 seconds**	**High**
NFR2	**The model can be navigated by element type in tree-form**	**High**
NFR3	**The interface shall be understandable to navigate separating its functions in tabs and providing help information.**	**High**
NFR4	**When selecting a component, the API shall extract its unique id**	**High**
NFR5	**When searching metadata, loading time will not exceed 120 seconds**	**High**
NFR6	**The information shall be customized for four/five different users**	**Medium**
NFR7	**Sensory data shall have indications of limits and average**	**Medium**
NFR8	**An algorithm links user complaints to faults detected**	**Medium**

In developing the functional and non-functional requirements, a systematic approach was employed to ensure that stakeholders' demands were thoroughly addressed. First an investigation of the current process, identifying areas that could benefit from integration. This analysis provided insights into existing inefficiencies and opportunities for improvement, forming the foundation for requirement development.

Subsequently, a use case diagram - *Figure 14* - was created to visualize and clarify the needs of each user, ensuring that the diverse activities of all stakeholders were captured. This diagram served as the primary input for formulating functional requirements, transforming user needs into specific actions that the system must be capable of performing.

Finally, a system architecture - *Figure 15* - was developed, which provided a structured framework for the design process. This architectural representation paved the way for a coherent design for the platform.

3.5.1 The Current Process

Three types of contracts are particularly prominent in the company:

Contract Type 1: Design-Build

Under this contract, a project is assigned to a design team responsible for developing a BIM model and associated drawings. Following the completion of the design phase, construction activities are carried out, during which the BIM model is utilized for clash detection and the documentation of task completion. The project is subsequently handed over to the client upon the completion of all installations.

Contract Type 2: Design-Build-Maintain
This contract extends beyond the scope of Contract Type 1 by incorporating a maintenance phase. After the project is designed and constructed, it continues to be maintained by the company for a predetermined period, as per the agreement with the client.

Contract Type 3: Maintain-Only
This contract involves the maintenance of an existing facility, typically secured through a successful tender process. The focus is exclusively on ensuring the operational performance and upkeep of the facility over the specified duration.

The primary activities performed by individual stakeholders under the maintenance contract are analyzed and presented in the *Figure 13*. Activities highlighted in red are those expected to benefit significantly from the adoption of a BIM platform.

Currently, the maintenance manager is responsible for defining the fundamental maintenance plan based on general information about the entire system and the acceptance of overall budget. Following this, the detailed planning and scheduling of these activities, including material order and personnel assignment within the ERP system, fall under the responsibility of the contract manager or maintenance planner. The operator of the building management system or the remote control engineer is not involved either in the preparation of the maintenance plan or its execution and approval. Thus, the current process does not allow for condition-based maintenance as the people concerned with developing the maintenance plan have no insights to dynamic data and can only visually inspect the condition of the equipment.

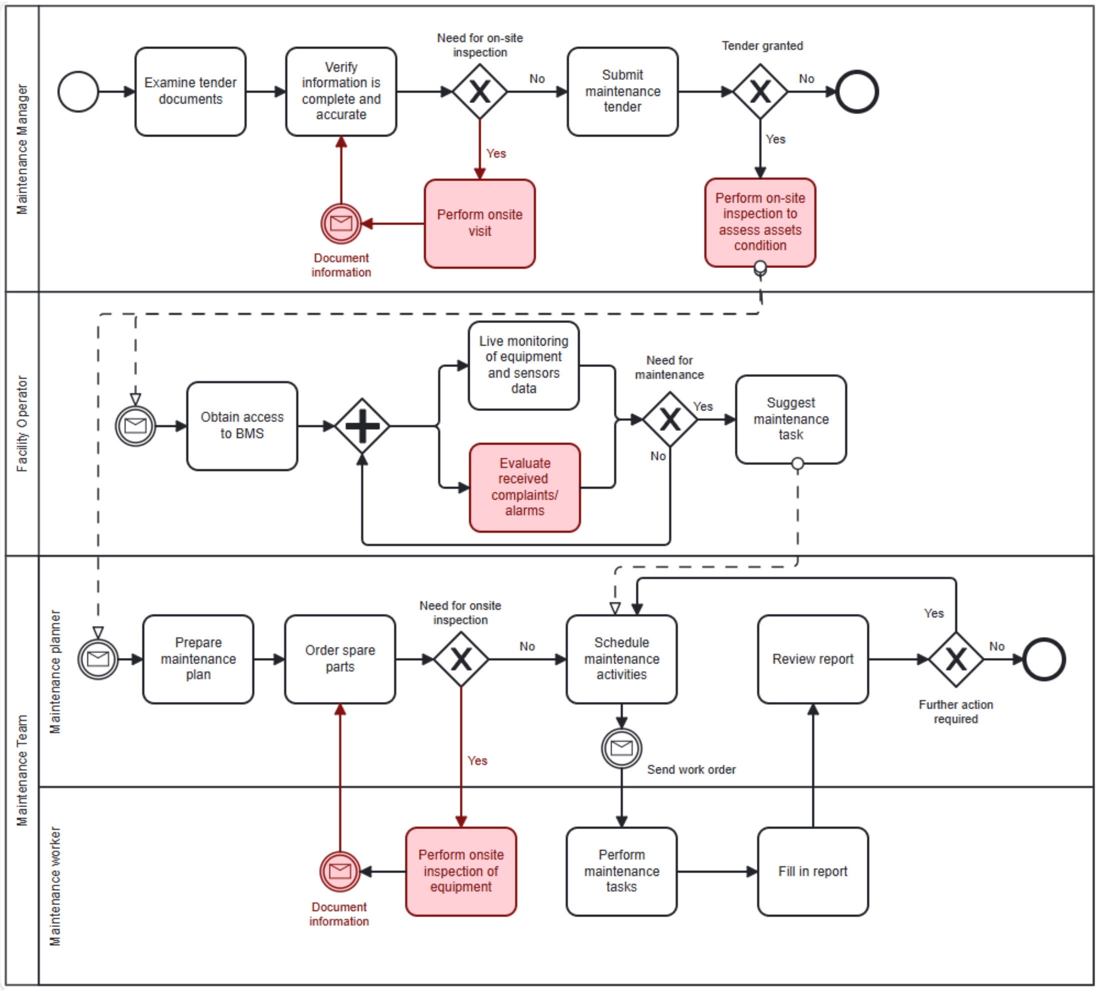


Figure 13: Process of maintenance contracts

3.5.2 Use Case Diagram

The use case diagram in *Figure 14* illustrates the interactions between various actors—including the maintenance manager, facility operator, maintenance worker, maintenance planner, facility users, and facility owners—and the Maintenance BIM Platform. Each actor has specific activities that they want to perform, depicted by the use cases and eventually incorporated as a functional requirement.

On the right side of the diagram, the associated data sources involved in the interactions are represented, though in a vague and generalized form. Specific information requirements were assessed in the interviews and the results are discussed in Section 4.2. However, for the use case it is crucial to show data sources, as this underlines the core objective of the new system: rather than generating entirely new data, the platform is designed to effectively structure and leverage existing data to improve accessibility and availability for all stakeholders.

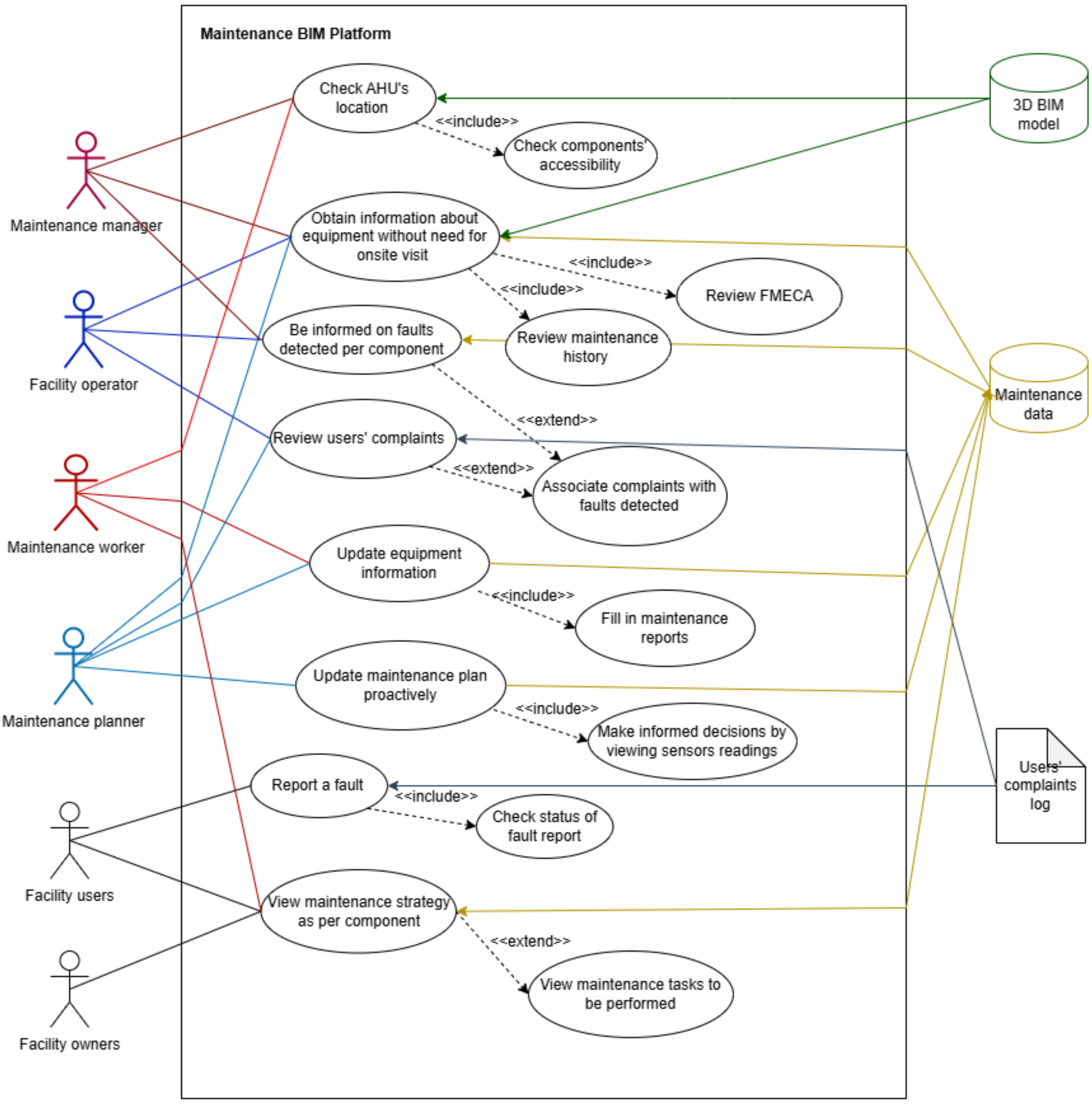


Figure 14: Use Case Diagram

3.5.3 System Architecture

The system architecture of the Maintenance-BIM platform, *Figure 15*, is proposed to integrate multiple data sources, microservices, and maintenance management systems. The aim is to establish a robust, flexible, and scalable structure. The existing data sources are streamlined in the architecture making information more accessible and usable for informed decision-making. The platform's user interface must be intuitive and cater to the needs of different user profiles and can be conveniently accessed from different devices including mobile phones, tablets.

The API gateway serves as the secure access bridge, enabling communication between components, handling data queries, processing information, and retrieving necessary insights. It facilitates reliable and effective interactions between the users and the data repositories. Moreover, while the diagram illustrates newly introduced microservices—such as the RCM Process and IFCtoRDF conversion services—this architecture is built with flexibility in mind, allowing for the inclusion of other existing services as well as new ones that might be integrated over time.

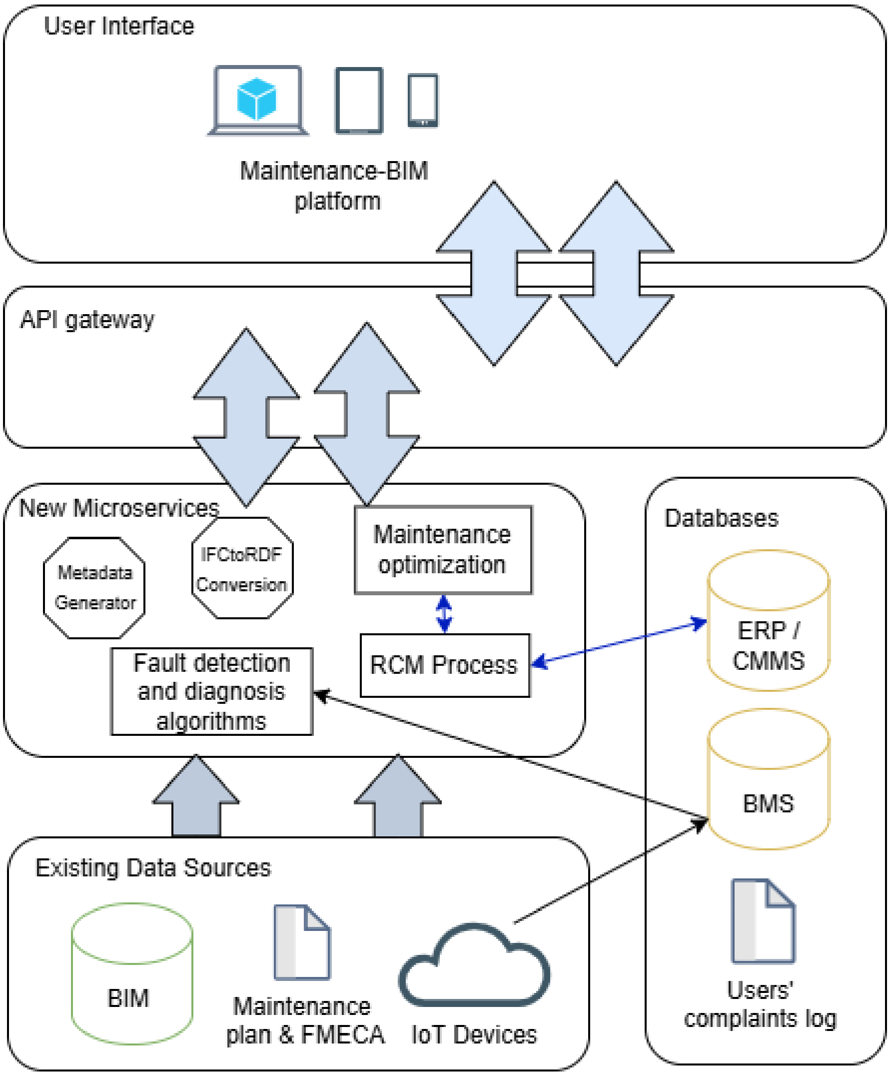


Figure 15: System Architecture

3.5.4 Maintenance-BIM Platform Data Modelling

The integration of data into the platform is achieved by mapping various data sources and documents into a unified environment, allowing for users' interaction and visualization. The platform serves as an interface that uses a BIM model as visualization basis in an XKT format; able to extract information from the graphical representation of building; visualize sensor readings; and maps data from maintenance management systems, while preserving the integrity of existing databases and software. This ensures that the platform functions as a central hub, capable of enhancing and leveraging data from multiple sources.

As shown in *Figure 16*, the initial phase of the platform design utilizes a BIM-SIM API that communicates with the back-end, querying the GraphDB while extracting time-series data from MongoDB. This process is kept intact to ensure flexibility and efficiency. RDF-based graph representations of the IFC model are created, and ontologies are employed to add semantic richness. RDF offers several advantages for semantic modelling. First, it facilitates easy and efficient data querying through the established SPARQL query language. Second, it allows metadata to be enhanced using formalized ontologies such as Brick, SSN and SOSA, enabling richer and more structured data.

In this conversion, the IFC model is translated into the ifcOWL ontology, which is then augmented with the Brick ontology. This allows connections to be established between sensors, their dynamic readings, and the spaces they monitor. The semantic modelling process allows it to be extensible. Beyond the Brick ontology, additional standardized ontologies can be incorporated to describe metadata required for specific maintenance purposes. This extensibility ensures that the platform can adapt to its needs and integrate diverse datasets into a unified semantic graph representation of the building and its processes.

Within the scope of this research, the Maintenance-BIM platform will be enhanced to map the maintenance plan and the FMECA to the corresponding building elements. The current prototype utilizes the outputs from the RCM process in CSV format. However, further research should explore incorporating these outputs into the platform's graphical representation to enable a more comprehensive and efficient querying methodology, improving data accessibility and linkage.

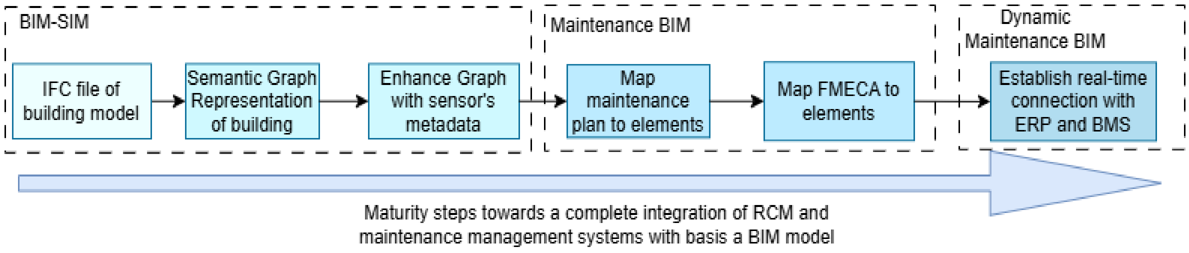


Figure 16: Data Modelling steps for platform design

4 Results

This chapter presents a full analysis of the research findings. The first section focuses on the implementation of the RCM framework, using the AHU case study as explained in the previous chapter. This implementation is systematically detailed through the AHU system breakdown, functional diagram, and the FMECA. Furthermore, the decision logic is applied to determine the optimal maintenance strategy for each of the components analyzed.

The second section addresses the generic information requirements of maintenance personnel that must be incorporated within the integration platform to support effective decision-making and efficient execution of maintenance tasks.

Finally, after having established the FMECA, the RCM-based maintenance decision logic, and the maintenance plan for the AHU, as well as identified the necessary information requirements and incorporated them in the development of the platform, the results of the designed prototype are presented in Section 4.3. This prototype demonstrates the practical application and feasibility of the proposed integration framework.

4.1 RCM Framework Implementation

In implementing the RCM framework, the systematic process outlined in the methodology is followed, providing a detailed analysis and addressing areas that could potentially cause ambiguity or present challenges in the implementation. However, it is important to acknowledge that the age exploration phase constitutes a significant challenge and is component-specific and can be largely extensive. More on this in the subsequent discussion section.

Although the RCM framework established can be used on mechanical equipment, the output of the implementation is case-specific. These ideally manifest in the development of a FMECA, applicable to AHUs with similar components.

Step 1: Set analysis boundary

The analysis will concentrate on the main components encompassed in the AHU casing located in the AHU room on the second floor. More specifically, the RCM framework will be applied to the supply air process, focusing on the components that initially treat outside air before it is distributed into the rooms.

Step 2: Define system and its functions

The two main functions of the AHU within the analysis boundaries are identified as:

1. To supply clean air to enhance quality of indoor air
2. To adjust the temperature of the supplied air to maintain thermal comfort

Figure 17 illustrates the two primary functions along with the subfunctions that contribute to them

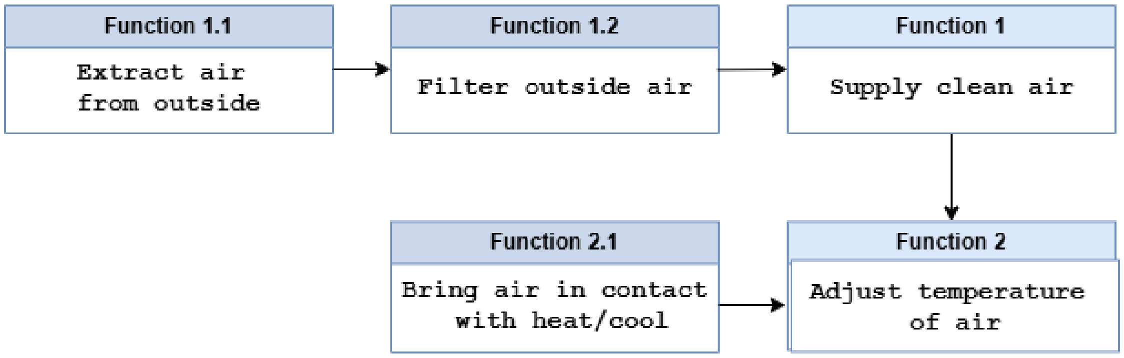


Figure 17: Functions of supply air AHU

Step 3: Divide system into components and their functions

The entire AHU system consists of mechanical and electrical components; distribution elements such as pipes and ducts; sensors and control elements as well as the outer casing with the supporting frame. *Figure 18* presents a system breakdown structure of AHU within the boundary of the analysis. The focus of the research is on the mechanical components, which will be further analyzed for their functions.

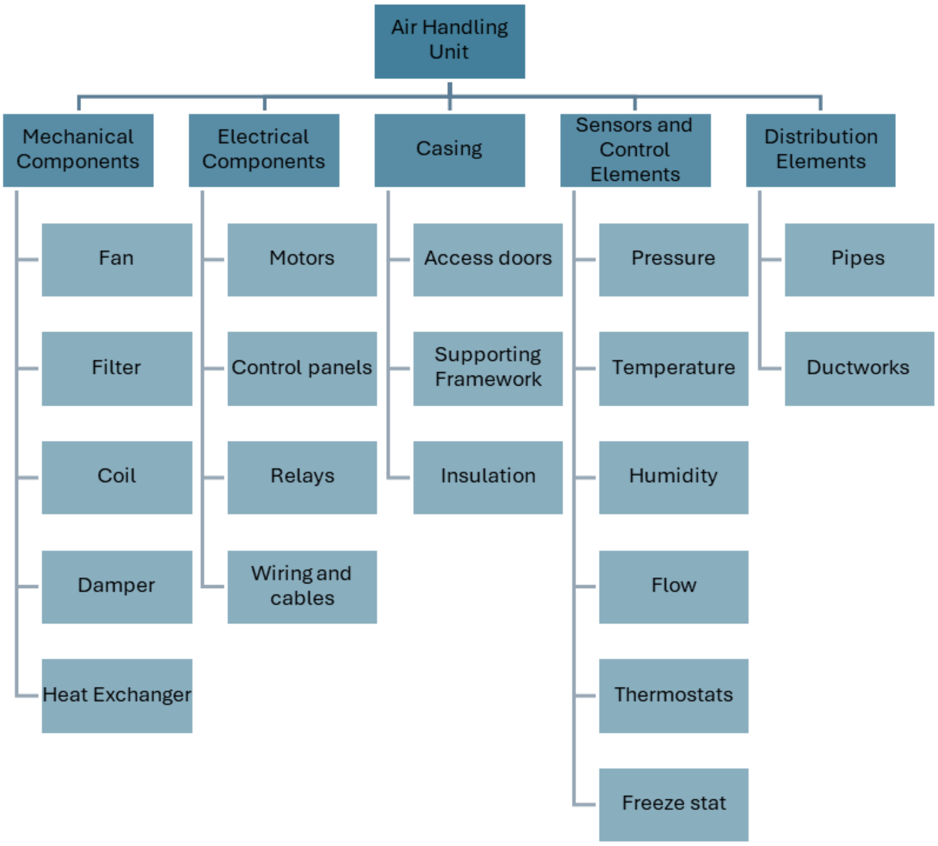


Figure 18: System breakdown structure

The five components in the supply air of the AHU are: supply air damper, supply air filter, heat recovery wheel, heating coil and fan, which are arranged as shown in the schematic diagram in *Figure 19.* The function of each component is listed in *Table 12*. Each component may also have an attached sensor or a control element, such as a motor or an actuator, which are linked to the BMS to monitor the performance and/or operation of the component. These are also defined in *Table 12*.

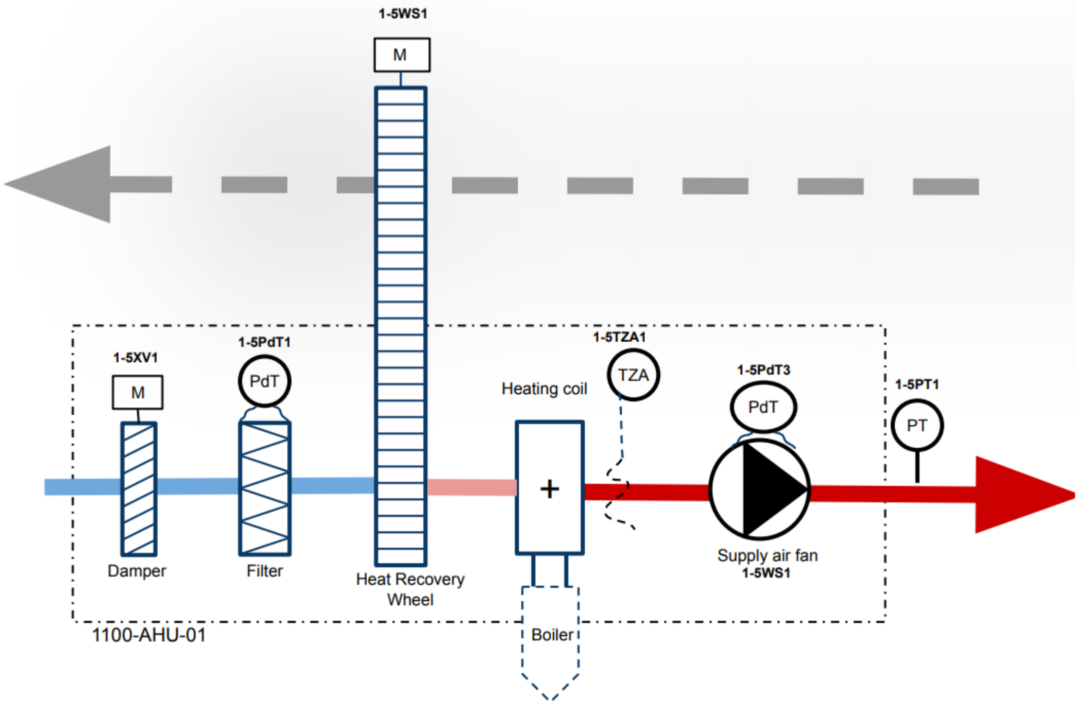


Figure 19: Schematic representation of supply air AHU components

Table 12: Mechanical components and their functions

Component	Function			
Damper	regulates the amount of supply air that enters	Actuator	1-5XV1	
Filter	filters the air from any particulate matter	Differential pressure transmitter	1-5PdT1	Measures the drop in pressure through filter
Heat Recovery Wheel	uses the heat from the extracted air to warm the supply air	Motor	1-5WS1	Operates the component
Heating Coil	provides further heating for the supply air to meet the indoor temperature demand			
Supply air fan	generates an air flow to overcome pressure losses in order to suction and draw air	Motor	1-5WS1	Operates component
		Differential pressure transmitter	1-5PdT3	Measures the drop in pressure through fan

Step 4: Specification Compliance

The components are checked against any maintenance requirements enforced by regulations. Additionally, it is advisable to review relevant standards and operation manuals for maintenance recommendations.

The air filters are bag filters from manufacturer CAMFIL of type Hi-Flo P7, the manufacturer's manual prescribes a change of when the pressure drop reaches the initial drop plus 100 Pa. The manual further suggests adhering to the VDI 6022 Hygiene standard, which recommends replacing filters annually.

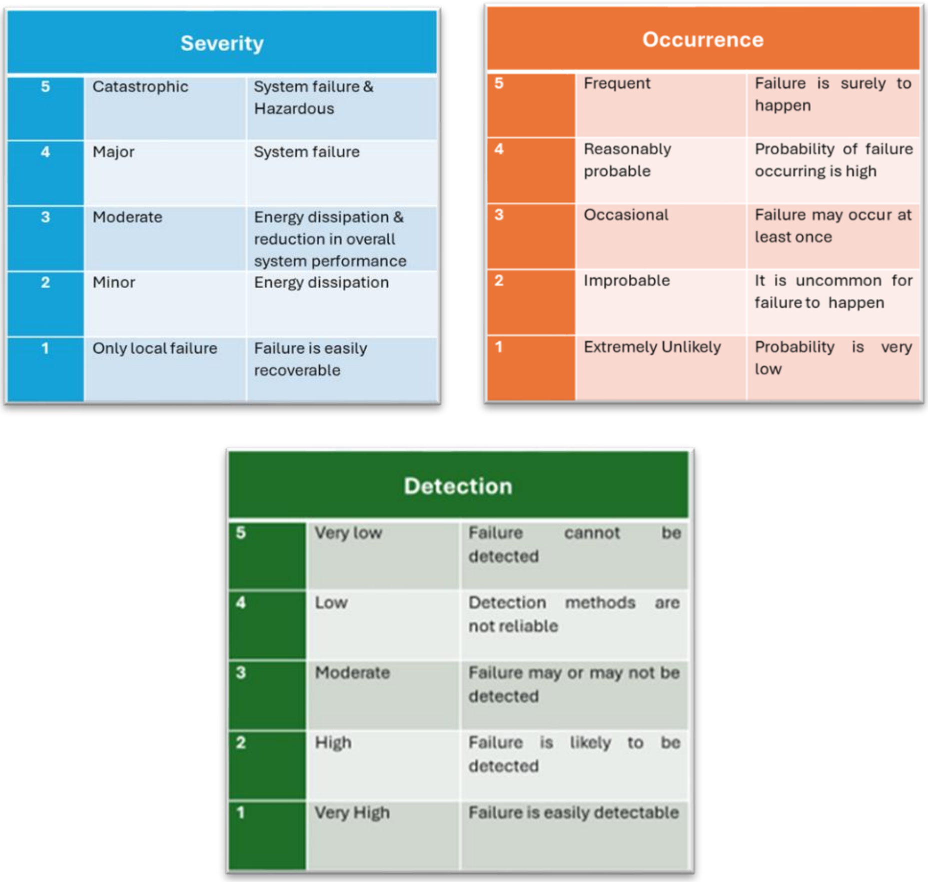
The supply air fan, a Ziehl-Abegg bluefin of type GR45I-ZID.GG.CR, has a recommended service life of 30,000-40,000 operating hours. Given an average of 8 working hours per day and 250 working days per year, this equates to approximately 15 to 20 years.

Step 5: Failure, Mode, Effect Analysis

The FMEA analysis was conducted based on the literature review. The reason that literature is consulted is the lack of failure records. Even though the ERP System has maintenance reports, no failure has been recorded for the past five years. A possible reason for this is that maintenance is performed in-house, allowing personnel to immediately address failures without perceiving the need to document them. The FMEA is presented in *Table 13*.

Step 6: Criticality assessment

To validate the FMEA and assign ratings to the identified failures, the technical leader and building's operator were consulted. In the interview each failure mode was evaluated based on the rating scale provided in *Figure 20*. The consultation process included detailed discussions on the severity, occurrence, and detectability of each failure, contributing to a comprehensive FMEA.



Severity		
5	Catastrophic	System failure & Hazardous
4	Major	System failure
3	Moderate	Energy dissipation & reduction in overall system performance
2	Minor	Energy dissipation
1	Only local failure	Failure is easily recoverable

Occurrence		
5	Frequent	Failure is surely to happen
4	Reasonably probable	Probability of failure occurring is high
3	Occasional	Failure may occur at least once
2	Improbable	It is uncommon for failure to happen
1	Extremely Unlikely	Probability is very low

Detection		
5	Very low	Failure cannot be detected
4	Low	Detection methods are not reliable
3	Moderate	Failure may or may not be detected
2	High	Failure is likely to be detected
1	Very High	Failure is easily detectable

Figure 20: Rating Scale for Severity, Occurrence, Detection

Table 13: Failure Mode, Effect Analysis for AHU

Failure, Mode, Effect Analysis (FMEA)						
Component Id	**Component**	**Failure Id**	**Failure Description**	**Failure Mode/Cause**	**Failure Effect on System**	**Type of failure**
Damper	1-5XV1	F1.1	damper stuck (closed)	actuator not operating or control not received	high static pressure leading to system failure if entirely closed, otherwise high energy consumption	Actuator or Control Failure
		F1.2	damper stuck (open)	actuator not operating or control not received	continuous flow of supply air, risk of faster filter's degradation or freezing coil in winter	Actuator or Control Failure
Filter	1-5FR1	F2.1	filter fouling	accumulating dirt/particles	Reduced air flow leading to higher energy consumption, inefficiency and gradual failure of system	Component Failure
		F2.2	filter breakage	damaged filter	Particles enter the system, higher risk of damaging components and system failure. Failure in supplying clean air	Component Failure
Heat Recovery Wheel	1-5WS1	F3.1	drive belt failure	belt broken	No heat recovery leading to higher energy consumption in heating coil	Component Failure
		F3.2	wheel not operating	motor failure	No heat recovery leading to higher energy consumption in heating coil	Actuator or Control Failure
Heating coil	1-5CL1	F4.1	coil fouling	accumulated fine particles/contaminants	Reduced contact surface leading to reduced efficiency	Component Failure
		F4.2	coil not heating	failure in the system (valve/pump) providing heat	No heating of air, failure of requirement for thermal comfort	Actuator or Control Failure or Component Failure
Fan	1-5WS1	F5.1	impeller wearing off	chemical corrosion	Gradual system failure as fan cannot supply air	Component Failure
		F5.2	fan not operating	motor breakage	System failure as fan cannot supply air	Component Failure

Step 7: Decision logic

The applicable maintenance strategies are as follows:

1. Run-to-failure Maintenance
2. Corrective Maintenance: Yearly inspection for degradation or hidden failure.
3. Condition-based Maintenance: Continuous performance monitoring.
4. Preventive Maintenance: Periodic or age dependent maintenance (typically based on manufacturer or specifications recommendation)

Each failure mode is examined individually, and an appropriate maintenance strategy is selected to mitigate its occurrence. This selection process is guided by the decision tree illustrated in *Figure 21*.

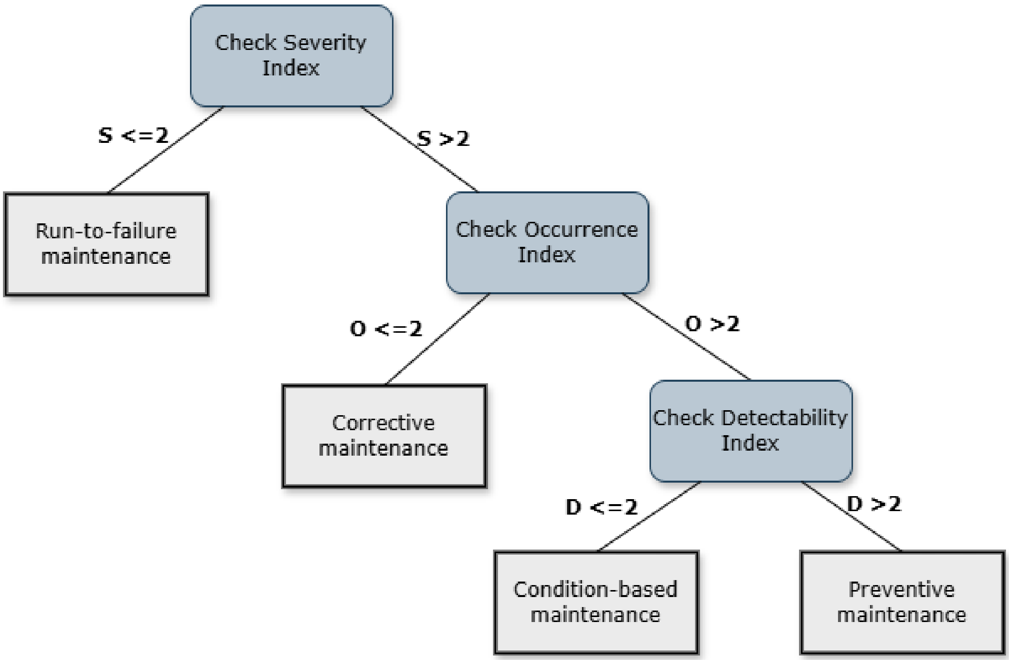


Figure 21: Decision tree for selecting maintenance strategy

Step 8: Form maintenance plan and assess cost

To develop a comprehensive maintenance plan, some additional considerations must be evaluated:

1. **Equipment cost**
   If the equipment is expensive, a run-to-failure strategy is generally not advisable, even if the probability of failure is low. Instead, it is recommended to implement an appropriate form of proactive maintenance that balances cost and reliability.

2. **Spare parts availability**
   While condition-based maintenance is often the most preferred maintenance strategy, its lack of a prescheduled maintenance plan can be a limitation. Therefore, it is essential to establish thresholds for purchasing and stocking spare parts to ensure timely availability - especially if a delay is expected in delivery time.

3. **Condition-Based Maintenance reliability**
   The effectiveness of condition-based maintenance depends on several factors, including the reliability of the IoT devices used for monitoring, the experience and expertise of the personnel involved, and the algorithms employed for data analysis.

Step 9: Age Exploration

No standard was found that defines formal steps or a methodology to perform age exploration. It can be simple or complex depending on the significance of the component and the availability of reliable data. NASA's framework for RCM of facilities defines age exploration as an approach to varying key elements that can help further optimize maintenance plans, such as:

Technical Content: Ensuring that existing maintenance tasks effectively address identified failures while maintaining the required reliability.
Performance Interval: Continuously adjusting maintenance intervals until the rate at which resistance to failure declines is determined.
Task Grouping: Grouping tasks with the same maintenance period to minimize downtime and increase efficiency. (NASA, 2008)

The replacement time of the filter is further investigated for optimization of the interval. First, the age of the filter upon replacement is calculated from the past five years of work orders, *Table 14.*

Table 14: Maintenance reports of the past five years

Year	Date	Work order No	Task Description	Age of filter on replacement
2018	09/11/2018	801306	Filter Replacement	Unknown
2020	08/09/2020	885967	Filter Replacement	22 months
2022	06/01/2022	1003168	Filter Replacement	16 months
2023	22/03/3023	1081419	Filter Replacement	14 months
2024	02/04/2024	1124101	Filter Replacement	12 months

By reviewing the replacement dates of filter, it is observed that the replacement period was not strictly adhered to. It should be noted that for the year 2020, the age of the filter is not reliable as it was calculated from the work order creation date, which may not equal the actual maintenance date. Considering that the maintenance worker forgot to input the maintenance date, I am unable to determine when it precisely happened. Appendix A shows how the work order looks, and the dates referred to. In *Figure 22*, the readings from 1-5PdT1, the differential pressure transmitter around the filter, are presented for maintenance on 02/04/2024. The graph shows that a non-working filter has a differential pressure of around 10 Pa, the degraded filter has readings of over 100 Pa, and when replaced, the clean filter has a pressure drop of around 70 Pa.

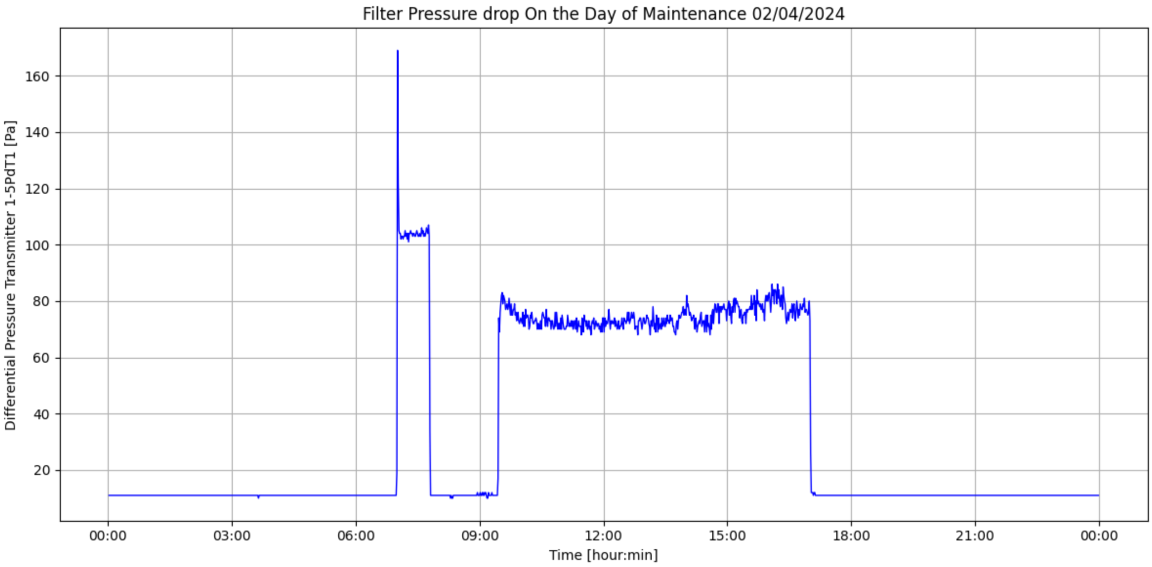


Figure 22: Line chart of maintenance day

The approach followed for age exploration of the supply filter is as follows: First, a threshold limit is set based on the manufacturer's recommendation of 110 Pa, extracted from the O&M manual. Second, the mean values of the pressure drop for last five days before the scheduled maintenance were examined, *Table 15*. The mean value had already exceeded the threshold, which clearly signified that the filters needed replacement before maintenance day. Next, the trend for the entire year is plotted, *Figure 23*. It is to be noted that for both analysis the values are filtered for when the filter was in operation (8 am to 4 pm).

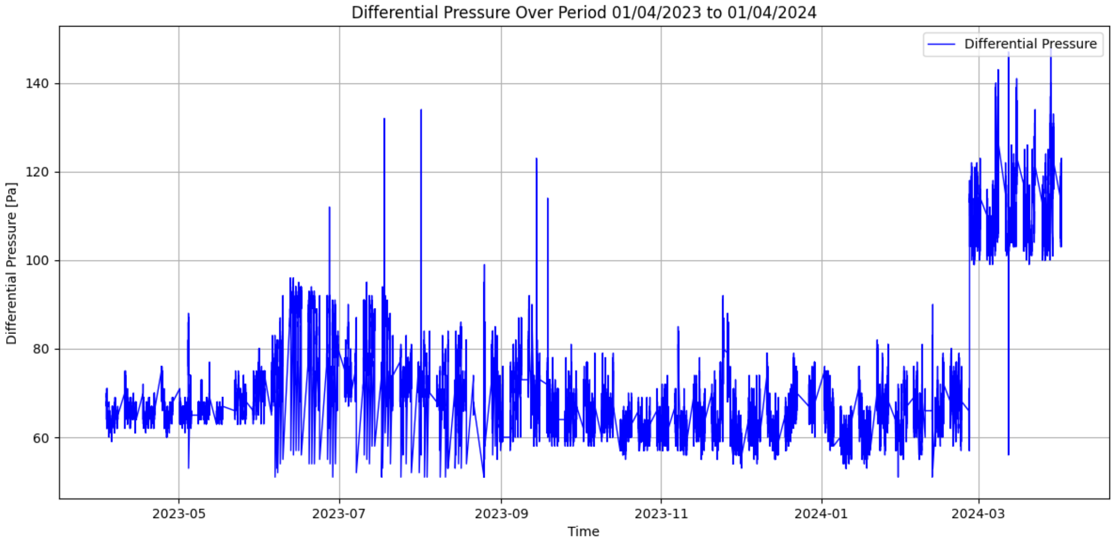
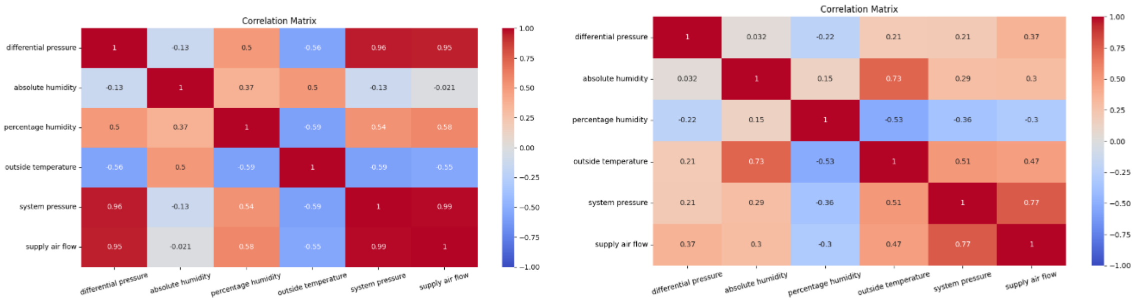


Figure 23: Line chart of the annual differential pressure readings

The chart shows a sudden increase in pressure drop around March. This observation aligns with the study conducted by Alimohammadi et al. (2022), which investigated the remaining useful life of HVAC filters. In their research, the health indicator was modeled using an exponential equation. The study employed a hybrid method that first retrieved parameters using machine learning from a data-driven model and then used these parameters in a physics-based equation to calculate the remaining useful life and plot it. The study also controlled variables such as external temperature, humidity level, fresh air damper position, and HVAC power supply voltage, concluding that the main health indicator of the filters is the differential pressure across the filter.

To validate our observations and agree with the study, data were retrieved from air quality sensors installed in the AHU. This additional data included temperature and humidity of the outside air, as well as system flow and pressure. When a correlation matrix, *Figure 24 left* of the entire dataset was plotted, a high correlation between differential pressure, flow rate, and system pressure is observed. This is expected, as increased pressure flow setpoints during AHU operation naturally lead to higher differential pressure across the filter. However, since our focus was on analyzing the aging of the filter, the data is filtered to include only values during operation times, as has been done previously.



	differential pressure	absolute humidity	percentage humidity	outside temperature	system pressure	supply air flow
differential pressure	1	-0.13	0.5	-0.56	0.96	0.95
absolute humidity	-0.13	1	0.37	0.5	-0.13	-0.021
percentage humidity	0.5	0.37	1	-0.59	0.54	0.58
outside temperature	-0.56	0.5	-0.59	1	-0.59	-0.55
system pressure	0.96	-0.13	0.54	-0.59	1	0.99
supply air flow	0.95	-0.021	0.58	-0.55	0.99	1

	differential pressure	absolute humidity	percentage humidity	outside temperature	system pressure	supply air flow
differential pressure	1	0.032	-0.22	0.21	0.21	0.37
absolute humidity	0.032	1	0.15	0.73	0.29	0.3
percentage humidity	-0.22	0.15	1	-0.53	-0.36	-0.3
outside temperature	0.21	0.73	-0.53	1	0.51	0.47
system pressure	0.21	0.29	-0.36	0.51	1	0.77
supply air flow	0.37	0.3	-0.3	0.47	0.77	1

Figure 24: Correlation matrix

The conclusion drawn from the resulting correlation matrix was that the degradation of the filter is not significantly affected by the investigated features. One additional feature that could have been examined, but was not due to lack of available data, was the presence of particulate matter in outside air. However, as particulate matter was not explicitly defined in the study and the filter is in the same location and the goal is not comparing different installations, the hypothesis is that the only significant health indicator is the age of the filter.

A simple approach to age exploration recommends incrementally increasing or decreasing the maintenance interval until a point is reached where reliability is not compromised. Since the threshold set (110 Pa) mirrors the reliability requirements of the filter, the period during which the pressure drop had already exceeded this threshold has to be established and the first five days are shown in *Table 15*. The complete Python code used in this age exploration step is included in Appendix B.

Table 15: Five days before maintenance day and first five days exceeding 110 Pa

Date	Mean Value	Date	Mean Value
01/04/2024	111.583	29/02/2024	112.927
31/03/2024	10.992	07/03/2024	117.319
30/03/2024	11.085	13/03/2024	120.617
29/03/2024	116.604	14/03/2024	110.058
28/03/2024	117.046	15/03/2024	120.392

Hence the results indicate that the filter should have been replaced one month earlier. Therefore, it is recommended to schedule the maintenance before the day the threshold is crossed, which suggests an optimal replacement period of 10-11 months. However, it is important to repeat the age exploration process annually to ensure that the maintenance interval remains effective.

4.2 Information Requirements

In this section, the information requirements for integrating RCM with BIM are investigated. The RCM process, which combines various maintenance strategies and is driven by optimization methods, relies not only on static information but also on dynamic data generated during O&M phase. This section addresses a key question: what information is necessary to decide on an optimal maintenance strategy, as well as to schedule and execute it effectively? This question was explored with stakeholders to ensure the validity of results.

As showed by the results, previous research has predominantly focused on reactive and preventive maintenance approaches, which primarily rely on static information. In contrast, this research highlights the significance of dynamic information in providing insights to support the RCM process. It is also important to clarify that the term "information requirements" in this context does not refer to information embedded within the IFC model itself, but rather to the external platform that serves as the integration interface. Consequently, the identified information requirements may not exist within, nor necessarily belong to, the IFC model. The system architecture is designed to maintain data within their respective sources and presenting an API that connects to the existing data sources. Therefore, this section distinguishes between the information requirements that are expected to be included within a BIM model and those that must be integrated via the API.

4.2.1 Establishing Information Requirements

To derive the information requirements for this research, the study conducted by Dias and Ergan (2020) served as the primary reference. This study was chosen by two key reasons: first, Dias and Ergan specifically investigate the information requirements for corrective and preventive maintenance of HVAC systems, which aligns closely with the use case of the current research. Thus, additionally incorporating dynamic sensor data and FMECA enables the implementation of predictive and reliability-centered maintenance fulfilling the overall objective of the research. The second reason is that their study involved 40 experts, divided into six focus groups, the average experience of each group is over 20 years, ensuring substantial credibility and depth to the findings.

The study identified ten information items as necessary by all six focus groups for both corrective maintenance and preventive maintenance. Nine additional items were included despite being deemed unnecessary by one of the focus groups. This specific group consisted of only two maintenance supervisors. Due to the minimal size of this group, the decision was made to retain these nine items, as their exclusion could potentially lead to gaps in the system’s comprehensiveness.

Another relevant study on defining specific information requirements was conducted by Benn & Stoy (2023). However, their focus was on elevator systems, which means that several properties identified by Dias and Ergan (2020), such as storey number, room number, assembly place, and production year, are not applicable to the elevator use case. Notably, Benn and Stoy (2023) include a maintenance information category about maintenance performed that was not addressed by Dias and Ergan (2020). Moreover, both studies consider corrective and preventive maintenance, the focus of Benn and Stoy (2023) being periodic inspection of elevators, there is no mention of predictive maintenance in either study. Predictive maintenance is directly linked to monitoring equipment conditions, detecting faults, and assessing operational data. Consequently, to support predictive maintenance and principally RCM, three properties—failure modes and causes, fault detection, and live sensor data—are included as information requirements for the platform. This reasoning can be backed up by Yang and Ergan (2017) who also provide valuable insights into information requirements by investigating "effective and efficient troubleshooting of HVAC-related problems." Their findings include the importance of user complaint logs, component historical information, and dynamic information, among others. This research utilized both focus group discussions and the exploration of eight BMS, as well as approximately 420 work orders from a CMMS, to provide a comprehensive overview of the necessary information requirements. As a final literature reinforcement, the study by Matarneh et al. (2019) employed a survey to prioritize information requirements to support facility management systems. The survey results identified warranty information, asset location, manufacturer/vendor information, identification numbers, asset descriptions, and preventive maintenance schedules as among the top six priority items.

The 27 requirements identified as relevant from the literature were subsequently evaluated through the interviews with stakeholders. Both interviewees agreed that component identity information must be included, although one interviewee found the commissioning date to be irrelevant. However, in the category about manufacturer and warranty information, maintenance managers expressed disinterest in detail such as acquisition date, assembly location, warranty identifier, and the point of contact.

The interviewees' professional responsibilities were reflected in their preferences regarding the third category of requirements. The first interviewee, who is responsible for long-term maintenance planning of the HVAC system (including corrective and preventive maintenance), showed no interest in service life duration, mean time between failures, or live sensor data. In contrast, the second interviewee, who is the head of the BMS service unit, considered these items relevant but was not interested in the frequency of scheduled maintenance activities.

The information requirements identified and presented in *Figure 25* are categorized into three distinct types: **static**, **semi-static**, and **dynamic**. While the first and last categories are widely recognized, the second category—semi-static information—is being proposed based on the discussions and interviews conducted during this research.

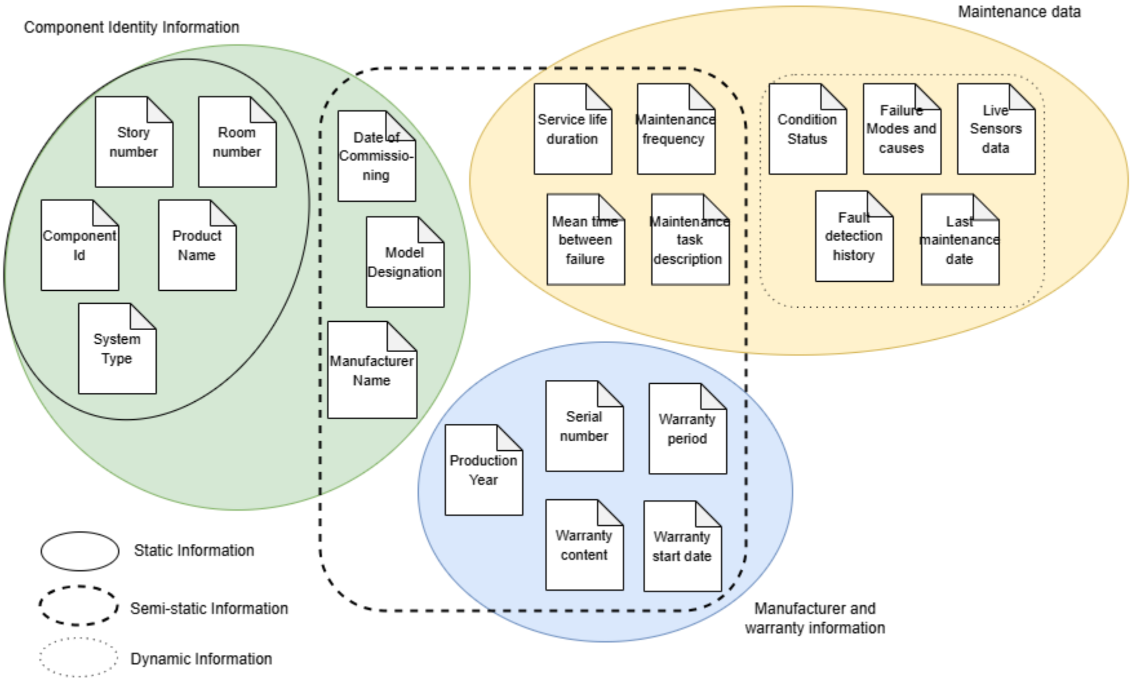


Figure 25: Maintenance information requirements

Static Information: This category encompasses properties that are commonly unchanging, such as component identity, geographical location within the building, system type, and known identifier. These properties are typically assigned during the design or construction phase and are easily retrievable from BIM systems, as confirmed in the literature.

Dynamic Information: Dynamic information includes data generated during the operational phase of a component. Examples of dynamic data are condition inspections, fault detection history, FMECA, work orders, and sensor readings. These types of data are typically not part of a BIM model and instead reside in other relevant software databases, such as BMS or CMMS or separate documents.

Semi-Static Information: Semi-static information is a newly proposed category that captures component-related data that requires periodic updates or revisions as the building ages. This category was emphasized during interviews, particularly concerning buildings that are no longer new, where BIM-derived asset lists often become outdated due to modifications or replacements of building components. An example of this challenge was highlighted during the investigation of the AHU. Although the installation documents referenced a V-belt supply fan, a site visit revealed that the fan had been replaced with a centrifugal one, necessitating the provision of updated documentation. Semi-static information, therefore, refers to information that may change with the replacement or update of components.

This proposed categorization of semi-static information reflects the dynamic nature of building systems over time, which is often not adequately captured by static or dynamic classifications alone. If the decision is to contain semi-static information within the IFC model, then a challenge emerges in ensuring its reliability throughout the whole lifecycle of the building.

4.2.2 Validating Information Requirements

The results shown in *Figure 25* were extracted from literature and confirmed by the stakeholders. The interviews with stakeholders emphasized that information needs must be directly linked to the specific activities to be performed. Therefore, a more insightful approach to investigating information requirements involves listing all maintenance activities and defining the associated information needs. Therefore, this reinforces the importance of defining LOIN rather than LOD for maintenance purposes. Additionally, each asset component has specific information that must be further considered.
Despite this, this subsequent step involves checking the model against the established requirements. Initially, it must be determined whether the required information is to be embedded within the model, linked through metadata, or stored and connected via an API.

Validating the model against information requirements can be approached in several ways. The appropriate validation method can be selected while defining an integration process. The most basic approach is a manual survey of individual components using online IFC viewers; however, this method is time-consuming and impractical for large buildings. Alternatively, commercial software tools such as BIMCollab and Solibri provide capabilities for validating BIM models, offering more efficient means compared to manual inspections.

A possible method for information validation is using IDS – which can also be implemented into commercial software. As discussed in the background research, IDS is a machine-readable document that specifies the LOIN for objects. In this implementation the *IfcTester*[2] package developed within *IfcOpenShell* is used to define an IDS that describes the five static properties of the AHU. These properties as defined earlier include component ID, product name, system name, storey number, and room number.

It is important to reiterate that IDSs are created by the client, and in this context, it is the platform developer who is responsible for drafting the IDS and sending it to the BIM modeller. The modeller ensures that the model includes the attributes and properties specified in the IDS and subsequently sends the IFC file for validation. Since IDS uses IFC specifications, it defines the *IfcElement*, along with

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[2] https://github.com/IfcOpenShell/IfcOpenShell

its attributes and properties, and may impose restrictions on their specific values and their occurrences.

The first attribute to be defined is the Component ID. Although it is standard for each object in a BIM model to have a *GlobalId*, which uniquely identifies it, this alone is often insufficient for practical use by maintenance personnel. Instead, the *GlobalId* should be supplemented with an identifier that is easily recognizable by maintenance teams, such as an identifier from P&ID or one established during the construction phase as an Asset Identifier. *Listing 1* is an extract from the IDS created to validate the static information. The whole IDS can be found in Appendix D.

On the other hand, spatial information such as Storey Number and Room Number is inherently linked to the component through the *IfcRelContainedInSpatialStructure* relationship, which defines the spatial containment of elements within the building structure. However, the developer of the IDS may choose, for enhanced clarity and usability, to explicitly ask for them to be defined within a property set in the IFC model.

```python
import ifcopenshell
from ifctester import ids, reporter

# create new IDS
maintenance_ids = ids.Ids(title="Maintenance-BIM integration IDS")

# add specification to it
my_specf = ids.Specification(name="IFC file validation against static maintenance information")
my_specf.applicability.append(ids.Entity(name="IfcDistributionElement"))
global_Id_attribute = ids.Attribute(
    name="GlobalId",
    instructions="Each IfcDistributionElement must have a unique GlobalId.",
    minOccurs=1,
    maxOccurs=1 )
my_specf.requirements.append(global_Id_attribute)

AssetID_property = ids.Property(
    name="AssetIdentifier",
    propertySet="Pset_ConstructionOccurence",
    instructions="An asset identifier must be stated.",
    measure="IfcLabel",
    minOccurs=1,
    maxOccurs=1 )
my_specf.requirements.append(AssetID_property)
```

Listing 1: Extract of ids created to check static information

Another method to verify spatial assignments is a supplementary script to parse the IFC file and extract relevant spatial containment information using *IfcRelContainedInSpatialStructure*. This can be achieved with the *GetInverse()* function from *IfcOpenShell*, which facilitates the retrieval of inverse relationships within the IFC schema. To effectively utilize this approach, it is necessary to understand the internal structure of the IFC file. *Listing 2* presents an excerpt of three lines from the IFC file used in the development of the platform. The first line defines the *IfcSpace* – room - that contains the AHU. The second line specifies the AHU as an *IfcDistributionElement*, with its attributes, while the third line is the *IfcRelContainedInSpatialStructure* relationship that establishes the connection between the room and the AHU. The relationship's last two attributes describe *RelatedElements* and *RelatingStructure*, essentially the set of elements which are contained within the space and the space itself.

```
#139=IFCSPACE('1WB99UeHj3wxSwo32P_7co',#20,'1',$,$,#130,#138,'Space',.ELEMENT.,.INTERNAL.,$);
#4525=IFCDISTRIBUTIONELEMENT('0PnOOaq8T3yR4bjxu8hA2a',#20,'57_MEE_HHWBC_2000D_144:AHU2141:396727
',$,'57_MEE_HHWBC_2000D_144:AHU2141',#4524,#4518,'396727');
#8218=IFCRELCONTAINEDINSPATIALSTRUCTURE('0BXi5zdd93wwqYfC_GMpRr',#20,$,$,(#4525,#6286,#6963,#708
7,#7176,#7278,#7382,#7482,#7696,#7923,#7975),#139);
```
Listing 2: Specific line snippets from the IFC model

For semi-static information, *Table 16* provides recommendations for specific property names and their corresponding property sets, should the decision be made to incorporate them within the IFC model rather than adding them as metadata to the components.

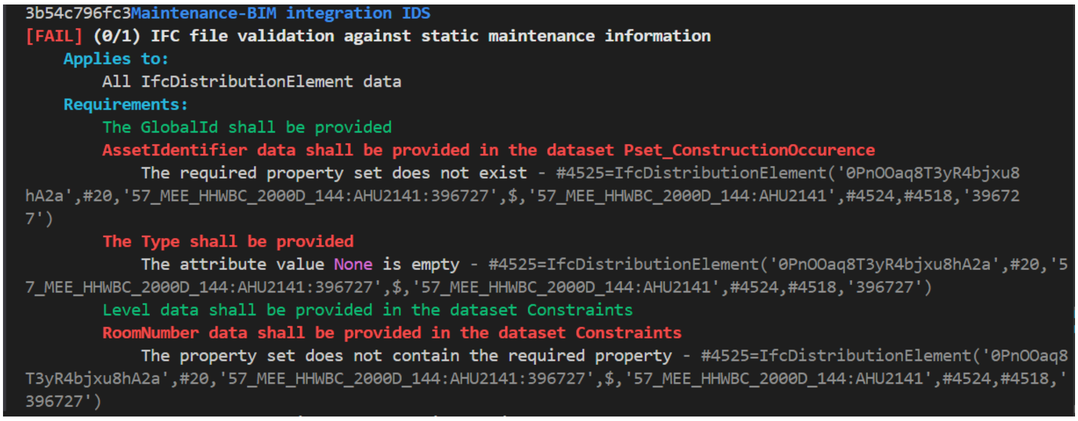
On the other hand, dynamic information will not be embedded directly in the IFC model but instead will be integrated into the platform. This facilitates real-time updates and a more flexible and efficient way for the integration to take place.

Table 16: Proposed properties and property sets for semi-static information

	Information Requirement	*IFC Property Name*	*Property Set*	*Data Type*
1	Date of Commissioning	PutIntoOperationDate	Pset_InstallationOccurence	IfcDate
2	Model Designation	ModelLabel	Pset_ManufacturerTypeInformation	IfcLabel
3	Manufacturer Name	Manufacturer	Pset_ManufacturerTypeInformation	IfcLabel
4	Production Year	ProductionYear	Pset_ManufacturerTypeInformation	IfcLabel
5	Serial Number	SerialNumber	Pset_ManufacturerOccurence	IfcIdentifier
6	Warranty Content	WarrantyContent	Pset_Warranty	IfcText
7	Warranty Start Date	WarrantyStartDate	Pset_Warranty	IfcDate
8	Warranty Period	WarrantyPeriod	Pset_Warranty	IfcDuration
9	Service Life Duration	ServiceLifeDuration	Pset_ServiceLife	IfcDuration
10	Mean time between failure	MeanTimeBetweenFailure	Pset_ServiceLife	IfcDuration
11	Maintenance frequency	DurationMaintenaceLevel	Pset_MaintenanceTriggerDuration	IfcDuration
12	Maintenance task description	MonitoringType	Pset_MaintenanceStrategy	PEnum_MonitoringType

The validation was conducted on the model presented in *Figure 28* in Section 4.3.1. The results are illustrated in *Figure 26*.

This validation primarily serves as a demonstration of the process for creating IDSs to validate the IFC file. The objective was not to provide an exhaustive IDS or to restructure the data within the IFC model, but rather to guide and emphasize the importance of establishing a structured approach for ensuring the inclusion of accurate information in the BIM model from initial stages of the project design phase. By doing so, the overall aim is to emphasize the significance of properly defining the information structure required for consistency and ease of data accessibility.



```
3b54c796fc3Maintenance-BIM integration IDS
[FAIL] (0/1) IFC file validation against static maintenance information
    Applies to:
        All IfcDistributionElement data
    Requirements:
        The GlobalId shall be provided
        AssetIdentifier data shall be provided in the dataset Pset_ConstructionOccurence
            The required property set does not exist - #4525=IfcDistributionElement('0PnOOaq8T3yR4bjxu8
hA2a',#20,'57_MEE_HHWBC_2000D_144:AHU2141:396727',$,'57_MEE_HHWBC_2000D_144:AHU2141',#4524,#4518,'39672
7')
        The Type shall be provided
            The attribute value None is empty - #4525=IfcDistributionElement('0PnOOaq8T3yR4bjxu8hA2a',#20,'5
7_MEE_HHWBC_2000D_144:AHU2141:396727',$,'57_MEE_HHWBC_2000D_144:AHU2141',#4524,#4518,'396727')
        Level data shall be provided in the dataset Constraints
        RoomNumber data shall be provided in the dataset Constraints
            The property set does not contain the required property - #4525=IfcDistributionElement('0PnOOaq8
T3yR4bjxu8hA2a',#20,'57_MEE_HHWBC_2000D_144:AHU2141:396727',$,'57_MEE_HHWBC_2000D_144:AHU2141',#4524,#4518,'
396727')
```

Figure 26: Results of validating IFC file against IDS

4.3 Maintenance-BIM Platform Development

Following the establishment of the concept for integrating BIM with maintenance processes, along with the development of the system architecture as well as functional and information requirements, it becomes essential to validate the feasibility of the proposed concept through a case study. The primary focus is on developing functionalities that align with the principles of the RCM process. This section begins by discussing the outcomes of the model preparation phase, followed by an evaluation of both existing and newly developed functionalities, specifically in terms of their value for maintenance users. The final part of this section presents proposed further development and integration functionalities.

4.3.1 Model preparation

The first step in developing the Maintenance-BIM platform and contributing to a proof-of-concept for concept is the availability of a suitably developed BIM model. *Figure 27* illustrates the architectural model alongside a portion of the mechanical model, which includes the HVAC system and piping.

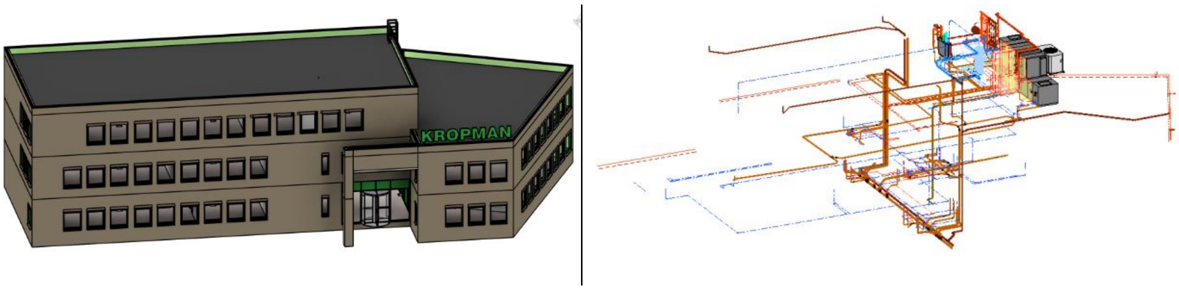


Figure 27: BIM models in Revit software

As previously discussed, objects in BIM are typically assigned to specific spaces, and the BIM-SIM API relies on locating sensors within these spaces (Chamari et al., 2022). Without defined spaces, it becomes impossible to link sensors to their respective locations. Consequently, when examining the Revit model which lacks spaces and given the primary focus of this is the AHU a more practical approach was adopted. The AHU was extracted and placed within one empty room space. This approach offers a notable advantage in terms of file management: by isolating the AHU, the size of the IFC file remains manageable, for the iteration process until a complete version of the prototype is developed. For viewing the 3D model, the platform’s API utilizes XKT files—an easy conversion from IFC files. *Table 17* presents the sizes of the merged model from Figure 27 and the simplified AHU in one room model of Figure 28 that has been used in platform design.

Table 17: Comparison of RVT and XKT file size

	IFC	XKT
ACTUAL MODEL	64.3 MB	3.6 MB
CASE STUDY MODEL	419 KB	29 KB

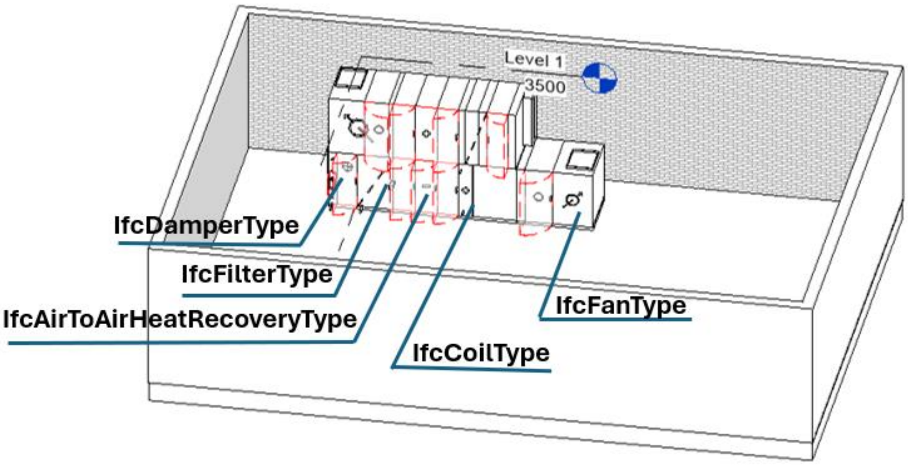
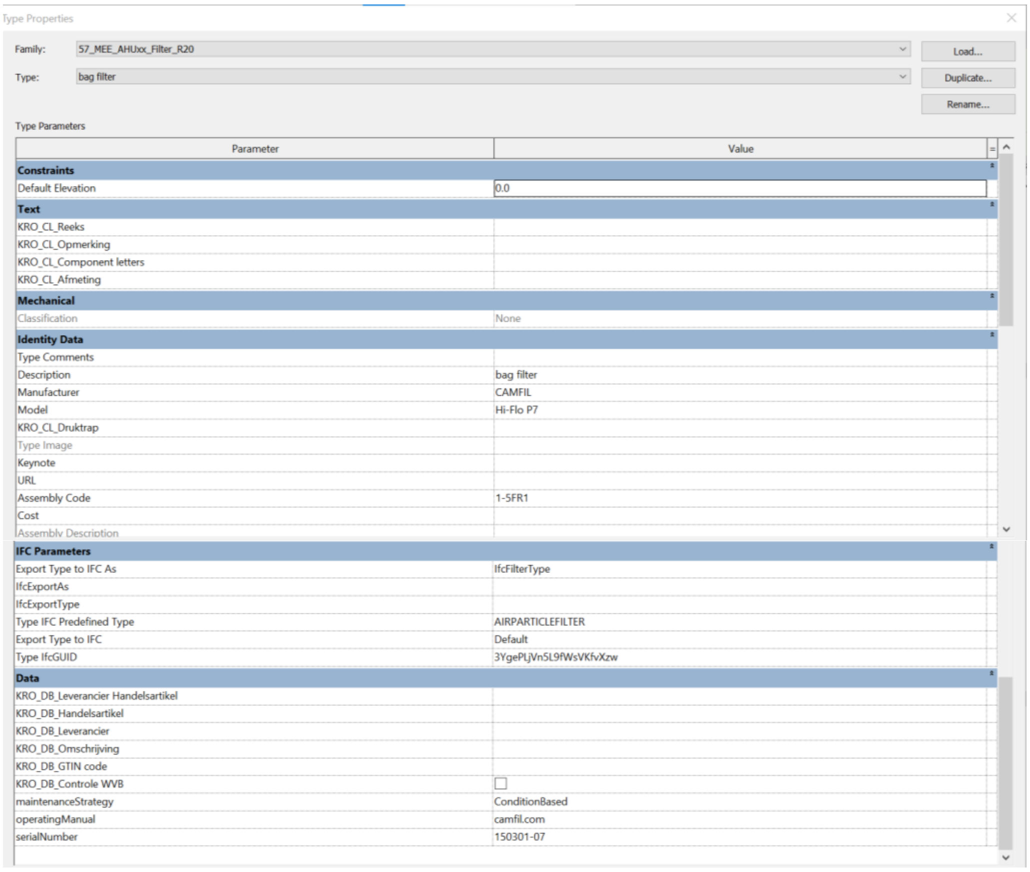


Figure 28: Representation of model used as case study

The AHU is modelled as a set of Revit families that represent its various components; however, none of the objects currently had any properties assigned to it. Consequently, the next step involves exporting these families, defining the necessary properties, and ensuring proper IFC export. If the objects are not explicitly mapped to their corresponding IFC entities, the export process will default generate elements as *IfcBuildingElementProxy*. This type serves as a generic classification for building elements that lacks a defined semantic meaning.

The information collected earlier for the RCM process, such as manufacturer name, model, serial number, and P&ID code have been incorporated into the model, *Figure 29*. Moreover, when exporting the model to IFC, it is critical to verify the export settings to ensure that all relevant property sets are included.



Type Properties

Family: 57_MEE_AHUxx_Filter_R20

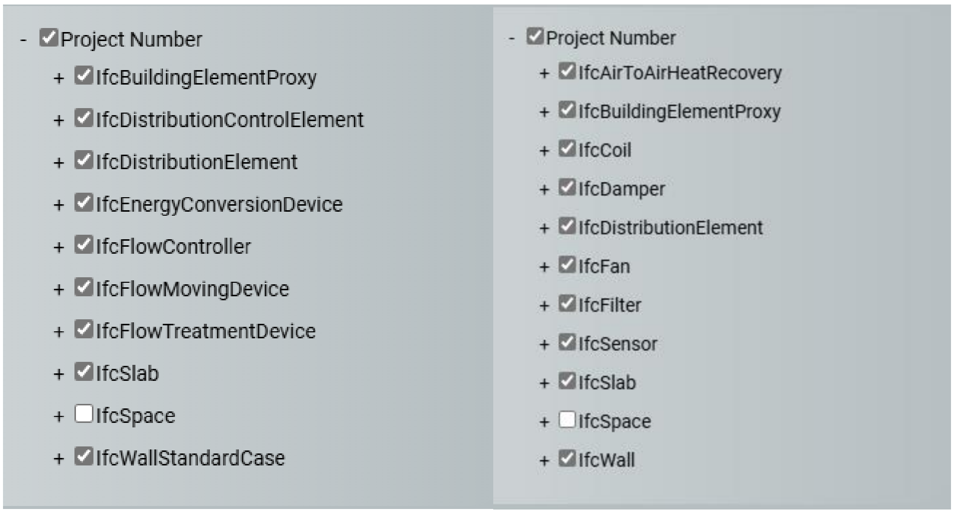
Type: bag filter

Type Parameters

Parameter	Value
Constraints	
Default Elevation	0.0
Text	
KRO_CL_Reeks	
KRO_CL_Opmerking	
KRO_CL_Component letters	
KRO_CL_Afmeting	
Mechanical	
Classification	None
Identity Data	
Type Comments	
Description	bag filter
Manufacturer	CAMFIL
Model	Hi-Flo P7
KRO_CL_Druktrap	
Type Image	
Keynote	
URL	
Assembly Code	1-5FR1
Cost	
Assembly Description	
IFC Parameters	
Export Type to IFC As	IfcFilterType
IfcExportAs	
IfcExportType	
Type IFC Predefined Type	AIRPARTICLEFILTER
Export Type to IFC	Default
Type IfcGUID	3YgePLjVn5L9fWsVKfvXzw
Data	
KRO_DB_Leverancier Handelsartikel	
KRO_DB_Handelsartikel	
KRO_DB_Leverancier	
KRO_DB_Omschrijving	
KRO_DB_GTIN code	
KRO_DB_Controle WVB	☐
maintenanceStrategy	ConditionBased
operatingManual	camfil.com
serialNumber	150301-07

Figure 29: Properties of the filter object in Revit software

From the model preparation phase, it can be concluded that employing appropriate techniques during the design phase is essential to producing a model that is suitable for integration with adequate information. An important step in this phase is the proper allocation of objects to their corresponding IFC types. Additionally, the choice of IFC version plays a role in this specific research for mechanical equipment. The default export setting typically uses IFC 2x3, which results in a model structure, as illustrated in *Figure 30*, on the left side. However, switching to IFC4 (Building Services) allows for a more precise representation, with defined subtypes clearly displayed. This improves the model's utility for maintenance purposes, as it aligns more closely with the terminology familiar to maintenance personnel. For example, although *IfcFilter* belongs to *IfcFlowTreatmentDevice*, as shown previously in *Figure 5*, maintenance teams are typically not acquainted with such IFC classifications. Instead, they recognize more specific and applied name, *IfcFilter*. Ensuring that the model uses terminology familiar to end-users enhances its user-friendliness and effectiveness in the integration.



- ☑Project Number
  - + ☑IfcBuildingElementProxy
  - + ☑IfcDistributionControlElement
  - + ☑IfcDistributionElement
  - + ☑IfcEnergyConversionDevice
  - + ☑IfcFlowController
  - + ☑IfcFlowMovingDevice
  - + ☑IfcFlowTreatmentDevice
  - + ☑IfcSlab
  - + ☐IfcSpace
  - + ☑IfcWallStandardCase

- ☑Project Number
  - + ☑IfcAirToAirHeatRecovery
  - + ☑IfcBuildingElementProxy
  - + ☑IfcCoil
  - + ☑IfcDamper
  - + ☑IfcDistributionElement
  - + ☑IfcFan
  - + ☑IfcFilter
  - + ☑IfcSensor
  - + ☑IfcSlab
  - + ☐IfcSpace
  - + ☑IfcWall

Figure 30: Tree-form of IFC file of case study

It is worth noting that in both IFC extracts, there exists an instance of *IfcDistributionElement* representing the AHU as a whole unit. This element can serve as a system-level entity, enabling the assignment of properties that belong to the overall system. Properties such as installation date, flow design values, and control parameters. However, since the focus of this research is on RCM, which relies on a component-level analysis, this *IfcDistributionElement* instance was left unpopulated.

4.3.2 Existing BIM-SIM API functions

A web-based interface was selected for the platform as maintenance personnel, have minimal to no experience with specialized BIM software. Therefore, to properly serve its purpose and a broader user base, the platform must be vendor-neutral and avoid terminology or functionalities that are unfamiliar to its users. This approach was validated through interviews, where participants reviewing the first mock-up expressed a desire to view only relevant and easily comprehensible information.

BIM-SIM, developed as a Digital Twin, links static semantic building information with dynamic sensor data using the Brick Ontology. The existing functionalities of BIM-SIM are retained, and are briefly discussed here; for detailed methodology, see Chamari et al. (2022). Additionally, two new functionalities are introduced, and two more proposed for future development, demonstrating their practical application in a real-world case study.

3D Model Visualization

The BIM-SIM API employs the XKT format for viewing models within the browser. This format is chosen for its fast-rendering capabilities and the preservation of object GUIDs (Chamari et al., 2022). Originally used in BIM-SIM to identify spaces for sensor placement, the GUID will now also serve to identify the mechanical components of the AHU. This allows for the extraction of component-specific information, as well as mapping it within the maintenance plan and FMECA.

Querying RDF Files

The semantic representation of the building is captured in RDF Models, which are generated using the IFCtoRDF[3] converter. Linked Data offers significant advantages, such as the ability to enrich models with other domain-specific ontologies, exchange heterogeneous information, and derive new insights from the semantic graph (Chamari et al., 2022). This capability is particularly valuable for integrating various aspects of the O&M phase.

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[3] https://github.com/pipauwel/IFCtoRDF

Querying RDF files requires familiarity with the ontology structure, the API currently supports SPARQL queries, interfacing with a GraphDB repository containing the RDF files. While this approach is effective for extracting metadata, it can only be used by the developers or data engineers. Users of the interface, on the other hand, require an alternative searching method to retrieve specific element properties.

Viewing Sensor Readings

The functionality for viewing sensor readings was validated using the data extracted from the differential pressure transmitter (1-5PdT1). As noted by Chamari et al. (2022), real-time data visualization is achievable through the use of an MQTT JavaScript client with WebSocket; however, this was not implemented, as the current focus is on proving the concept of integration through the prototype.

For time-series data storage, MongoDB was employed. Listing 3 presents an extract from the RDF file, demonstrating how the Brick Ontology was used to define the sensor, assign its spatial location, and connect it with its readings.

```
inst:distributionControlElement_7975
    a brick:Sensor,
    brick:Filter_Differential_Pressure_Sensor;
    brick:hasUnit "Pa";
    brick:hasLocation inst:space_139;
    brick:timeseries [
        brick:hasTimeseriesId "1-5PdT1";
        brick:storedAt "mongodb://localhost:27017/bim-sim"
  ] ;
```

Listing 3: metadata of sensor associating it with its readings

4.3.3 Semantically enhancing Sensor data

While the current API approach provides a foundational framework for further development, it falls short of fully supporting the integration needs for condition-based maintenance. The mechanical components which are monitored by the sensors are often located within the same physical space such as those in the case study AHU. Therefore, although it is normal to associate sensors with the spaces in which they are installed, from a maintenance perspective, the association with the component being monitored is more critical. For instance, the AHU in the case study contains two differential pressure transmitters: one (1-5PdT1) monitors the supply air filter, while the other (1-5PdT2) monitors the extracted air filter. In the current interface, if both sensors are integrated, their readings alone would not explicitly indicate which sensor corresponds to which filter unless this information is further defined in the graphical representation or referenced via a P&ID diagram.

To improve usability, it would be more convenient for maintenance personnel to access sensor data directly by selecting the corresponding component. However, a simple enhancement that retains the core API structure is to display additional information on the chart, specifying the sensor's associated component and such information must be included in the metadata. Furthermore, including the manufacturer's recommended operational thresholds—such as the 110 Pa value for the differential pressure drop—as an alarm is essential to enhance the utility of the sensor data for decision-making.

Having used the filter as a case study to illustrate concepts, the semantic description of filter clogging fault will be examined to enhance the clarity of sensor metadata. In the context of the case study at hand, the filter is represented in the RDF graph as an instance of *IfcFlowTreatmentElement*, but it can also be semantically defined as *brick:Filter* or more specific as *brick:Intake_Air_Filter* within the Brick Ontology. Additionally, installed across this filter is a differential pressure transmitter, modelled as

IfcDistributionControlElement and further semantically enriched as *brick:Sensor*, *brick:Differential_Pressure_Sensor*, or more specifically *brick:Filter_Differential_Pressure_Sensor.*
Although one might expect a specific relationship between the sensor and the filter, such a relation is not present. The Brick ontology offers the *brick:isPointOf* relationship, which is generic and lacks specificity. The SOSA ontology, however, provides a more semantically precise relation, *sosa:isHostedBy*, which describes an association between a sensor and the platform on which it is mounted. Even though the class *sosa:Platform* remains generic and could refer to any entity, *sosa:isHostedBy* provides greater semantic accuracy compared to *brick:isPointOf*.

In the event of sensor readings exceeding the value of 110 Pa, this signals the occurrence of filter clogging, an unfavourable condition that represent a recognized filter fault also as per FMECA. The SSN ontology defines *ssn:Stimulus* as “an event in the real world that triggers the Sensor,” which closely aligns with the concept of observable property in this context being the filter’s condition.

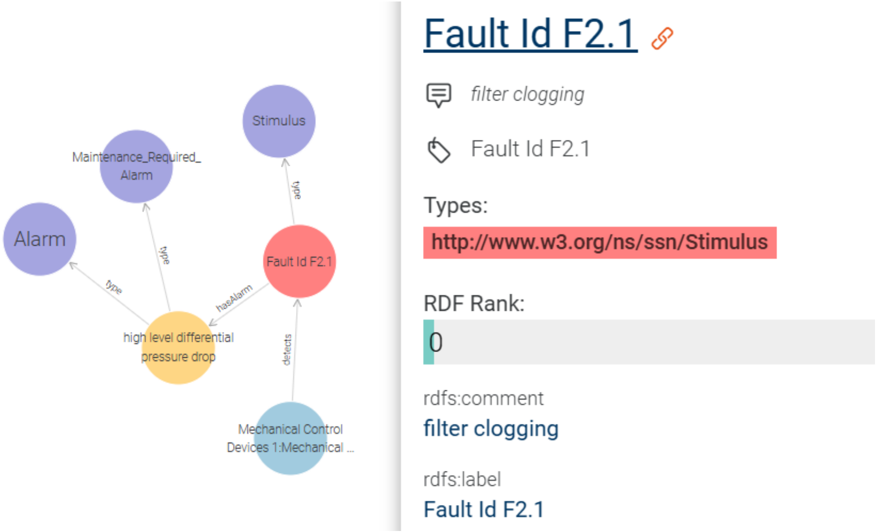
After a thorough examination it is found that the Brick Ontology defines specific entities such as *brick:Status*, *brick:Setpoint*, *brick:Alarm*, *brick:Command*, and *brick:Parameter* - all classifications of *brick:Point*, and the relationship used to connect them *brick:isPointOf*. The concept provided in the Brick Schema defines a *hasPoint* connection which can be further defined as *hasAlarm.*
Listing 4 presents the whole semantic description of the sensor, filter clogging fault and alarm associated to it. *Figure 31* shows the graphical representation in GraphDB.

```
inst:distributionControlElement_7975
    a brick:Sensor,
    brick:Filter_Differential_Pressure_Sensor;
    brick:hasUnit "Pa";
    brick:hasLocation inst:space_139;
    brick:timeseries [
        brick:hasTimeseriesId "1-5PdT1";
        brick:storedAt "mongodb://localhost:27017/bim-sim"
    ] ;
    sosa:isHostedBy inst:flowTreatmentDevice_6963;
    ssn:detects inst:fault_F2.1.

inst:fault_F2.1
    a ssn:Stimulus;
    rdfs:label "Fault Id F2.1";
    rdfs:comment "filter clogging";
    brick:hasAlarm inst:filterPdT_alarm.

inst:filterPdT_alarm
    a brick:Alarm,
     brick:Maintenance_Required_Alarm;
    rdfs:label "high level differential pressure drop";
    rdfs:comment "filter replacement required";
    rdf:value "110" ;
    brick:hasUnit "Pa"
    .
```

Listing 4: metadata of sensor associating it with fault and alarm



Fault Id F2.1

filter clogging

Fault Id F2.1

Types:

http://www.w3.org/ns/ssn/Stimulus

RDF Rank:

0

rdfs:comment

filter clogging

rdfs:label

Fault Id F2.1

Figure 31: Graphical representation of Fault Clogging

4.3.4 Newly developed Maintenance-BIM functions

This research began by analysing the RCM process to optimize maintenance strategies. The analysis resulted in a FMECA and a maintenance plan for the five primary mechanical components of the AHU supply air. The additional platform functionalities aim to make the information easier to locate and visualize by mapping the to the relevant components. Both the FMECA and the maintenance plan are stored as CSV files in the public folder of the interface. The decision to use Excel spreadsheets is based on its widespread familiarity and use.

Viewing Maintenance Information and Plan

The RCM process defined a maintenance strategy for each component individually, based on its failure modes and criticality assessment. However, many components in the AHU, such as pipes, ducts, and the casing, are non-critical and do not require specific attention for maintenance. By enabling workers to quickly identify the components requiring maintenance and the associated tasks, the platform streamlines their workflow. Therefore, a button was included to color-encode the components based on their maintenance strategy.

To retrieve information of the mechanical components, the query executed retrieves properties: *props:host*, *props:type*, *props:serialNumber*, *props:manufacturer*, *props:model*, and *props:assemblyCode* which were the only properties, identified in Section 4.2 and included in the graphical model**.** A SPARQL Query is illustrated in *Listing 5* where "Guid_Value" will be assigned through the API when an element is selected. Additionally, a mapping function was implemented to replace technical terms with user-friendly labels, enhancing the interface's accessibility for maintenance personnel.

```
SELECT ?property ?value
WHERE {
  ?instance props:hasCompressedGuid "Guid_Value".
  VALUES ?property {
    props:host
    props:type
    props:serialNumber
    props:manufacturer
    props:model
    props:assemblyCode }
  ?instance ?property ?value.
} LIMIT 10
```

Listing 5: Query to extract properties

Viewing FMECA

To integrate the FMECA into the platform and link it to specific components, the same method used for the maintenance plan was applied. An additional column was appended to the FMECA file, containing the Compressed GUIDs of the relevant components. A new function was then developed to read the Excel file and display key information, including failure modes, causes, effects, and criticality ratings. Additionally, a function was developed to allow users to input ratings for severity, occurrence, and detectability. These ratings are then processed through the decision logic to determine the appropriate maintenance strategy for the failure. A pseudocode of these two functions is presented in *Listing 6*.

```
# First function to read the FMECA Excel
def readExcelFile():
    # Check if a component is selected
    if picked == "Compressed GUID":
        # Search for the Compressed GUID in FMECA data
        filteredResults = [item for item in FMECA['Compressed GUID'] == picked]

        # If results are found, display them
        if filteredResults:
            print(filteredResults)  #Print results in a table-like format
        else:
            print("No results found for the selected GUID.")

# Second function to input criticality parameters and output maintenance strategy
def maintenanceStrategy(input_criticality_values):
    severity, occurrence, detectability = input_criticality_values

    # Determine maintenance strategy based on criticality values
    if severity <= 2:
        strategy = "Run-to-failure"
    elif severity > 2:
        if occurrence <= 2:
            strategy = "Corrective"
        elif detectability <= 2:
            strategy = "Condition-Based"
        else:
            strategy = "Preventive"

    # Output the determined maintenance strategy
    print("Recommended Maintenance Strategy:", strategy)

```

Listing 6: Pseudocode of viewing FMECA functionality

4.3.5 Further development

The interface is designed to be adaptable and flexible, supporting further development beyond the one outlined by incorporating RCM functionalities. This modular design allows for the gradual realization of the entire integration concept, with the potential to incorporate additional functionalities as the platform evolves. Two further developments are briefly described, and some aspects of the integration are discussed.

Integrating Work Orders

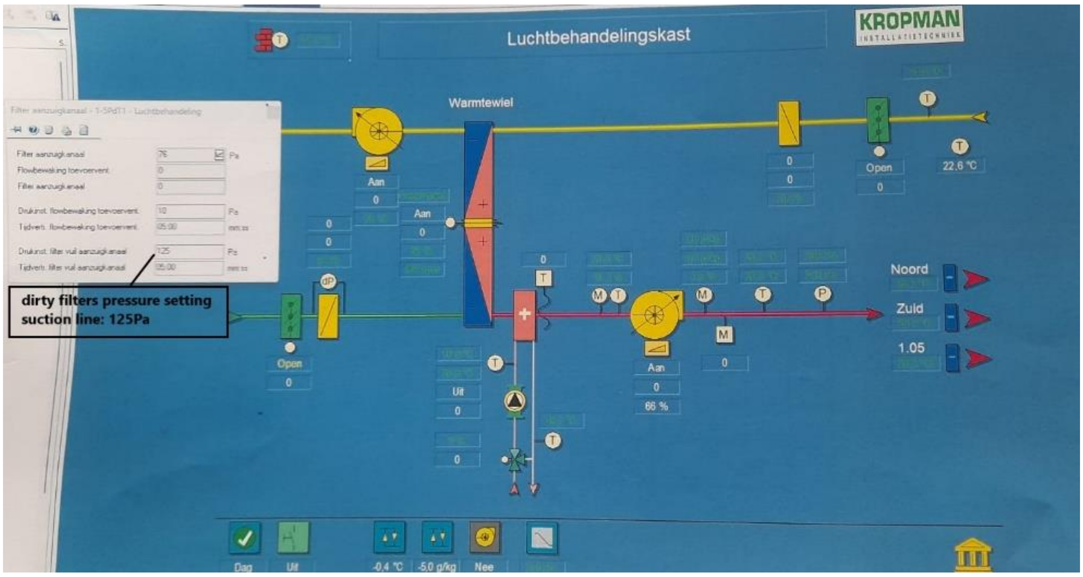
The prototype includes a manual integration of past work orders as a demonstration. The extracted maintenance reports were recorded in a spreadsheet, and a function was implemented to read and view this data based on component selection, similar to the approach used for integrating the FMECA and maintenance plan. Automating this process is based on two key parameters: Service Contract and Service Location. If these parameters can reliably identify the AHU in an ERP system, the next step involves correctly mapping individual components. However, an examination of current maintenance reports reveals that specific components are not explicitly identified.

To facilitate an automated integration in the future, a standardized, structured approach to generating work orders would ensure that components are properly mapped with relevant description.

Fault Detection and User Complaints

Fault alarms are typically received via the BMS and assessed by facility operators based on their expertise and experience. The BMS as can be seen in *Figure 32*, shows 2D depiction of components with no additional information apart from the reading and the P&ID Identity tag if present. Similarly, user complaints are logged and either addressed remotely through the BMS or, if necessary, require on-site intervention. However, as highlighted by one of the interviewees, remote operators often lack detailed background knowledge of the physical installation, leading to potential delays in alarm assessments.

Associating faults with BIM objects provides a more complete context for fault diagnosis. By linking alarms to BIM objects, operators gain access to additional parameters such as the size of the affected space, the age of the component, and the history of its maintenance. This holistic view enables more informed decision-making and enhances the accuracy of fault assessments.


Filter aanzuigkanaal - 1-5PdT1 - Luchtbehandeling

Filter aanzuigkanaal 76 Pa
Flowbewaking toevoervent. 0
Filter aanzuigkanaal 0
Drukinst. flowbewaking toevoervent. 10 Pa
Tijdvert. flowbewaking toevoervent. 05:00 mm:ss
Drukinst. filter vuil aanzuigkanaal 125 Pa
Tijdvert. filter vuil aanzuigkanaal 05:00 mm:ss

dirty filters pressure setting suction line: 125Pa

Figure 32: Screenshot from AHU BMS

Given that one of the primary functions of the AHU is to ensure thermal comfort—closely tied to user satisfaction— providing users with an intuitive reporting platform could encourage more frequent and straightforward feedback. Furthermore, combining user complaints and fault alarms within a single interface may advance the diagnosis and resolution process by allowing operators to identify correlations between user-reported issues and system-generated alarms.

4.3.6 User Profile

The maintenance personnel have been grouped into three primary roles - maintenance engineer, facility operator and maintenance worker - each with distinct requirements from the platform. The requirements were identified and discussed during interviews, while also reviewing two mock-ups of the platform: system-level and component-level interfaces. The interviewees jointly confirmed that both levels of information are essential for the platform to fulfill its intended purpose.

However, for the platform to be both usable and efficient, it must display only the information relevant to the user's specific role and the task at hand. The nature of the task determines the type of information required. Therefore, the platform should provide filtered information and functions, tailored not only to the user's role but also to the specific task they intend to execute.

Table 18 provides a brief analysis of the functions linked to the four user profiles. Considering that the information is aligned with specific activities and a comprehensive list of all maintenance-related activities falls outside the scope of this research the information per user profile will not be discussed. Moreover, a customized access as per *Table 18* signifies that users can view specific information but may be restricted from inputting data or utilizing certain functions of the module

Maintenance Engineer
The maintenance engineer profile encompasses two previously identified roles: the maintenance manager, responsible for inspecting the condition of AHU upon contract acquisition and drafting long-term maintenance plans, and the maintenance planner, who schedules tasks and allocates resources.

In the current process, maintenance engineers rely heavily on their expertise and knowledge of AHUs to fulfill these responsibilities, particularly when assessing component conditions and determining maintenance plans. These plans are typically fixed, with annual intervals. The proposed platform, however, would enable the engineer to make more data-driven decisions. With access to AHU maintenance data, faults that are not visually detectable can be identified, allowing for a more comprehensive assessment.

Given the direct involvement of the maintenance engineer in maintenance planning, it is anticipated that they would require full access to all platform functionalities, including system-level information. This level of access is essential for initial assessments.

Facility Operator
The facility operator profile represents a remote engineer who monitors and controls HVAC system operations, assesses system performance, and strives to optimize energy efficiency. Additionally, the operator receives fault alarms and user complaints, arranging remedial actions as required.

In the existing process, the facility operator is not involved in maintenance planning or scheduling and typically lacks detailed information on AHU condition or maintenance history. Their insights are largely limited to sensor readings, and alarms from BMS. The ideal set-up would be for the maintenance engineer to be the same as facility operator but that is rarely the case.

Using the platform, the facility operator would gain the ability to make proactive adjustments. With access to AHU location data and FMECA, the operator could adjust thresholds to align with condition-based maintenance needs. As a result, alarms could be tailored to indicate potential failures based on condition, rather than signify complete component failure. Some system-level information is also relevant for the operator to assess overall system performance.

Maintenance Worker
The maintenance worker profile supports the execution of maintenance tasks.
In the current process, a maintenance worker typically receives a work order with written instructions and a location address. The proposed platform, however, would enable the worker to visualize the precise location of the AHU and quickly identify components requiring maintenance, along with specific tasks. Accessing the platform from a tablet would further facilitate real-time updates, allowing the worker to complete reports and update information promptly.

Facility Users and Owner

In the current process, communication with facility owners is conducted through traditional means, often inefficiently and limited in transparency. Moreover, facility users do not get any feedback on their complaints.

With the platform, facility users and owners would be kept more informed and involved in maintenance operations. This digital communication channel would enhance streamline information sharing, ensuring users are well-informed of ongoing and scheduled maintenance activities.

Table 18: Defining users need for functionalities (FA= Full Access; CA: Customized Access; NA: No Access)

	Maintenance Engineer	**Facility Operator**	**Maintenance Woker**	**Facility Users & Owner**
Existing Functions				
3D Model Visualization	FA	FA	FA	FA
Querying RDF Files	FA	NA	NA	NA
Viewing Sensor Readings	FA	FA	NA	LA
Developed Functions				
Viewing Maintenance Information	FA	FA	CA	CA
Viewing Maintenance Plan	FA	CA	FA	CA
Viewing FMECA	FA	FA	NA	NA
Further Development				
Integrating Work Orders	FA	FA	FA	CA
Fault Detection and User Complaints	FA	FA	NA	CA

The activity diagram in *Figure 33* illustrates the redefined workflow implementing the integration of a CMMS with the Maintenance BIM Platform. In this workflow, work orders are inherently created and managed within the CMMS by the Maintenance Engineer. Once a work order is completed, the Maintenance BIM Platform automatically detects it, maps the associated information to relevant building components, and notifies the engineer of the successful mapping.

To access the platform, the engineer must log in using their credentials. At this stage, the planner has the opportunity to review the mapped information and make necessary updates if discrepancies are identified. Once the work order is confirmed, it is forwarded to the Maintenance Worker through the Maintenance BIM platform. The worker then accesses the work order, completes the assigned tasks, and submits the maintenance report. This report is subsequently stored in the CMMS as a finalized and completed record.

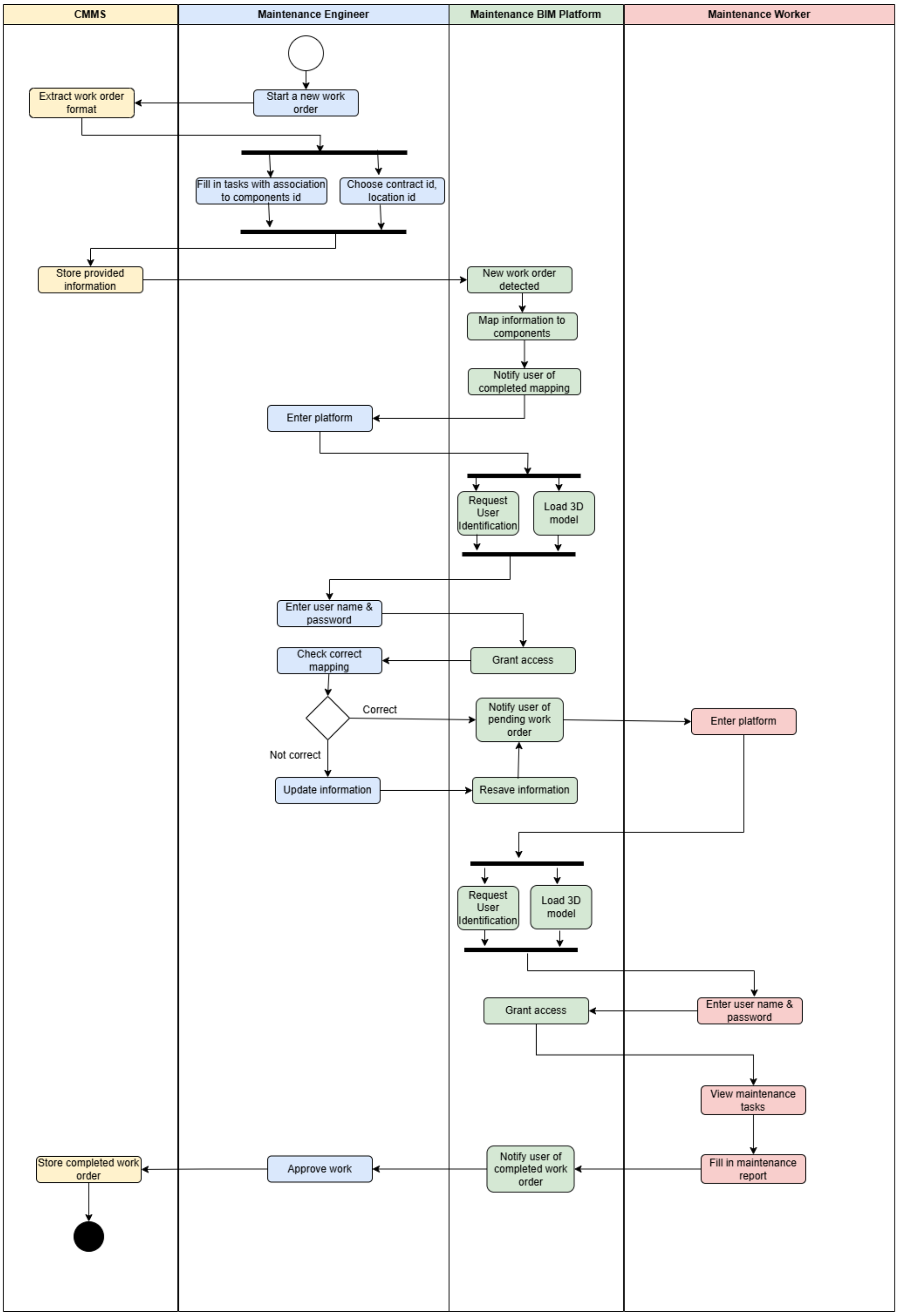


Figure 33 Activity diagram

4.3.7 Summary of Results

The RCM framework consisting of nine-step process was successfully implemented on an AHU within a HVAC System. This application demonstrated the systematic approach of the process in analysing mechanical components and choosing an optimal maintenance strategy. The resulting FMECA ensures that potential failure of components is considered even if resulting in higher energy consumption and not only system breakdown.

Key information requirements for effective maintenance were identified and categorized. These included both static and dynamic information, as well as a category in between named semi-static information. The identified requirements attempt to address the specific needs of maintenance personnel to facilitate decision-making and efficient execution of tasks. Moreover, a method to validate the presence of static information in a BIM model was suggested.

A Maintenance-BIM platform prototype was developed, incorporating innovative functionalities that align with maintenance personnel's requirements. The platform integrates RCM outputs, including the FMECA and maintenance plan, and presents this information, component-specific, through a user-friendly interface. Essential features such as 3D visualization and querying capabilities are presented While the prototype demonstrated the concept's viability, further integration with maintenance systems and real-time data streaming was recommended.

Maintenance encompasses different activities performed by different people and as such the platform needs to have various users. The results also define four users' profiles that must be accounted for, suggested functionalities that cater to their needs are presented.

Challenges associated with BIM data structures and semantic modelling were also addressed. The research employed the Brick ontology as well as SSN and SOSA to semantically describe filter clogging and enhance of the graph model.

5 Testing and Validation

The prototype was developed through an iterative design cycle, involving multiple iterations to improve the interface and ensure it accurately reflects user needs. This iterative process enabled continuous validation throughout the design phase, reducing uncertainties and simplifying the need for an extensive final validation check. Moreover, since no cost or technology assessments were conducted during this project, the emphasis of the development remained strictly user-centric, so did the validation.

The initial step in the development involved creating a demo mock-up to demonstrate how information is linked at both the system and component levels, as well as to illustrate the functionality of various integration tabs. Given that the RCM process is naturally component-based, it was decided to implement the interface at the component level rather than for the entire system.

The first iteration of the interface was presented to users for feedback. The users highlighted the importance of limiting or customizing information based on user profiles while including the ability to further search for specific properties. Additionally, the existing RDF query functionality was identified as suitable primarily for data engineers, prompting the need for a more user-friendly search engine. Users also stressed that property terminology should be intuitive, avoiding BIM-specific or ontology-related terms.

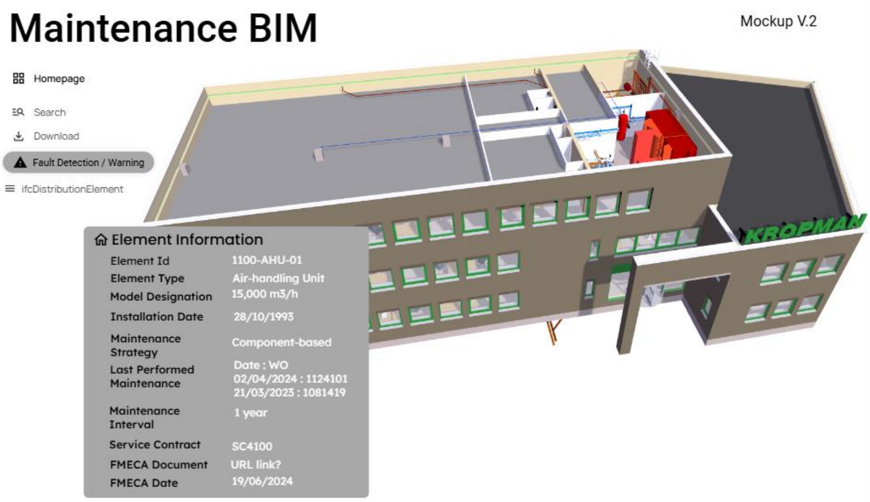
After incorporating this feedback, a second version of the interface was developed. While improvements were noted, two recurring comments emerged: the need for two search engines—one to locate components and another to search for properties.

5.1 The Mock-ups

The first mock-up was created at the start of the concept development phase to serve as a tangible, visual representation of the proposed interface, enabling stakeholders to better comprehend the objectives of integration. It included several interactive screens, such as the homepage, fault detection interface, and views for both system-level and component-level information *Figures* 3*4 and 35*.

The mock-up played a crucial role in informal discussions with stakeholders, assisting in the identification and formation of both functional and non-functional requirements. For instance, while the mock-up initially displayed FMECA extracts and the last performed maintenance together with component information, the visual examination led to the decision to segregate different types of information into distinct tabs rather than presenting them in a combined format. This adjustment aimed to improve usability and clarity by organizing integrations in a more understandable manner. Additionally, this enables allocating users to specific tabs based on their roles and tasks, as well as making the interface expandable. Each tab can represent a subsystem or microservice, aligning with the system's modular architecture to enhance flexibility.

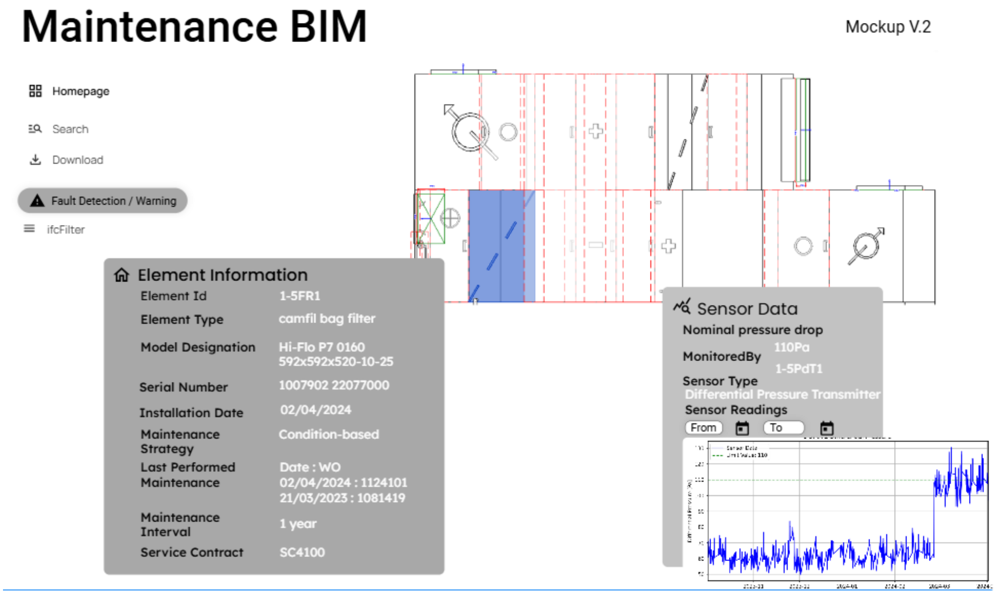
Subsequently the prototype started forming to gather constructive feedback from stakeholders in the interviews. Given the large volume of information within the interface, stakeholder feedback on the platform's usability and content presentation was critical. One key point of improvement that drove the iterations was the need to avoid ambiguous names for tabs and navigation elements, ensuring users could easily locate the information they require.



Element Information

Element Id	1100-AHU-01
Element Type	Air-handling Unit
Model Designation	15,000 m3/h
Installation Date	28/10/1993
Maintenance Strategy	Component-based
Last Performed Maintenance	Date : WO 02/04/2024 : 1124101 21/03/2023 : 1081419
Maintenance Interval	1 year
Service Contract	SC4100
FMECA Document	URL link?
FMECA Date	19/06/2024

Figure 34:Mockup showing System-level information



Element Information

Element Id	1-5FR1
Element Type	camfil bag filter
Model Designation	Hi-Flo P7 0160 592x592x520-10-25
Serial Number	1007902 22077000
Installation Date	02/04/2024
Maintenance Strategy	Condition-based
Last Performed Maintenance	Date : WO 02/04/2024 : 1124101 21/03/2023 : 1081419
Maintenance Interval	1 year
Service Contract	SC4100

Sensor Data

Nominal pressure drop	110Pa
MonitoredBy	1-5PdT1
Sensor Type	Differential Pressure Transmitter
Sensor Readings	

Figure 35: Mockup showing Component-level information

5.2 Validating functional requirements

The functional requirements previously defined were assessed based on the final prototype design. Each of the eleven requirements was accommodated in a specific functional module as described in Section 4.3 and accounted for a degree of integration. The results, summarized in *Table 19*, indicate that four requirements were fully implemented, three were partially implemented, three were not implemented, and one was implemented as a demonstration to guide future development.

Given that the research focuses on RCM, key components such as FMECA and the ability to view maintenance strategies were fully integrated into the platform. Partial integrations included:

- **Property search functionality (FR3):** The RDF query is functional for retrieving metadata, but lacks user-friendliness, which persists as an identified limitation by users.
- **Work orders (FR4)**: Maintenance history is available but requires manual input, indicating a need for an automated integration with the ERP system.

- **Sensor readings (FR9)**: Historical sensor data is integrated, but the live connection was not established limiting real-time monitoring.

Although user profiles were also defined, task-specific functionalities and input features tailored to individual users were not implemented within the scope of this research. The integration of fault alarms and user complaint reporting was identified as an important feature for meeting the platform's scope. Although these features were not fully implemented, a demonstration view illustrated how they could be displayed in the interface.

Table 19: Validation of functional requirements (C: Completely; P: Partially; D: Demonstrational; NI: Not implemented)

Id	*Description*	*Functionality Tab*	*Degree of integration*
FR1	**User shall be able to navigate 3D model and zoom into spaces**	**3D Model Visualization**	**C**
FR2	**User shall be able to select components within AHU**	**3D Model Visualization**	**C**
FR3	**User shall be able to search and view information of AHU/Components**	**Querying RDF Files + Viewing Maintenance Information**	**P**
FR4	**User shall view maintenance history of AHU/Components**	**Integrating Work Orders**	**P**
FR5	**User shall search for components by unique id**	**3D Model Visualization**	**NI**
FR6	**User shall be able to navigate FMECA**	**Viewing FMECA**	**C**
FR7	**User can view system by maintenance strategy**	**Viewing Maintenance Plan**	**C**
FR8	**User can view faults generated from BMS or fault detection algorithms**	**Fault Detection and User Complaints**	**D**
FR9	**User can view dynamic/live readings of sensors**	**Viewing Sensor Readings**	**P**
FR10	**Building's users can report suspected faults**	**Fault Detection and User Complaints**	**NI**
FR11	**Maintenance worker has access to fill in maintenance report**	**Viewing Maintenance Plan**	**NI**

5.3 Validating non-functional requirements

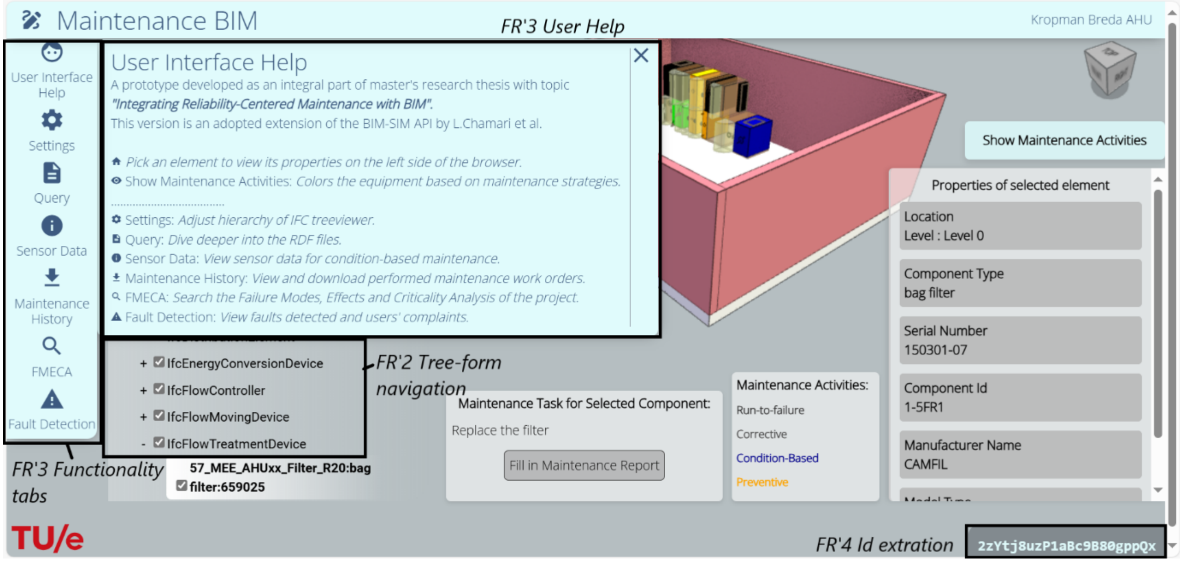
Non-functional requirements define the performance and capabilities of the platform, ensuring it meets the quality standards expected by end-users. During the concept development phase, eight requirements were identified. *Table 20* shows that three of these requirements belong to future development functionalities and, as such, cannot be tested or validated using the current prototype. *Figure 36* demonstrates how three of the requirements are implemented within the user interface.

The final two requirements that necessitate further validation are:

- **NFR1 (3D Model Loading Time):** To validate this requirement, the full model will be loaded, and the loading time will be assessed.
- **NFR5 (Metadata Search Time):** Validation will involve setting up two SPARQL queries to extract metadata. The searching time for each query will be analyzed.

Table 20: Validation of non-functional requirements

Id	Description	Priority	
NFR1	**The 3D model shall load in less than 120 seconds**	**High**	**Existing development**
NFR2	**The model can be navigated by element type in tree-form**	**High**	**Existing development**
NFR3	**The interface shall be understandable to navigate separating its functions in tabs and providing help information.**	**High**	**Existing development**
NFR4	**When selecting a component, the API shall extract its unique id**	**High**	**Existing development**
NFR5	**When searching metadata, loading time will not exceed 120 seconds**	**High**	**Existing development**
NFR6	**The information shall be customized for four different users**	**Medium**	**Further development**
NFR7	**Sensory data shall have indications of limits and average**	**Medium**	**Further development**
NFR8	**An algorithm links user complaints to faults detected**	**Medium**	**Further development**



User Interface Help

A prototype developed as an integral part of master's research thesis with topic *"Integrating Reliability-Centered Maintenance with BIM".*
This version is an adopted extension of the BIM-SIM API by L.Chamari et al.

Pick an element to view its properties on the left side of the browser.
Show Maintenance Activities: *Colors the equipment based on maintenance strategies.*
....
Settings: *Adjust hierarchy of IFC treeviewer.*
Query: *Dive deeper into the RDF files.*
Sensor Data: *View sensor data for condition-based maintenance.*
Maintenance History: *View and download performed maintenance work orders.*
FMECA: *Search the Failure Modes, Effects and Criticality Analysis of the project.*
Fault Detection: *View faults detected and users' complaints.*

+ ☑ IfcEnergyConversionDevice
+ ☑ IfcFlowController
+ ☑ IfcFlowMovingDevice
- ☑ IfcFlowTreatmentDevice
57_MEE_AHUxx_Filter_R20:bag
☑ filter:659025

Maintenance Task for Selected Component:
Replace the filter

Maintenance Activities:
Run-to-failure
Corrective
Condition-Based
Preventive

Properties of selected element
Location
Level : Level 0
Component Type
bag filter
Serial Number
150301-07
Component Id
1-5FR1
Manufacturer Name
CAMFIL

2zYtj8uzP1aBc9B80gppQx

Figure 36: A depiction of non-functional requirements validation

NFR1 (3D Model Loading Time):

Given that the case study model was simplified and had a loading time of approximately 50 milliseconds, it was crucial to test the system with the real-life building model. Even though, the loading time for the real-life model was 516 milliseconds, which indicates that the interface is highly capable it is recommended that the platform be tested with more complex models to further evaluate its performance under varying levels of model complexity.

NFR5 (Metadata Search Time):

The first query, *Listing 7*, is written to search for mechanical equipment in the graphical representation of the building, extracting both the types and location. This query provides basic information for obtaining the spatial location and categorization of mechanical components within the building model that may require maintenance.

```
SELECT ?component ?type ?location WHERE {
  ?component props:category "Mechanical Equipment".
  ?component props:type ?type.
  ?location bot:containsElement ?component .
} LIMIT 10
```

Listing 7: SPARQL query to extract mechanical equipment, their type and location

The second query, *Listing 8*, focuses on identifying sensors located in a specific room, given the room's compressed GUID. It retrieves the sensors in the room, and IDs which associates them with time-series data. This query also links the sensors to the components which they monitor making it particularly useful for identifying the sensors in condition-based maintenance.

```
SELECT ?sensor ?id ?component WHERE {
  ?location props:hasCompressedGuid "1WB99UeHj3wxSwo32P_7co".
  ?sensor brick:hasLocation ?location.
  ?sensor brick:timeseries ?arr.
  ?arr brick:hasTimeseriesId ?id.
  ?sensor sosa:isHostedBy ?component.

} LIMIT 10
```

Listing 8:SPARQL query to extract sensors in a space

Both queries were executed successfully, in less than one second. The results are presented in *Tables 21 and 22,* respectively. This demonstrates the efficiency of the platform's querying system, ensuring that information and metadata of equipment are easily retrievable.

Table 21: Results of first query, listing 7

Component	Type	Location
http://linkedbuildingdata.net/ifc/resources20241002_163242/flowTreatmentDevice_6963	"bag filter"	http://linkedbuildingdata.net/ifc/resources20241002_163242/space_139
http://linkedbuildingdata.net/ifc/resources20241002_163242/flowTreatmentDevice_7087	"bag filter"	http://linkedbuildingdata.net/ifc/resources20241002_163242/space_139
http://linkedbuildingdata.net/ifc/resources20241002_163242/energyConversionDevice_7176	"Heating Coil"	http://linkedbuildingdata.net/ifc/resources20241002_163242/space_139
http://linkedbuildingdata.net/ifc/resources20241002_163242/energyConversionDevice_7278	"Heat Recovery Wheel"	http://linkedbuildingdata.net/ifc/resources20241002_163242/space_139
http://linkedbuildingdata.net/ifc/resources20241002_163242/flowMovingDevice_7382	"FAN"	http://linkedbuildingdata.net/ifc/resources20241002_163242/space_139
http://linkedbuildingdata.net/ifc/resources20241002_163242/flowMovingDevice_7482	"FAN"	http://linkedbuildingdata.net/ifc/resources20241002_163242/space_139
http://linkedbuildingdata.net/ifc/resources20241002_163242/flowController_7696	"57_MEE_AHUxx_Jaloezieklep_R20"	http://linkedbuildingdata.net/ifc/resources20241002_163242/space_139
http://linkedbuildingdata.net/ifc/resources20241002_163242/flowController_7923	"57_MEE_AHUxx_Jaloezieklep_R20"	http://linkedbuildingdata.net/ifc/resources20241002_163242/space_139

Table 22: Result of second query, listing 8

Sensor	Id	Component
http://linkedbuildingdata.net/ifc/resources20241002_163242/distributionControlElement_7975	"1-5PdT1"	http://linkedbuildingdata.net/ifc/resources20241002_163242/flowTreatmentDevice_6963

6 Conclusion

This chapter concludes this graduation report by reviewing and providing summarized answers to the research sub-questions to ultimately answer the overall research question of:

> *How can Reliability-Centered Maintenance be integrated with Building Information Modelling to optimize maintenance strategies for multi-component systems and enhance the process efficiency?*

Section 6.1 discusses the contributions of this research within both scientific and societal contexts, highlighting its significance and broader impact. Subsequently, the research sub-questions are addressed, providing comprehensive answers based on the findings. Throughout this report, critical reflections on the methodology and results have been presented; however, Section 6.3 examines a few particularly challenging aspects that require further consideration. Finally, Section 6.4 outlines the limitations of the study and proposes directions for future research.

6.1 Scientific and Societal Contributions

Scientific and societal contributions are essential to guide and justify the significance of research. The objectives identified at the outset of this study shaped the anticipated contributions of the research, and the results further concretize them. This section provides a detailed outline of these contributions.

6.1.1 Scientific Contribution: RCM Process

This research offers facility managers a systematic and analytical framework for implementing the RCM process, addressing ambiguities and making the methodology more practical. The study discussed in depth, particularly, the three core steps of criticality assessment, decision logic and age exploration.

The development of the proposed platform is also a significant contribution to promoting condition-based maintenance as well as integrating data-driven insights with expert knowledge for decision-making in maintenance processes. The platform leverages dynamic data combined with FMECA results and maintenance history providing a comprehensive decision-support system. This hybrid approach enhances the reliability and precision of maintenance strategies

6.1.2 Societal Contribution: Intelligent, Sustainable and Healthier Buildings

This research contributes to the societal goal of developing intelligent, sustainable, and healthy buildings.

Intelligent Buildings are represented by promoting predictive maintenance, enabling early detection and resolution of potential failures. Additionally, the efficient use of data by integrating various information sources into a unified decision-making platform enhances the overall reliability and performance of the building.

Sustainable Buildings are addressed by optimizing maintenance which extends the lifespan of HVAC systems, reducing waste and the need for premature replacements. Furthermore, failures that significantly affect energy consumption and contribute to building's energy usage are appropriately prioritized through FMECA and not overlooked.

Healthier Buildings in which HVAC systems play a critical role in maintaining healthy indoor air quality and adequate temperature. The platform's emphasis on reliable maintenance practices ensures that the system operate effectively. Additionally, involving the building's users in fault reporting fosters a sense of belonging and satisfaction.

6.2 Answering the Research Questions

This research addressed three sub-questions as part of the investigation into the overall research question. The detailed research into these sub-questions was presented and discussed extensively in the results section. However, this section provides concise summaries of these answers, highlighting the key findings derived from the comprehensive results.

Q1. How can the appropriate maintenance strategy be selected, considering a multi-component system within a building, its role, components, and BIM representation?

The selection of an appropriate maintenance strategy for a multi-component system within a building, considering its role, components, and BIM representation, can be achieved through the implementation of the RCM process. This process begins by identifying the system to be analyzed and its functions, followed by dividing it into separate components and their function. Subsequently defining the failure modes of each component and their effects on the system's functionality and finally deciding a maintenance strategy to mitigate the most critical failures. Three key steps in the RCM process—criticality assessment, decision logic, and age exploration—pose apparent ambiguity but are addressed in this research with practical solutions.

The criticality assessment is achieved using expert knowledge with a defined rating scheme. The decision logic is structured to determine the optimal maintenance strategy for each component, progressing from run-to-failure to corrective, condition-based, and preventive maintenance, depending on the failure's criticality assessment. For age exploration, an observation method is used due to limited data availability, with recommendations for future enhancements through machine learning.

The successful implementation of the RCM process relies on the availability of system drawings and operation data, which were gathered from unlinked data sources in different formats during this research. While the BIM representation, IFC file, was not directly utilized in this case study for data extraction due to insufficient information, it is proposed that a fully developed BIM model with information requirements established in this research can be used as a comprehensive data source.

Q2. What are the information requirements necessary to include in a BIM platform to enhance the efficiency for maintenance selection and execution considering an AHU within an HVAC system?

The information requirements necessary to include in an integrated platform to enhance the efficiency for maintenance selection and execution considering an AHU within an HVAC system depend on the role of the user and the activities they aim to perform. These requirements can be assessed at two levels: system-level and component-level. Although currently maintenance planning is predominantly performed at the system level, relying on generic information and the expertise of maintenance engineers, this research promotes a more data-driven approach for increased precision in decision-making and condition-based maintenance. Overall, the information requirements identified through interviews were defined into three categories static, semi-static, and dynamic information. Static information are unchanging component identity information required for maintenance personnel to identify and locate AHU components. Semi-static information are component-specific details that may require periodic updates. Examples include serial number, service lifespan, and maintenance frequency. This information supports scheduling activities and task-specific decisions. Dynamic information, on the other hand, is real-time or frequently updated data, such as sensor readings, maintenance history, and fault detection logs. Dynamic information is essential for condition-based maintenance and fault assessment.

Q3. How can the RCM documents, maintenance information and BIM model be integrated allowing a user to interact with them to enhance the efficiency of maintenance process?

RCM documents, maintenance information and BIM be integrated **t**hrough a user-friendly interface that aims to meet the practical needs of maintenance personnel for efficient system management. To develop such a platform a systems engineering approach was employed. During the concept development phase, input was gathered through semi-structured interviews with prospective users of the interface. As such, the current maintenance process was analyzed, leading to the creation of a use case diagram that identifies key activities the platform must address.

Based on this analysis, functional and non-functional requirements for the interface were established. These requirements guide the platform's design resulting in a prototype that demonstrates eight functionalities, some of which were fully developed while others require further automation and integration. These functionalities include:

1. **3D Model Visualization**: The 3D model allows users to navigate the building and locate components requiring maintenance.
2. **Querying RDF Files**: The access to semantic data through queries allows users to retrieve specific information about components and their relationships.
3. **Viewing Sensor Readings**: By displaying real-time and historical sensor data, users can monitor system performance and detect when maintenance is required.
4. **Viewing Maintenance Information**: A customized functionality depending on the user and the activity to be performed where component information is presented.
5. **Viewing Maintenance Plan**: The colouring of components based on maintenance strategy allows users to easily identify the activities to be performed.
6. **Viewing FMECA**: The mapping of FMECA results to exact components helps decision-making based on the criticality of failures.
7. **Integrating Work Orders**: The integrated work orders inform users maintenance history.
8. **Fault Detection and User Complaints**: Allowing building occupants to report failures builds on users' satisfaction.

6.3 Discussion

This discussion section provides reflections on two key aspects central to the research. First, it explores the general understanding of optimizing maintenance and underscores the importance of adopting the RCM process. Second, it reassess the established rating scheme of failures, evaluating its applicability and effectiveness.

6.3.1 Optimizing Maintenance

Traditionally, maintenance optimization has focused on extending the interval between maintenance activities to reduce costs. However, as highlighted by the FMECA conducted in this study, many failures do not result in system breakdowns but rather in increased energy consumption. This finding challenges the typical concept that maintenance is primarily performed to prevent complete system failure.

Instead, the rationale should shift to consider that a potential failure leading to higher energy consumption may result in operation costs exceeding those of regular maintenance. Therefore, optimization in some cases, as recommended in this research, may involve shortening the maintenance intervals to prevent secondary costs associated with inefficient energy use. However, this study relies on theoretical hypotheses to support this conclusion, as it does not include a detailed cost analysis.

6.3.2 Criticality Assessment

The absence of a standardized rating scheme for severity, occurrence, and detectability presents challenges in determining the Risk Priority Number (RPN), which is the product of these three factors. The RPN is commonly used to identify the most critical failures requiring maintenance prioritization. However, a limitation of the current approach can be demonstrated with the following example:

- **Failure 1**: Severity = 4, Occurrence = 1, Detectability = 4
- **Failure 2**: Severity = 4, Occurrence = 4, Detectability = 1

While both failures have an RPN of 16, it is inappropriate to treat them equally. **Failure 1** is severe but has unlikely occurrence and a low detectability. In contrast, **Failure 2**, with same severity but higher occurrence and high detectability is a good candidate for condition-based inspections.

This difference in significance of these three parameters and how it is associated with maintenance strategies resulted in the development of the decision logic for maintenance in this study. However, after applying the defined rating scheme and analyzing the results, it became evident that a five-point rating scale is insufficient and inaccurate. Despite providing detailed descriptions for each rating, the scale's confined nature made it challenging to determine the precise threshold where a different maintenance strategy should be employed. Therefore, a more detailed and granular rating scheme is required to enhance decision-making accuracy.

6.4 Limitations and Further Research

The limitations of this research are linked to the project-specific nature of its implementation. While the RCM process is a generic framework applicable to mechanical equipment, phases such as decision logic and age exploration are highly tailored to the specific characteristics and requirements of the system being analyzed. This section examines the limitations identified during the case study implementation, emphasizing how each constraint presents an opportunity for future research to address these challenges and broaden the applicability of the findings.

6.4.1 RCM for AHUs

Although RCM is an effective approach, its application remains largely dependent on expert judgment and is primarily qualitative in nature. At the initial stages of this research, an attempt was made to retrieve work orders documenting failure events; however, this approach proved unproductive due to the specific nature of the case study. Failures in AHUs are rarely categorized as severe and, as a result, are often neither reported nor documented with detailed failure causes.
For instance, a critical component to the HVAC System – not investigated in this research - is w the heating pump. In cold climates, the heating pump is essential for maintaining the supply air temperature. Its failure results in the system's inability to perform its intended function and is therefore likely to be registered in an ERP system. Conversely, less critical failures, such as a damper being stuck in an open or closed position, are typically resolved immediately without recording the original cause or effect.

This limitation suggests the possibility for future research involving a different case study with a comprehensive failure history for relevant components. Such an investigation results in a data-driven analysis of failure modes and provides a more accurate criticality assessment.

6.4.2 Age Exploration Phase

The age exploration phase in RCM was found to be underexplored in the literature with no clear methodology on how to systematically approach. However, given its importance in maintaining a dynamic RCM process, the age exploration phase is promising to transition toward predictive mainteannce approaches.

Initially, the use of machine learning techniques was considered for the age exploration phase to predict component aging and remaining useful life. However, during the data extraction process, it was discovered that the available reliable data only commenced from 1/8/2023, preventing the retrieval of even two full years of maintenance records. This limited dataset hindered the feasibility and reliability of employing machine learning methods. Given this limitation, a simplified approach was examined based on literature and recommended earlier replacement dates.

Nevertheless, as more data becomes available over time, the development of a machine learning algorithm to predict the remaining useful life of filters is to be considered. Such an algorithm can leverage historical data and more accurate replacement times for filters.

6.4.3 Maintenance BIM platform development

The effectiveness of the proposed platform is highly dependent on the accuracy and comprehensiveness of the input data. Inaccurate or incomplete data, or a poorly developed BIM model, compromises the platform’s functionality and its intended objective.

Although this research sets a foundation for generic information required by maintenance personnel, it does not consider component-specific requirements. To build upon this foundation, future studies should investigate precise and detailed information requirements specific to individual components.

Furthermore, the development of the platform requires an understanding of the semantic web and linked data principle. The knowledge of SPARQL query language plays an important role in leveraging the platform to its full potential. A possible direction for future research would involve representing all integrated components as semantic data. For example, translating the FMECA into metadata structured within its own ontology would allow it to be queried alongside other metadata in the RDF model. This approach would not only enhance standardization and organization in FMECA development but also provide a more efficient and structured method for its storage and reuse compared to conventional spreadsheets.

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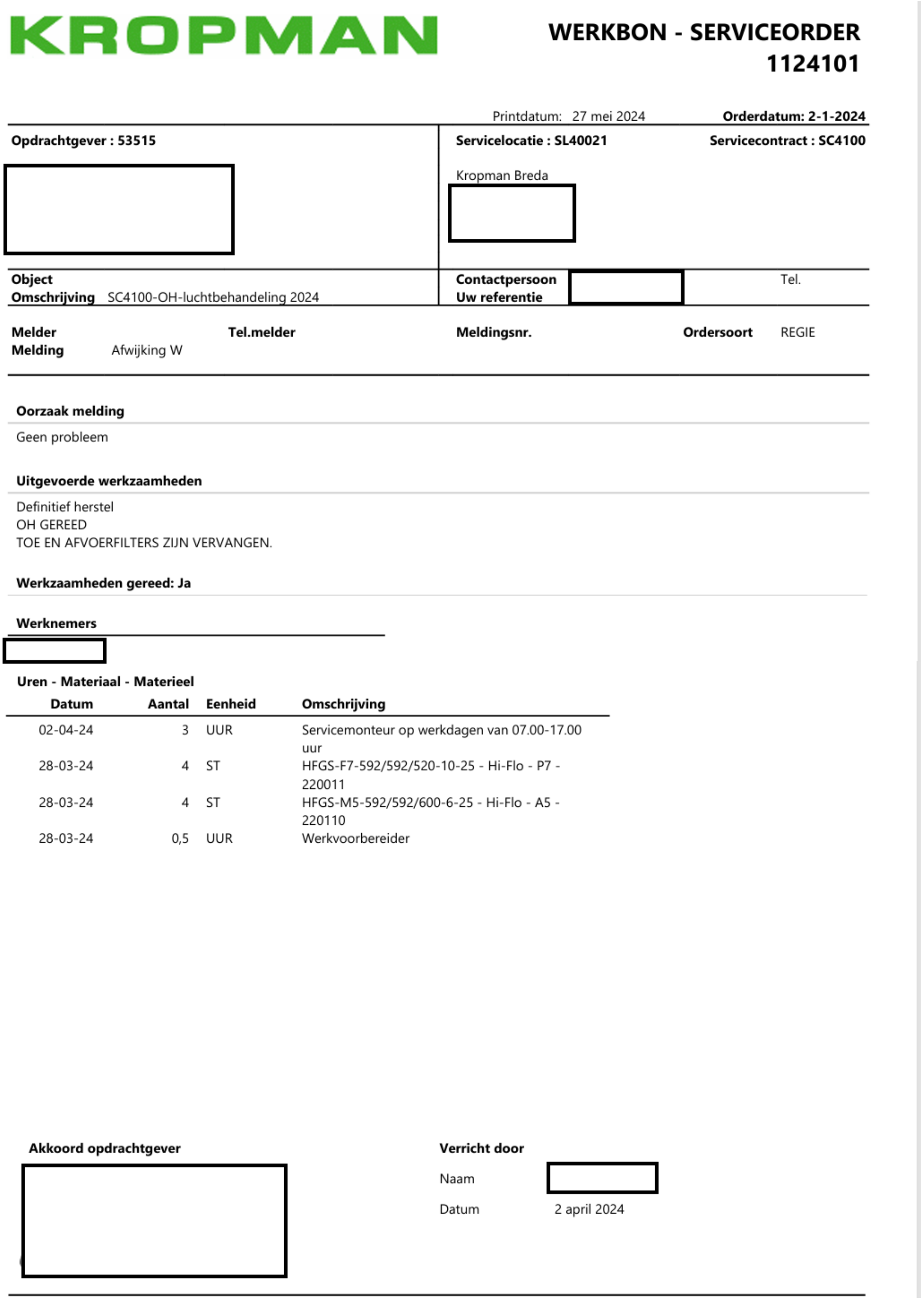
Zhao, J., Gao, C., & Tang, T. (2022). A Review of Sustainable Maintenance Strategies for Single Component and Multicomponent Equipment. *Sustainability, 14*(2992). https://doi.org/10.3390/su14052992

Zonta, T., da Costa, C. A., Righi, R. d., de Lima, M. J., da Trindade, E. S., & Li, G. P. (2020). Predictive maintenance in the Industry 4.0: A systematic literature review. *Computers & Industrial Engineering*. https://doi.org/10.1016/j.cie.2020.106889

Appendices

Appendix A: Raw Data



KROPMAN

WERKBON - SERVICEORDER
1124101

Printdatum: 27 mei 2024 **Orderdatum: 2-1-2024**

Opdrachtgever : 53515

[redacted]

Servicelocatie : SL40021 **Servicecontract : SC4100**

Kropman Breda

[redacted]

Object
Omschrijving SC4100-OH-luchtbehandeling 2024

Contactpersoon [redacted] Tel.
Uw referentie

Melder **Tel.melder** **Meldingsnr.** **Ordersoort** REGIE
Melding Afwijking W

Oorzaak melding

Geen probleem

Uitgevoerde werkzaamheden

Definitief herstel
OH GEREED
TOE EN AFVOERFILTERS ZIJN VERVANGEN.

Werkzaamheden gereed: Ja

Werknemers

[redacted]

Uren - Materiaal - Materieel

Datum	Aantal	Eenheid	Omschrijving
02-04-24	3	UUR	Servicemonteur op werkdagen van 07.00-17.00 uur
28-03-24	4	ST	HFGS-F7-592/592/520-10-25 - Hi-Flo - P7 - 220011
28-03-24	4	ST	HFGS-M5-592/592/600-6-25 - Hi-Flo - A5 - 220110
28-03-24	0,5	UUR	Werkvoorbereider

Akkoord opdrachtgever

[redacted]

Verricht door

Naam [redacted]

Datum 2 april 2024

Figure 1A: Work Order Structure (Maintenance of Year 2024 extracted from Microsoft Navision Dynamics

Table 1A: Information Requirements

	Dias & Ergan, 2020	*Benn & Stoy, 2023*	*Interviewee 1*	*Interviewee 2*
Component Identity Information				
Component ID	6/6	NP	Y	Y
Storey number	6/6	NA	Y	Y
Room number	6/6	NA	Y	Y
Product Name	6/6	Present (Lift Type)	Y	Y
Model Designation	6/6		Y	Y
Manufacturer Name	5/6	Present (Supplier)	Y	Y
System Type	X	Present	Y	Y
Date of Commissioning	6/6	Present	Y	N
Manufacturer and warranty information				
Serial number	6/6	Present	Y	Y
Acquisition Date	5/6	NA	N	N
Assembly place	5/6	NA	N	N
Production Year	5/6	NA	Y	Y
Warranty identifier	5/6	NP	N	N
Warranty start date	6/6	Present	Y	Y
Warranty period	5/6	Present	Y	Y
Warranty content	5/6	NP	N	Y
Point of contact	6/6	Present	N	N
Maintenance data				
Condition Status	5/6	NP	Y	Y
Last performed maintenance date	X	Present	Y	Y
Performed maintenance task description	X	Present	Y	Y
Maintenance scheduled frequency	X	Present	Y	N
Planned required maintenance	X	Present	Y	Y
Service life duration	6/6	NP	N	Y
Mean time between failure	5/6	NP	N	Y
Failure Modes and causes	X	NP	Y	Y
Fault detection history	X	NP	Y	Y
Live Sensors data	X	NP	N	Y

Table 2A: Summary of Interviews

The first semi-structured interview provided validation for the FMECA of AHU. The key points discussed for each component are summarized below.

Interview 1: Operation Manager

1. **Damper**:
   - A closed damper disrupts the entire AHU operation but is detectable through the control system, allowing timely intervention.
   - A damper stuck open or half-open is more critical during winter, as it can lead to coil freezing. These issues are not easily detectable unless the outdoor temperature is sufficiently low or manual inspection is performed.
   - Common failures include control issues and mechanical problems, such as actuator lubrication needs.
2. **Filter**:
   - Filters are replaced annually as standard practice. Excessive dirt is detected through differential pressure alarms in the system.
   - In cases where a filter develops a hole, systems with differential pressure transmitters can detect the anomaly, but those with simple pressure switches cannot.
3. **Heat Recovery Wheel (HRW)**:
   - HRWs must rotate weekly to ensure functionality. Improperly installed belts can break, though this is rare in the manager’s experience.
   - Older systems lack rotation percentage monitoring, making detection of failure challenging unless inspected manually or observed indirectly through higher energy consumption.
4. **Heating Coil**:
   - Dirt accumulation on heating coils is rare but impactful when it occurs, necessitating preventive measures such as clean filters.
   - Frozen coils, caused by extremely cold external temperatures, require replacement, necessitating the use of freeze stats to prevent such occurrences.
   - Coil heating issues are often related to the heating pump or valve, detectable through temperature sensors.
5. **Fan**:
   - Modern fans with directly mounted motors require minimal maintenance. However, older models with belts needed annual belt replacements and careful inspection during installation to prevent failure.
   - The fan's operational status is monitored through alarms and pressure readings.
6. **Additional Observations**:
   - Sensors are prone to faults and often lack calibration. Inaccurate temperature readings (e.g., one- to two-degree discrepancies) significantly impact heating energy consumption, emphasizing the importance of regular calibration.

The second and third semi-structured interviews provided inputs on the current process and concept development. The key points discussed are summarized below.

Interview 2: Maintenance Manager/Engineer

The maintenance manager is primarily involved in long-term maintenance planning and equipment inspections. He works with O-Prognosis, a system for condition inspection and maintenance planning. Their workflow begins with receiving an asset list from contract managers, which is often provided in Excel or PDF formats. This list is sometimes extracted

	from BIM models but can be overly detailed, containing modelled objects that are irrelevant for maintenance purposes such as casing and pipes. Inspections are conducted visually, with little to no access to previous maintenance or failure history, which is a limitation to the ability to make well informed evaluations. The interviewee mentioned challenges experienced that include outdated or inaccurate asset lists for older buildings and fragmented information management systems, as maintenance-related documents are often scattered across different platforms like OneDrive. The participant sees potential in BIM to improve planning and communication. For instance, using a 3D model to visualize the condition of assets or plan inspection routes could optimize the process. BIM could also assist in ensuring clients are better informed about what is being maintained and what is not. However, the lack of integration between BIM and maintenance systems means information is often incomplete or difficult to access. The participant emphasizes the importance of up-to-date information and collaboration to avoid inefficiencies, especially during the tendering phase, where inaccurate asset lists often lead to discussions.
	Interview 3: Manager of Remote Services The remote services manager oversees a team that handles fault notifications, remote diagnostics, and system monitoring using BMS like Schneider and Priva. They use Microsoft Navision Dynamics as an ERP system to create and track work orders. However, the workflow is semi-automated, requiring manual input to describe faults and components, which can lead to inefficiencies and incomplete feedback loops. A significant limitation of BMS is the lack of geometric information, which makes spatial context for faults unclear, complicating analysis. The participant sees numerous opportunities for BIM to enhance their work, particularly by providing location-specific information and 3D visualizations to streamline fault diagnostics and work order issuance. Challenges include data overload and inconsistencies in naming conventions across systems (e.g., BIM objects, CMMS assets, BMS elements). The participant stresses the importance of a user-friendly interface that limits displayed data to task-relevant information while keeping additional data accessible in the background. They believe such an approach would make the integration more practical and effective for all stakeholders in the service organization.

Table 3A: Results of Criticality Assessment

	Criticality Assessment			
Failure Id	Severity	Occurrence	Detection	RPN
F1.1	4	3	1	12
F1.2	2	4	4	32
F2.1	3	4	1	12
F2.2	4	2	2	16
F3.1	2	3	5	30
F3.2	3	2	4	24
F4.1	4	2	3	24
F4.2	3	2	2	12
F5.1	1	1	4	4
F5.2	4	4	2	32

Appendix B: Python Codes

```python
import pandas as pd

file_path_data = 'Data2024.csv'  # Load the yearly data for pressure drop analysis
df_data = pd.read_csv(file_path_data)

df_data.columns = ['Time', '1-5PdT1_Value'] # Rename columns

df_data['Time'] = pd.to_datetime(df_data['Time'], dayfirst=True, errors='coerce') # Set datetime format

working_hours_df = df_data[(df_data['Time'].dt.hour >= 8) & (df_data['Time'].dt.hour < 16)] # Filter to only working hours (8AM to 4PM)

daily_mean = working_hours_df.set_index('Time').resample('D').mean() # Calculate the daily mean

print("The mean value of the pressure drop around the working filter is:")
print(daily_mean.tail(10))

days_exceeding_110 = daily_mean[daily_mean['1-5PdT1_Value'] > 110] # Find days where the mean value exceeded 110

print("The first ten days where the mean value of the working filter exceeded 110 are:")
print(days_exceeding_110.head(10))

```

Listing 1B: Age Exploration

```python
import ifcopenshell
from ifctester import ids, reporter

# create new IDS
maintenance_ids = ids.Ids(title="Maintenance-BIM integration IDS")

# add specification to it
my_specf = ids.Specification(name="IFC file validation against static maintenance information")
my_specf.applicability.append(ids.Entity(name="IfcDistributionElement"))
global_Id_attribute = ids.Attribute(
    name="GlobalId",
    instructions="Each IfcDistributionElement must have a unique GlobalId.",
    minOccurs=1,
    maxOccurs=1 )
my_specf.requirements.append(global_Id_attribute)

AssetID_property = ids.Property(
    name="AssetIdentifier",
    propertySet="Pset_ConstructionOccurence",
    instructions="An asset identifier must be stated.",
    measure="IfcLabel",
    minOccurs=1,
    maxOccurs=1 )
my_specf.requirements.append(AssetID_property)

type_attribute = ids.Attribute(
    name="Type",
    instructions="Each IfcDistributionElement must have a defined type.",
    minOccurs=1,
    maxOccurs=1)
my_specf.requirements.append(type_attribute)

storey_property = ids.Property(
    name="Level",
    propertySet="Constraints",
    instructions="Storey number need to be stated.",
    measure="IfcLabel",
```

```
    minOccurs=1,
    maxOccurs=1)
my_specf.requirements.append(storey_property)

room_property = ids.Property(
    name="RoomNumber",
    propertySet="Constraints",
    instructions="Room number need to be stated.",
    measure="IfcLabel",
    minOccurs=1,
    maxOccurs=1)
my_specf.requirements.append(room_property)

maintenance_ids.specifications.append(my_specf)
my_ifc = ifcopenshell.open("AHU_final.ifc") # Load IFC model
maintenance_ids.validate(my_ifc)
reporter.Console(maintenance_ids).report() #Generate a validation report
```

Listing 2B: Information Delivery Specification

Appendix C: Maintenance BIM User Manual

This manual provides an overview of how users can interact with and utilize the prototype interface developed as part of this research. The components with developed functionalities can be found at:

[https://github.com/nemathmz/MaintenanceBIM]

The manual's scope is to present visuals of the platform and explain how the features operate.

Figure 1D illustrates the layout of the interface, highlighting the location of each functionality.

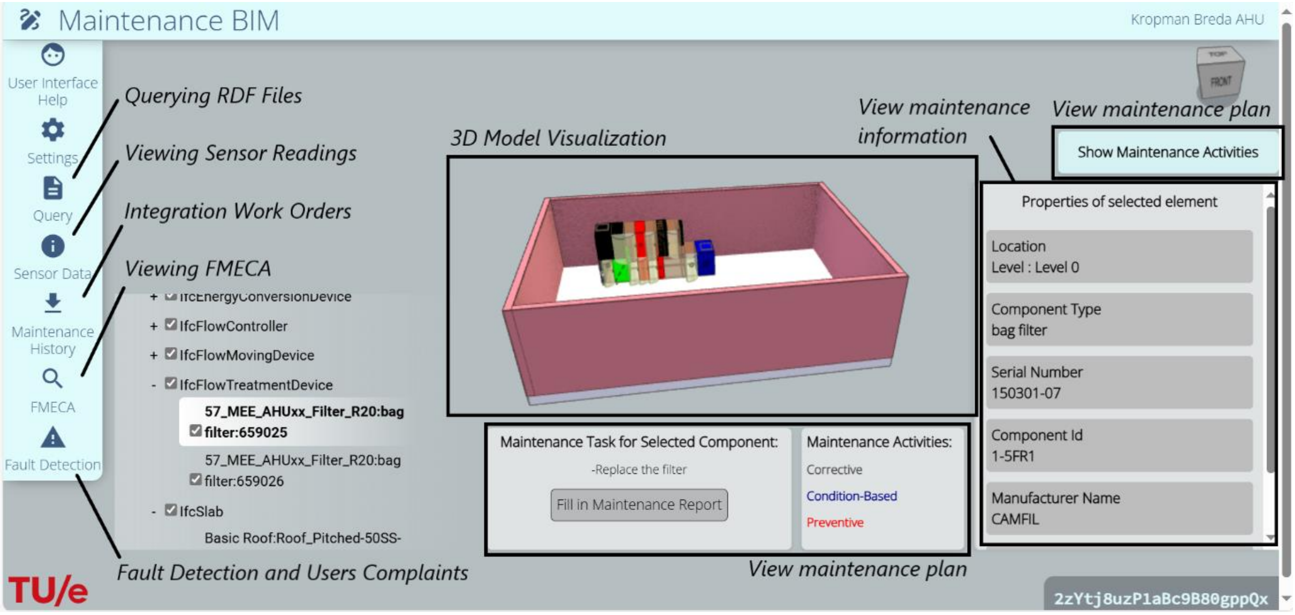
Figure 1D shows the final prototype of the interface. In this example, the "Show Maintenance Activities" button has been selected, coloring the components and showing the maintenance tasks. The interface reads from Table 1D.

Figure 3D demonstrates the dynamic readings of the differential pressure transmitter for a specified time period. After selecting the desired sensor, users can input the time range and choose the number of samples to be displayed on the chart.

Figure 4D displays the FMECA tab for a selected component—in this case, the heat recovery wheel. This view includes input fields for criticality parameters, allowing users to test alternative values and observe the corresponding recommended maintenance strategy.

Figure 5D represents the suggested integration with an ERP system. In the current prototype, the interface reads from a manually created Excel sheet (Table 2D). For future development, the system will require a real-time connection with an ERP database to automate this process and enhance functionality.

Finally, *Figure 6D* showcases the fault detection and user complaint visualization tab. This feature demonstrates how detected faults and reported issues can be integrated into the platform, providing maintenance personnel with an integrated overview.



Properties of selected element

Location
Level : Level 0

Component Type
bag filter

Serial Number
150301-07

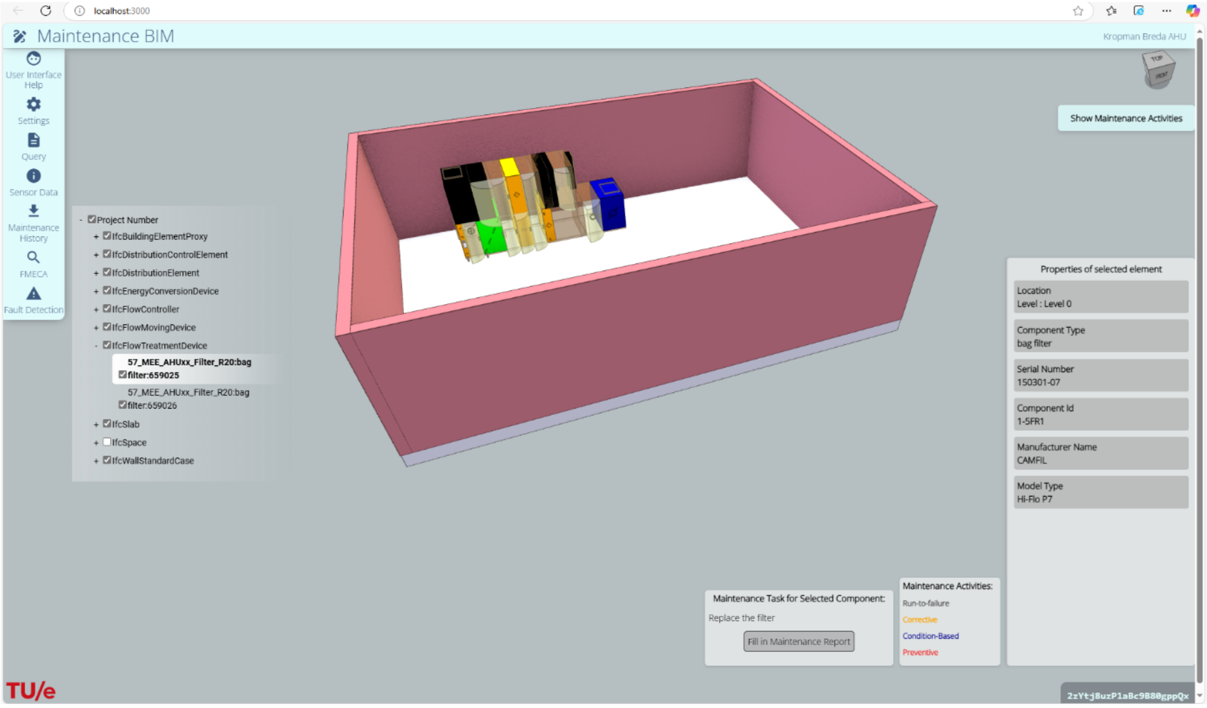
Component Id
1-5FR1

Manufacturer Name
CAMFIL

Maintenance Task for Selected Component:
-Replace the filter

Maintenance Activities:
Corrective
Condition-Based
Preventive

Figure 1D: A depiction of functionality modules



Maintenance Task for Selected Component:
Replace the filter

Properties of selected element

Location
Level : Level 0

Component Type
bag filter

Serial Number
150301-07

Component Id
1-5FR1

Manufacturer Name
CAMFIL

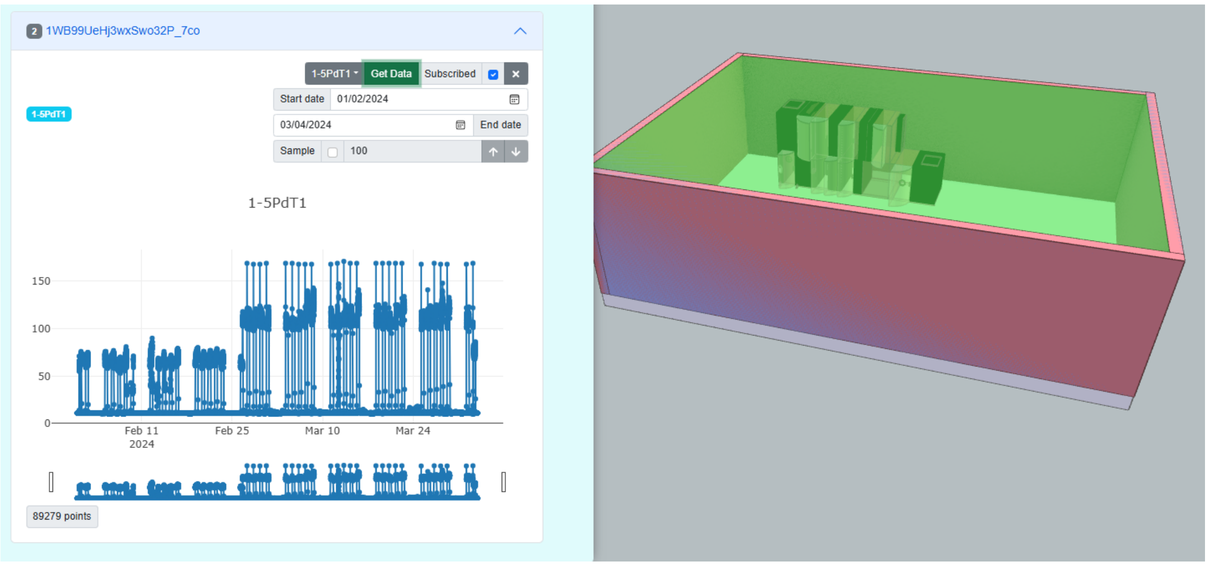
Model Type
Hi-Flo P7

2zYtj8uzP1aBc9B80gppQx

Figure 2D: The final prototype design

Table 1D: Maintenance Plan for the five components

GUID	**Maintenance Strategy**	**Maintenance Tasks**
2vtK3jGx157BtoTg_RUTO0	Corrective	-Check for damage and dirt -Ensure there are no signs of corrosion
2zYtj8uzP1aBc9B80gppQx	Condition-Based	-Replace the filter
1wbSO9wmL6JxyVV1JV_3Jq	Corrective	-Check the belt for excessive wear - Check damage, corrosion or wear of wheel - Check for oxidation and/or loose of nuts and bolts - Check for contamination of the wheel
1wbSO9wmL6JxyVV1JV_3Jt	Corrective	- Check for contamination on both sides - Check for corrosion and damage of pipes
1wbSO9wmL6JxyVV1JV_3Jo	Condition-Based	- Monitor for imbalance/vibration noise. If one of these factors or a combination is present, it indicates defect or wear of the fan or motor bearings - Monitor operation output

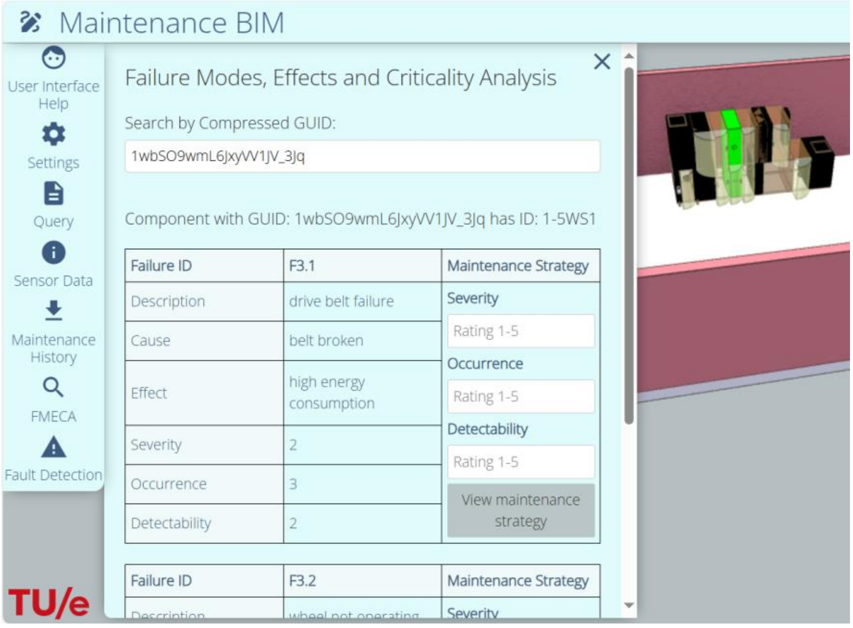


Start date 01/02/2024

03/04/2024 End date

Sample ☐ 100

Figure 3D: Maintenance BIM platform showing dynamic sensor data



Failure Modes, Effects and Criticality Analysis

Search by Compressed GUID:

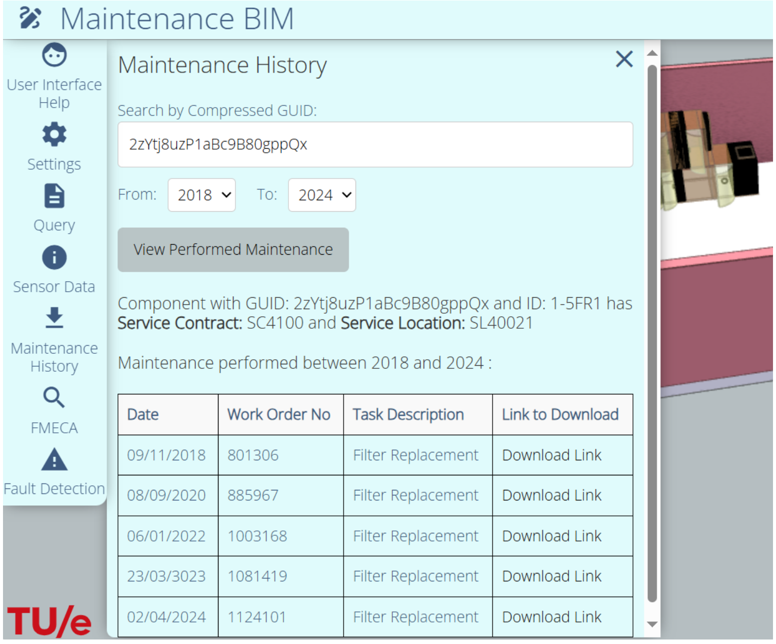
1wbSO9wmL6JxyVV1JV_3Jq

Component with GUID: 1wbSO9wmL6JxyVV1JV_3Jq has ID: 1-5WS1

Failure ID	F3.1	Maintenance Strategy
Description	drive belt failure	Severity
Cause	belt broken	Rating 1-5
Effect	high energy consumption	Occurrence Rating 1-5
Severity	2	Detectability Rating 1-5
Occurrence	3	View maintenance strategy
Detectability	2	

Failure ID	F3.2	Maintenance Strategy
Description	wheel not operating	Severity

Figure 4D: Maintenance BIM Platform showing FMECA



Maintenance History

Search by Compressed GUID: 2zYtj8uzP1aBc9B80gppQx

From: 2018 To: 2024

Component with GUID: 2zYtj8uzP1aBc9B80gppQx and ID: 1-5FR1 has **Service Contract:** SC4100 and **Service Location:** SL40021

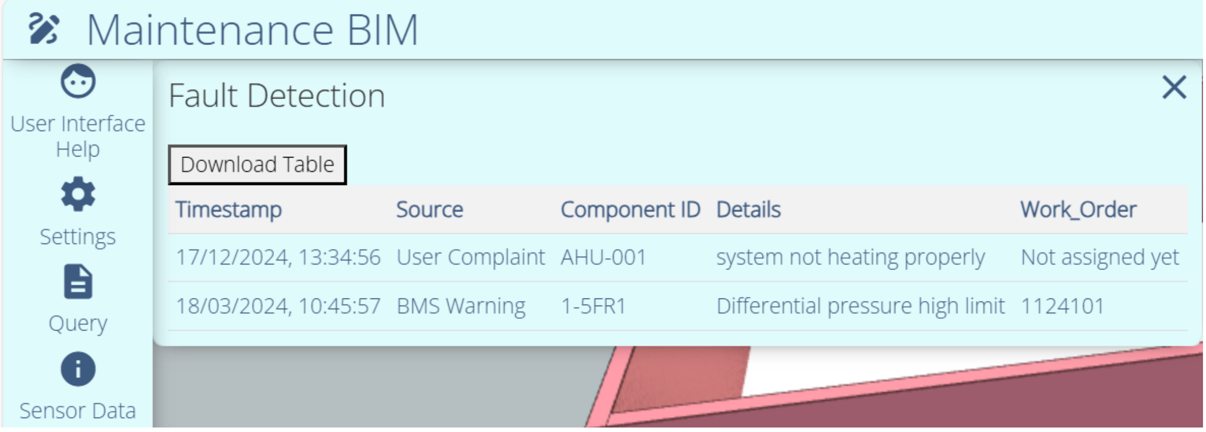
Maintenance performed between 2018 and 2024 :

Date	Work Order No	Task Description	Link to Download
09/11/2018	801306	Filter Replacement	Download Link
08/09/2020	885967	Filter Replacement	Download Link
06/01/2022	1003168	Filter Replacement	Download Link
23/03/3023	1081419	Filter Replacement	Download Link
02/04/2024	1124101	Filter Replacement	Download Link

Figure 5D: Maintenance-BIM Platform showing maintenance history

Table 2D: Historical Work Orders

YEAR	DATE	SERVICE CONTRACT	SERVICE LOCATION	WO NO	TASK DESCRIPTION	COMPONENT ID	COMPRESSED GUID	LINK TO DOWNLOAD
2018	09/11/2018	SC4100	SL40021	801306	Filter Replacement	1-5FR1	2zYtj8uzP1aBc9B80gppQx	ERP/AHU/reports.com
2020	08/09/2020	SC4101	SL40022	885967	Filter Replacement	1-5FR1	2zYtj8uzP1aBc9B80gppQx	ERP/AHU/reports.com
2022	06/01/2022	SC4102	SL40023	1003168	Filter Replacement	1-5FR1	2zYtj8uzP1aBc9B80gppQx	ERP/AHU/reports.com
2023	23/03/3023	SC4103	SL40024	1081419	Filter Replacement	1-5FR1	2zYtj8uzP1aBc9B80gppQx	ERP/AHU/reports.com
2024	02/04/2024	SC4104	SL40025	1124101	Filter Replacement	1-5FR1	2zYtj8uzP1aBc9B80gppQx	ERP/AHU/reports.com



Fault Detection

Timestamp	Source	Component ID	Details	Work_Order
17/12/2024, 13:34:56	User Complaint	AHU-001	system not heating properly	Not assigned yet
18/03/2024, 10:45:57	BMS Warning	1-5FR1	Differential pressure high limit	1124101

Figure 6D: Maintenance-BIM Platform showing a proposed fault detection and users' complaints integration