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Suneet Jain, Stuttgart 16.04.2018

Abstract

Effective communication from machines and embedded sensors, actuators in industries are crucial to achieve industrial digitalization. Efficient remote monitoring as well as maintenance methodologies helps to accomplish and transform the existing industries to Smart Factories. Monitoring and maintenance leads to the aggregation of the real-time data from sensors via different existing and new industrial communication protocols. Development of user-friendly interface allows remote Condition Monitoring (CM). Context aware analysis of real-time and historical data provides capability to accomplish active Predictive Maintenance (PdM). Both CM and PdM needs access to the machine process data, industrial network and communication layer.

Furthermore, data flow between individual components from the Cyber-Physical System (CPS) components starting from the actual machine to the database or analyze engine to the real visualization is important. Security and safety aspects on the application, communication, network and data flow level should be considered.

This thesis presents a case study on benefits of PdM and CM, the security and safety aspect of the system and the current challenges and improvements. Components of the CPS ecosystem are taken into consideration to further investigate the individual components which enables predictive maintenance and condition monitoring. Additionally, safety and security aspects of each component is analyzed. Moreover, the current challenges and the possible improvements of the PdM and CM systems are analyzed. Also, challenges and improvements regarding the components is taken into consideration. Finally, based on the research, possible improvements have been proposed and validated by the researcher. For the new digital era of secure and robust PdM 4.0, the improvements are vital references.

Keywords: Industry 4.0, Smart Factories, Cyber-Physical Systems, CPS, Security and Safety, Predictive maintenance, Condition monitoring, Benefits, Effects, Case study

Contents

List of Figures

List of Tables

List of Abbreviations

IIoT	Industrial Internet of Things
CPS	Cyber Physical Systems
PdM	Predictive Maintenance
CM	Condition Monitoring
PM	Preventive Maintenance
RAMI 4.0	Reference Architectural Model for Industry 4.0
OT	Operational Technology
IT	Information Technology
HMI	Human Machine Interface
PLC	Programmable Logic Controller
IDS	Intrusion Detection Systems
IPS	Intrusion Prevention Systems
FGD	Focus Group Discussion

1 Introduction

This section is an introduction to the thesis and consist of a concise training of the subject area and presents the motivation of this project and problem statement. Concludes with the outline of this thesis.

1.1 Maintenance and Monitoring

The Industrial Internet of Things (IIoT) assures to revolutionize the industries by empowering the procuring and availability of far greater amounts of data, at far greater speeds [1]. IIoT also enabled the evolution of connected Cyber Physical Systems (CPS). The data from each CPS system is gathered and sent over the network to internal processing units as well as to the cloud for further analysis or monitoring etc. Furthermore, it provides the power to control the physical systems remotely.

Maintenance had been a major hurdle from decades for the industries. Maintenance issues also led manufacturers financial losses because of under production and downtime [2]. Over the time industries and researchers have identified diversified and effective maintenance strategies [3, 4] but still they are not completely adapted because of peculiar reasons. Today in the era of Industry 4.0, Predictive Maintenance with condition-based monitoring is the most effective maintenance methodology. But the major concern for industries is how secure and safe the methodology is for their industry.

Security and safety aspects of all the components involved for monitoring and maintenance is very important for the industries to become safe, secure and smart factories [5, 6, 7]. A fundamental issue for Industry 4.0 is to understand the role of integrated safety, security, privacy and knowledge protection [8].

1.2 Problem Statement

Competition between organizations is driving both cost and advancement. To produce or manufacture the end products, organizations often procures materials, machines and further components. Investment for improvement of maintenance and monitoring is also the part of term Industry 4.0, which encapsulates the idea of 4th Industrial revolution. Maintenance being the noteworthy cost component in any organization's balance sheet, any solution with the likelihood to diminish maintenance costs is frequently sought after.

Plenty of research has already been done on the profits of condition monitoring and predictive maintenance but still many of the organizations are not completely ready to integrate the same within their ecosystem due to multiple factors like security and safety. There is a very limited research has been done on the security and safety norms specific to PdM and CM. To achieve PdM and CM, the data exchange from embedded sensors on machines, cyber physical systems to database or analyze engine and to the real visualization is very important. Safety and security standards on the application, communication and data flow level should be considered.

This project aims to establish a clear view for the practitioners on the benefits of PdM and CM and currently how the safety as well as security standards are coupled within the ecosystem. Furthermore, current challenges and their possible solutions are discussed.

1.3 Motivation

This case study has been conducted amid a student association with GPS GmbH in Stuttgart, Germany on the projects like Sicon IIoT Gateway & Services and with the digitalization department from J. Schmalz GmbH. For Industry 4.0., requirements from the Research and Development department of GPS GmbH provided the platform to identify the benefits of predictive maintenance and condition monitoring for manufacturing industries which are transforming to smart factories.

The researcher tries to discover how PdM and CM are integrated with cyber physical systems and how industries can benefit from them. Determine diversified methods for the PdM and CM of various components within the industry. To identify the industrial level communication protocols and data flow to achieve effective PdM and CM. Furthermore, analysis of security and safety aspects concerning to PdM and CM.

Industries are striving to achieve more productivity and less downtime. This study would help industries to get insights about the components involved in PdM and CM. The importance of data generated from different machines and components and How the data can be used effectively to achieve desired results. Identification of security and safety aspects within the ecosystem for PdM and CM could help to improve future projects.

Identified challenges, required improvements and the optimization of security and safety of different components involved to achieve effective PdM and CM could be a topic of further research for the industry.

1.4 Structure of the Thesis

The rest of the report is organized as follows:

- **Section 2** briefs existing monitoring and maintenance methodologies. Background and related work about predictive maintenance and condition monitoring is described.
- **Section 3** is the description of security and safety aspects for PdM and CM.
- **Section 4** describes the objective, protocol and approach of this case study.
- **Section 5** data analysis strategy, techniques and tool support has been presented.
- **Section 6** details design of this case study and coding of the collected data.
- **Section 7** the results and finding of the data analysis process have been presented
- **Section 8** confines with the conclusion and possible future work.

2 Maintenance, Monitoring and Industrial Architecture

This section gives a brief background information of maintenance and monitoring methodologies. PdM and CM are described in detail with their benefits and Industry 4.0 reference architecture with different components enabling next generation of maintenance and monitoring strategies is outlined.

2.1 Background and Related Work

With the present advancement of Industry 4.0, the data aggregated from production is turning into a progressively critical resource for maintenance tasks. Constant collection and analysis of production data can highly reduce the costs which are involved for strategies like corrective maintenance since malfunction of in production equipment can be averted [11]. Precise production data is the establishment to Predictive Maintenance (PdM). PdM as a maintenance strategy not only evaluates the current condition of the equipment but also takes historical data into consideration to identify possibility of failure in advance and initial phase.

According to the definition from EN-13306 (2010) [4], predictive maintenance is "condition-based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item." Investigation from several researchers have identified condition monitoring as the vital activity for the execution of predictive maintenance on production equipment. To achieve the objective functions, employment of the optimization model is common approach between the researchers [12, 13, 14].

With the exponential increase in requirement for e-maintenance and remote maintenance as well as monitoring, security and safety of the production equipment and data generated from them becomes crucial [15, 16]. Security and safety mechanisms on the data collection, aggregation, analyzation, exchange and on network as well as on the application level need to be considered.

2.2 Condition Monitoring and fault detection/diagnosis

With the evolution of cyber physical systems (CPS) [10] and Industry 4.0 [9], the machines in industries are equipped with embedded sensors which outputs the real-time data and are sent over the network to a monitoring system or data analysis engine. The generated data is also stored persistently to generate historical views. The historical data with real-time data becomes a base for the maintenance strategy like predictive maintenance.

The author of "Handbook of Condition Monitoring Techniques and Methodology" [21] defines condition monitoring as a management technique which evaluates real time condition of equipment, systems which are in operation with management goals and functions to optimize the total plant operation. Real time analysis of machine condition allows to achieve risk minimization through early fault detection and diagnosis. The input to condition monitoring systems is the data generated from machines and parameter mapping to the predefined functions. For example, the temperature sensor on a machines measures and sends temperature values and these values can be compared with the functions which defines that what is the acceptable high temperature where the machine's operation quality is not being degraded. Functions not only define the parameter value range, but it also defines fault associated in condition where the value range is violated. A function can also be equipped with definition of the measures to be taken under the scenario where fault is detected.

There are many techniques for condition monitoring, the major techniques which are currently used by the industries are as following: -

- Vibration analysis and diagnostics [21, 22]
- Wear debris analysis [21]
- Noise monitoring [21]
- Lubricant analysis [23]
- Infrared thermography [24]
- Visual inspection [21, 25]
- Acoustic based analysis [26]

A simple condition monitoring engine can be visualized from the Figure 1. Where data from different machines is first perused by the sensors and send the data over the network to the analysis engine. The live data stream is forwarded to the user for visualization and to the persistent storage. Analysis engine analyzes the data parameters with the pre-provided function and identifies if any of the machine has a fault. Analyzed data is forwarded for visualization as well as to the storage. If a fault is detected then it is additionally investigated with the help of provided function to discover fault classification, root cause analysis and it alerts to the user.

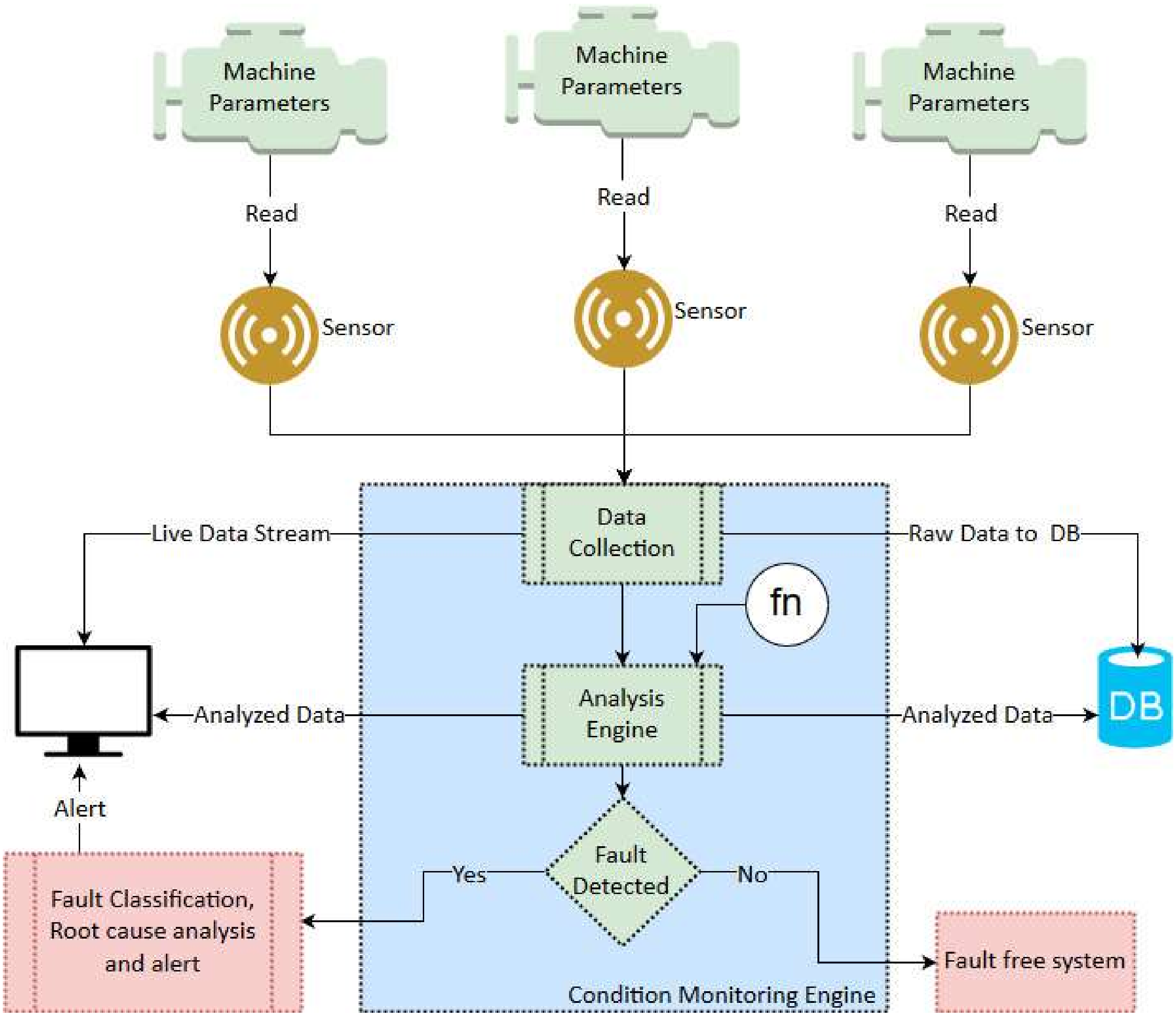


Figure 1: Condition Monitoring process and data flow chart (Adapted from [27])

In present days, historical fault diagnosis data and applied solution is used to find the issue and swift solution. The event is then further logged if the issue and solution is found in historical database or else it is stored as a new entity for future reference.

2.3 Maintenance Methods and PdM

According to EN-13306 (2010) "Maintenance is the combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" [4].

2.3.1 Maintenance Theory Fundamentals

Fundamentals of the maintenance theory has been defined by EN-13306 (2010) - Maintenance terminology which are defined below.

Figure 2: Maintenance theory fundamentals

Maintenance Management

Defined as "*all activities of the management that determine the maintenance objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics*" [4].

Maintenance Plan

It is defined as agreed, recorded and organized set of tasks that defines the activities, procedures, schedule and resources [4]. Where schedule means the timeline on which certain activity must be performed with defined procedures by a resource. Planning precedes scheduling.

Reliability

It can be defined as the competency of a system to operate orderly and continuously without any interruption [17]. K. Fowler and D.K. Pradhan defines reliability as quantitatively measured probability of a system in operation to work as expected amid a timeframe [18, 19].

Availability

EN-13306 (2010) defines availability as "*ability to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided*" [4]. It can be further defined as the total time a resource or system is functional over the planned duration of production without considering the downtime [20].

2.3.2 Maintenance Strategies

Divergence of maintenance strategies have emerged over a period of time. Some industries are still following "fail and repair" strategy whereas some have adapted advanced strategy like predictive maintenance. The three main maintenance strategies are specified as corrective maintenance, preventive maintenance and predictive maintenance. Figure 3 shows an overview of the types of maintenance and their hierarchy.

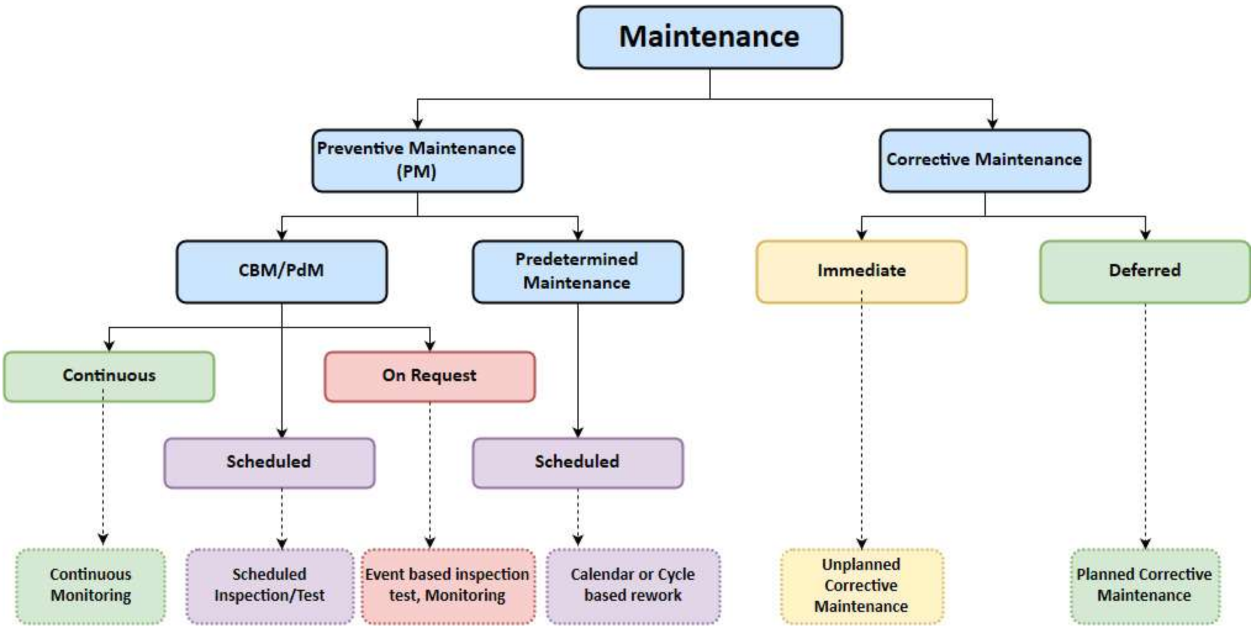


Figure 3: Maintenance Strategies overview (Adapted from [4])

Corrective Maintenance

The approach here is apply the solution when there occurs a problem. Hysterical maintenance [28], breakdown maintenance [29], run-to-failure (RTF) [30] etc. are the terms used to refer corrective maintenance. Corrective maintenance strategy is a set of tasks performed when an equipment or machine is identified to be not performing as per the intended functionality. Tasks includes identifying the problem, rectify it and restore the device to an operational state. As per the available data from industry, corrective maintenance is the approach being followed more than 55 percent by the maintenance departments in comparison to other maintenance approaches.

Preventive Maintenance

Performing maintenance activity on regular intervals or periodically to keep the equipment or machine in a stable state. Like corrective maintenance, this kind of strategy does not wait for the equipment to go into an unstable state and then applying maintenance activities. Preventive maintenance (PM) is the set of tasks executed before an equipment invade in a failed state [31, 32]. The philosophy behind PM is “Repair it before it breaks”.

PM activities are performed under the hypothesis that the equipment will deteriorate and go into a failed state. This type of strategy minimizes the probability of machine downtime with the cost of maintenance.

Predictive Maintenance

Predictive maintenance (PdM) works on the philosophy "Monitor, learn, predict and repair". Before attaining the eventual state of breakdown, equipment or machines show signs of imminent failures if pertinent actions are not performed timely. Inconsistent temperature, vibration, noise etc. can be the signs that the machine needs maintenance. Several techniques which exists within the industry today [33] can cater prior indications of the equipment degradation and becomes the base for the PdM.

PdM not only allows to achieve "Perform maintenance tasks, only when required" but also benefit by executing maintenance tasks not in conflict with the production schedules. This kind of approach directly or indirectly also benefit from the perspective of cost savings, increase in the profit and higher machine availability for production.

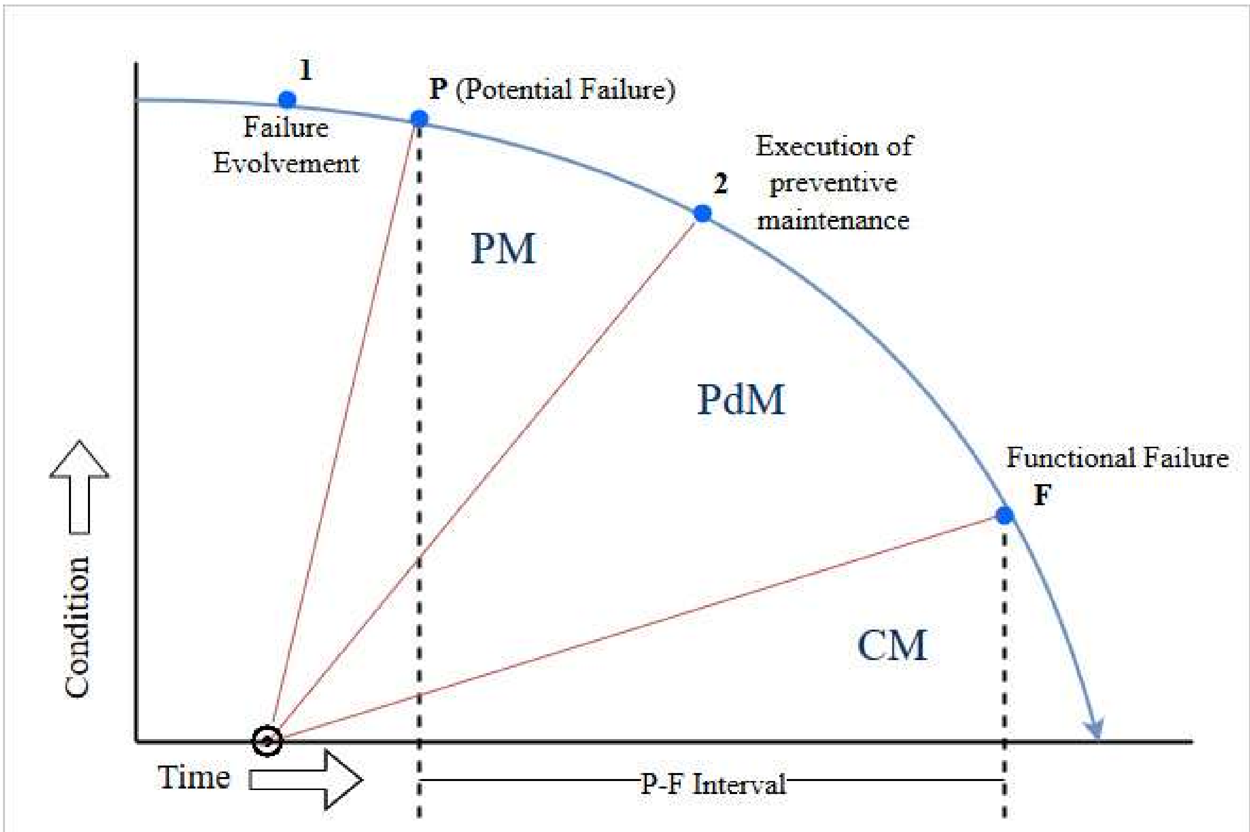


Figure 3: P-F Curve of maintenance

Figure 3 describes the maintenance strategies that are carried out over the time. At point 1 the failure begins to evolve, and it is not necessarily depicting the machine age. Preventive maintenance (PM) tasks are performed at an arbitrary point 2 where the machine has the probability of survival. Predictive maintenance (PdM) is executed to save the machine from swift transition to point "F". At point "F", the machine is in the state of failure and corrective maintenance tasks are implemented to recover the machine to a stable and production ready state.

2.4 Reference Architecture to enable PdM and CM

Platfform Industrie 4.0 defines the reference architectural model for Industry 4.0 (RAMI 4.0) [34] as a three-dimensional map and service-oriented architecture [35]. The three-axis architecture is a combination of elements, layered IT components and life cycle model which can be visualized from figure 4 and are further described below.

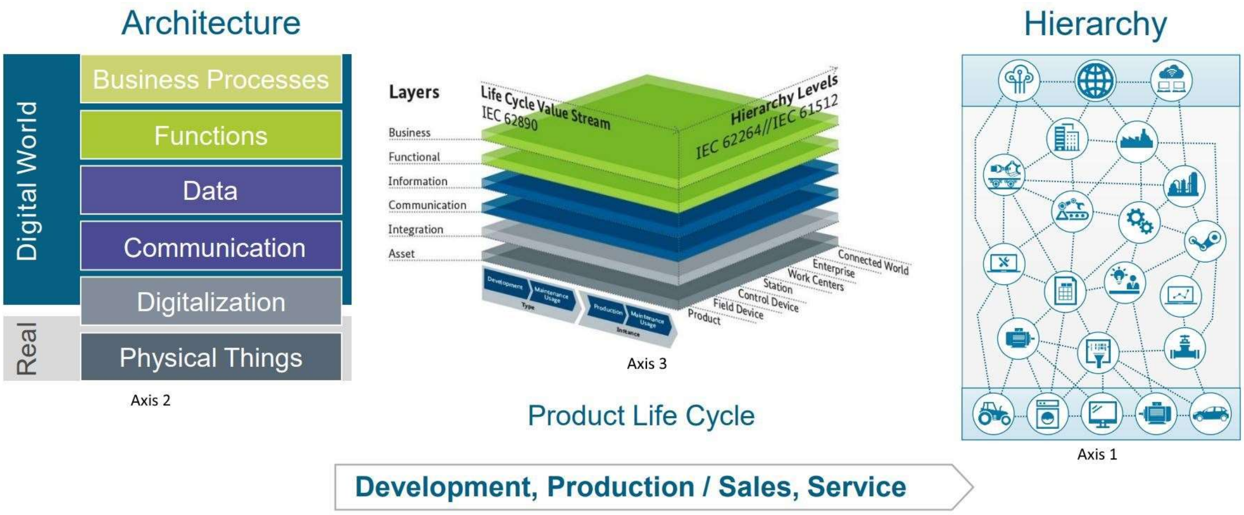


Figure 4: RAMI 4.0 – The Reference Architectural Model for Industry 4.0 [34, 35]

Axis 1 – Hierarchy Levels

Factory hierarchy forms the Axis 1 of RAMI 4.0 which consists of smart machines and flexible systems. Hierarchy levels combines different participants, allows interaction and communication between them. The different levels of Axis 1 include field devices, machines, control devices etc. Effective interaction and communication establishes the concept of connected world, smart products and smart factories.

Axis 2 – Architectural Layers

From physical assets to the business processes there are 6 components which fills in the architecture layers, which are defined below.

1. **Asset Layer** – Characterizes physical things on the factory floor and connects to the IT world through integration layer.

2. **Integration Layer** – Transition from physical to the digital world. This layer empowers the flow of gathered data from physical things to information layer via communication layer.
3. **Communication Layer** – This layer validates standardized communication between layer 2 and 4. Furthermore, service provision to control integration layer takes place at this layer.
4. **Information Layer** – Data received from integration layer is further processed and consistently integrated. Structured data is then exposed via a service interface for the functional layer. This layer also takes care of the data integrity.
5. **Functional Layer** – Formally defines functions of assets within the production system and supports business processes. This layer also facilitates remote access and horizontal integration. Temporary access of asset and integration layer takes place from functional layer for the purpose of maintenance.
6. **Business Layer** – The organization, business process and models, rules and policies are defined in business layer. Tasks of this layer also comprises orchestration of services of the functional layer.

Axis 3 – Life Cycle & Value Stream

This axis covers the entire life cycle of the products, equipment, machines etc. The life cycles are further categorized and fundamentally distincted as type and instance. In the type phase a product planning happens, and type is defined, prototyped, developed and goes through testing and validation. The output of type phase becomes the input for instance phase where the manufactured products are instances of the type phase and receives unique identification like serial number. What the customer receives is the instance of the product.

2.4.1 Communication Protocols

From the defined reference architecture of Industry 4.0 above it is easily realized that communication between the axis, layers and levels is very essential. Every component interacts and communicates within the ecosystem and there already exists industrial level communication standards and protocols. There are different protocols defined and used for different modules. Referring the axis 2 – architectural layers, OT (operation technology) side covers layer 1 to 4 and layer 5 to 6 is incorporated by IT (Information technology) side.

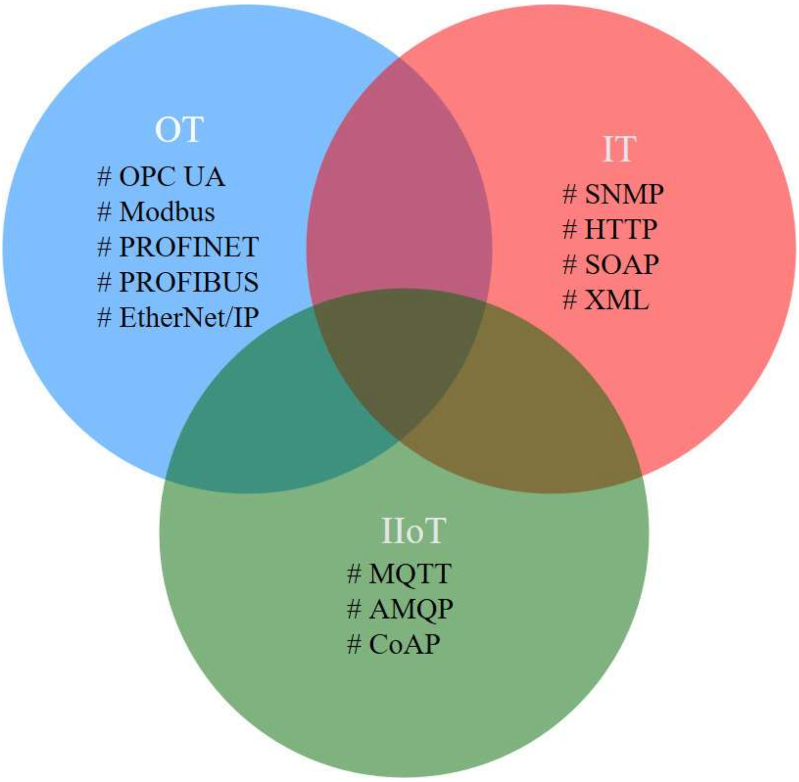


Figure 5: Communication protocols

For effective predictive maintenance and condition monitoring, the system which enables PdM and CM can interact or communicate through single or multiple protocols. In complex cases the interconnection between protocols is also significant.

2.4.2 Data and Control Flow

The data flow within different components and modules from asset to the cloud is very crucial. Data from sensors, actuators, PLC (Programmable logic controller) etc. plays a vital role for monitoring, maintenance and analytics. Predictive maintenance and condition monitoring systems exits in all the tiers to provide support for effective production run. Figure 6, provides a graphical overview of data flow and analysis and control flow.

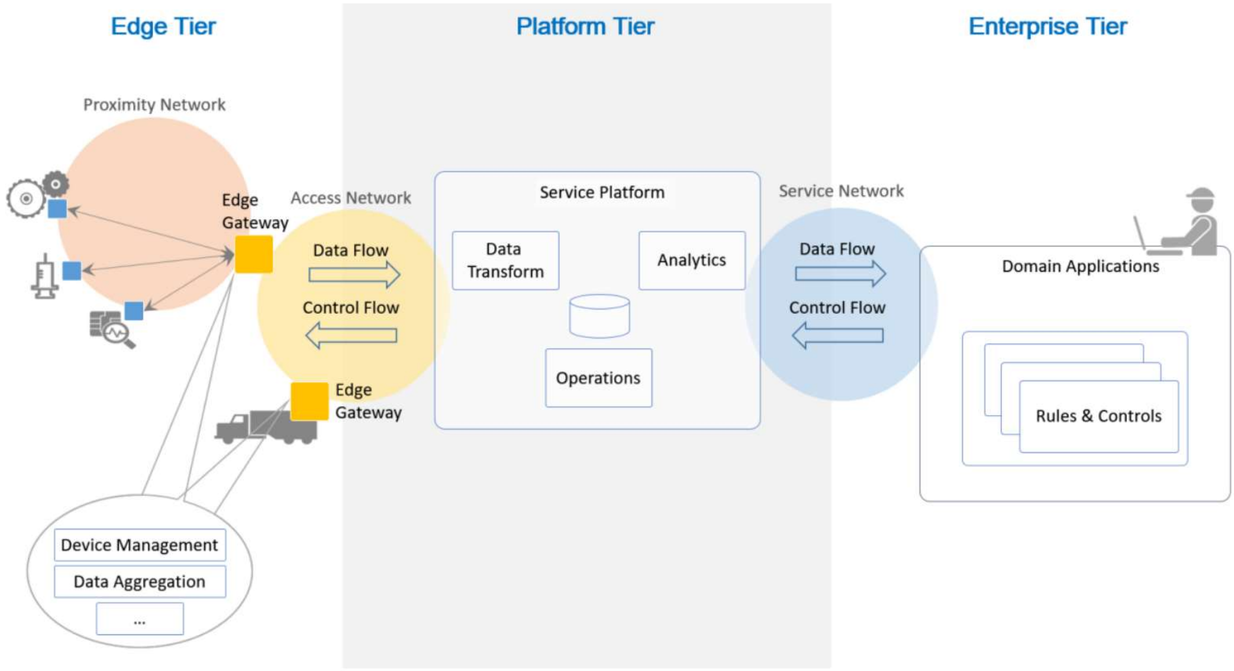


Figure 6: IIoT Data and control flow (Image: [36])

Edge Tier

Within edge tier, data is sent to edge gateways where data is aggregated from different machines and sent over to the next layers for further processing. Edge gateways also stores the subset of data persistently for the purpose of device management. Machines registers via PLC to gateways so that the data coming from them is identified, streamed and control events can be sent to them directly.

Platform Tier

Platform tier is composed of several services for data manipulation, analysis and operational processes. Each service is defined to have specific roles and functions. Data transformation service filters and unifies the data format, data is further stored in the persistent datastore and used by other services within/outside the tier. Processed data stream and historical data from the datastore are analyzed by the analysis service to cater condition monitoring and predictive maintenance activities. This tier also receives the control events from enterprise services, process them and forwards to the edge tier.

Enterprise Tier

Implements and defines domain specific rules, policies and functions. Enterprise tier also enacts decision support systems, different applications and provides different interfaces for the external applications and operations. This tier receives the data from other tiers for different services and applications within/outside the scope of the tier. Based on the defined functions, operations and support systems it generates control events for other tiers.

2.4.3 Data Analysis and Visualization

Raw or processed data becomes the base for PdM and CM systems. Depending upon the production and business use case data can be analyzed at any layer of the RAMI 4.0. On the lower level smart machines monitor their condition, generates control events for themselves and alerts to the upper layers if there is any maintenance required. HMIs on machines enables the visualization of ongoing process and condition monitoring.

On the information and functional layers (RAMI 4.0 architectural layers), system implemented for condition monitoring (section 2.2) access the live stream of data and analyze them with the help of predefined functions, rules and policies to identify any issues. On the other hand, PdM system access the historical machine data regularly and analyze them to identify if there is any maintenance activity required. PdM system can also access the live stream of data in combination with historical data for competitive and complex analysis. The information and events output from such systems are then used by internal visualization applications. Events are also triggered to the integration and asset layers for process changes or problem resolutions.

With the era of Industry 4.0 and evolvement of remote monitoring and maintenance strategies [37], the data is also accessed by external applications outside from organization for PdM and CM remotely or in cloud.

3 Security and Safety for PdM and CM

This section gives a background information of security and safety mechanisms at the different component levels for predictive maintenance and condition monitoring in the context of Industry 4.0 ecosystem.

3.1 Overview

Ensuring correct and eminent security and safety mechanisms integrated with predictive maintenance and condition monitoring are crucial for industries. For Industry 4.0, Security and safety being always given a top priority by the researchers and organizations. Security and safety required at the different component and data flow level. Industrie 4.0 Security Guidelines [38] recommends security and safety as the imperative aspects for the implementation of Industry 4.0 solutions. Guidelines also specifies that security and safety mechanisms should be taken in consideration from the beginning of the complete production development lifecycle. PdM and CM strategy needs access to the data and information available at different component levels and at different spaces. Information access is available only when a successful connection is established with the industrial network and communication layer as well to the data storage. The four phases of the product lifecycle, levels of applications and implementation responsibilities for the security and safety, defined by Industrie 4.0 Security Guidelines [38] are shown below.

Figure 7: Product lifecycle phases where security and safety mechanisms to be integrated (Image: [38])

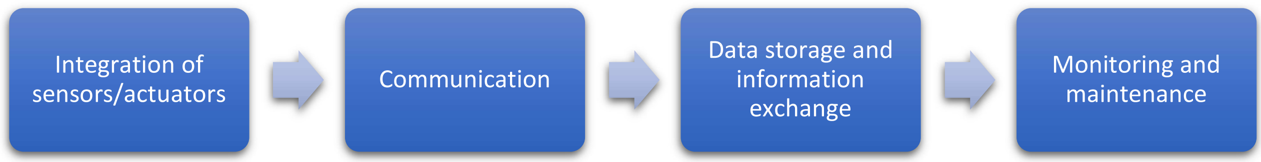


Figure 8: Application levels for security and safety (Adapted from [38])

Figure 9: Security and safety implementation responsibilities for groups (Adapted from [38])

3.2 Risk Analysis

In the complete product lifecycle phase, risk analysis is an integral part for the components involved to achieve effective PdM and CM with integrated security and safety. Risk analysis is the initialization of security assessment process. The subprocesses of the risk analysis, which are described below, need to be considered for all the components involved for maintenance and monitoring from the development phase to the operation phase.

Figure 10: Risk analysis steps

3.2.1 Component Identification

Identification of the components involved for the maintenance and monitoring lifecycle which needs protection becomes the first subprocess of the risk analysis process. Components can range from physical assets like sensors/actuators, hardware to the virtual components like network, communication protocols, datastore, applications, services etc.

Referencing the RAMI 4.0 architecture, risk analysis need to be done for components and modules at different levels and layers as this component are integral part of the PdM and CM strategy. Furthermore, applications and services outside of the factory and helps to achieve remote monitoring and maintenance need to be considered within risk analysis process.

3.2.2 Security and Safety Objectives Determination

Security and safety objectives can be applied on the components identified from risk analysis phase. Components which need high level of security and safety are considered as high value and objectives are defined for these components. For example, the edge gateway from figure 6 (section 2.4.2) is very critical because all the data and control flow to the actual physical assets go through this component. Unavailability or breach of such critical component can adverse the goals of PdM and CM. For the dataset generated from machine, objective can be integrity, availability etc. of the dataset.

3.2.3 Threat Identification

Threat analysis is the next step to examine the possible threats that can be associated with components which are identified from previous steps. The result of threat analysis delivers understanding of the threats that have the probability of occurrence during the life cycle of PdM and CM. Threat analysis also provides the prospect to map the solutions or actions to possible threats in advance. A distributed denial-of-service can be the possible threat for components like network and services and the possible solution mapping can be the integration of rule-based firewall.

3.2.4 Risk Assessment

Results from the threat analysis step becomes an input for the risk assessment step. Risk assessment measures the dimension and probability of a threat which can affect the operation. Risk assessment is done on a predefined model, which describes the presumed competences of a potential attacker and the attack method.

3.3 Network Security

Industry 4.0 defines the approach of segmented networking as the optimal implementation to enable highly secure and safe industrial networks. The network can be segmented at multiple levels, on the top level it can be visualized as segmentation of OT (operation technology) and IT (information technology) networks. OT network consists of all the assets on the production floor and IT network consists of applications, services.

From figure 11, a network segmentation strategy with three different defined zones can be visualized. Manufacturing zone consists of all the physical assets on the production floor such as machines, sensors/actuators, HMIs etc., which is further subdivided into OT (Levels 0-2) and IT (Level 3) segments. Demilitarized zone and enterprise zone consists of all the applications and services required for the business process and functionality.

The idea behind segmentation approach is to ensure minimum impact on other segments when a single segment is security breached. All the components which are required to work together and adheres to the same safety and security policies are kept in one zone, where each or multiple zones reflects a network segmentation. The separation of segments is done technically by firewalls etc. to keep each of the segments isolated from other segments. Anomalies related to network communication can be monitored and detected by the utilization of rules within the firewalls.

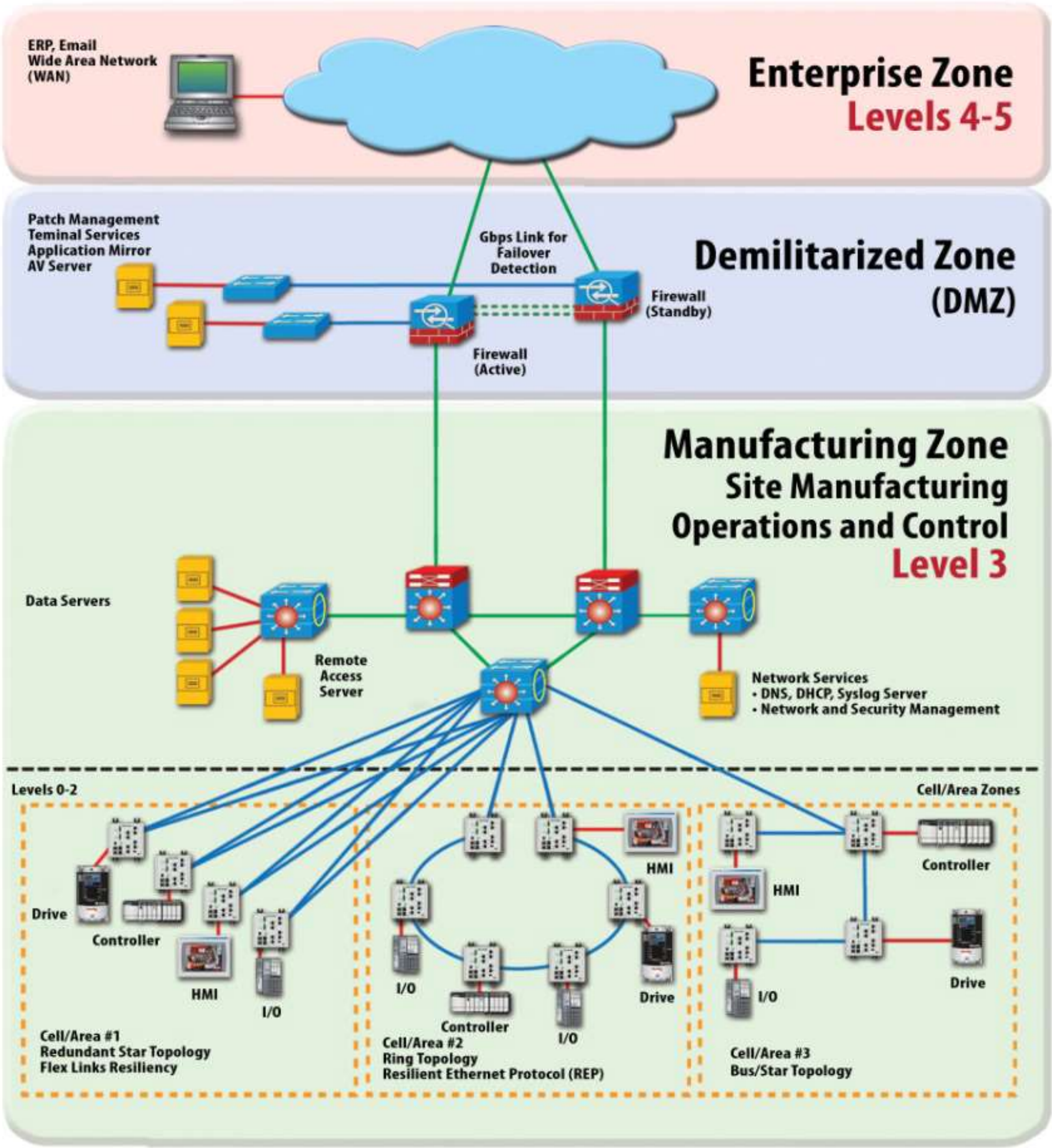


Figure 11: Network segmentation strategy (Image: [39])

3.4 Data Storage

Real time data and historical data are the base for predictive maintenance and condition monitoring. Data integrity, availability, consistency and accuracy is of utmost importance, which needs data security and safety mechanisms in place. Data need to be made available only to applications and services authorized to use the data and it should need secure access with proper identification, authorization and authentication mechanism in place.

Data loss/leak prevention challenges need to be addressed and mechanisms should be in place to ensure data is secure and safe.

3.4.1 Data Access Prevention

Machine parameters in the form of data are required for the PdM and CM. Data flow from machine to the PdM and CM engines and vice versa need to be monitored. Unauthorized data access can only be possible with accurately defined interfaces to access the data. Different interfaces for different group of applications and services need to be defined so that only required data is provided from each of the interface. For example, a single data interface serves only the data required for monitoring and another interface for the application which enables visualization of machine condition monitoring.

Industrial digitalization provided the possibility to visualize the actual ongoing and historical condition, process and activities of the production. Web applications with the access to factory data anytime anywhere enables interactive remote predictive maintenance and condition monitoring. But on the other hand, it is very critical that the application is only used by the entitled end user.

3.4.2 Data Manipulation Prevention

During the life cycle of production, many applications and services access the data from datastore and writes back the processed data. Data need to be categorized as which data is allowed to be manipulated and which data is read only. As PdM and CM engines require read only data, the interface defined to cater the same should have access to the required information only. A different interface is also required to store the output from PdM and CM engines.

The data should be exchanged securely using encryption methods on the network and communication layer between applications, services and interfaces to provide the capabilities for ensuring data safety.

3.5 Security Breach Detection

"Early detection, less loss". Many organizations today invest in the technologies or solutions to detect security breach at early stage. Intruders or attackers mostly tend to find the system vulnerabilities over the time when they get access to some part of the system. Security breach detection methods enormously provides the capability to keep majority of the system safe from the attacks. Furthermore, learning curve from detection logs allows to achieve more complexed safety and security measures on the weaker sections of the system.

There are many techniques and methods which can be integrated within the ecosystem to detect security break at early stages. Journal on topic "A survey of intrusion detection techniques in Cloud" [40] summarizes various IDS (Intrusion detection systems) and IPS (Intrusion prevention systems) with their advantages and disadvantages (figure 12).

IDS/IPS technique	Characteristics/advantages	Limitations/challenges
Signature based detection	• Identifies intrusion by matching captured patterns with preconfigured knowledge base. • High detection accuracy for previously known attacks. • Low computational cost.	• Cannot detect new or variant of known attacks. • High false alarm rate for unknown attacks.
Anomaly detection	• Uses statistical test on collected behavior to identify intrusion. • Can lower the false alarm rate for unknown attacks.	• More time is required to identify attacks. • Detection accuracy is based on amount of collected behavior or features.
ANN based IDS	• Classifies unstructured network packet efficiently. • Multiple hidden layers in ANN increase efficiency of classification.	• Requires more time and more samples training phase. • Has lesser flexibility.
Fuzzy Logic based IDS	• Used for quantitative features. • Provides better flexibility to some uncertain problems.	• Detection accuracy is lower than ANN.
Association rules based IDS	• Used to detect known attack signature or relevant attacks in misuse detection.	• It cannot detect totally unknown attacks. • It requires more number of database scans to generate rules. • Used only for misuse detection.
SVM based IDS	• It can correctly classify intrusions, if limited sample data are given. • Can handle massive number of features.	• It can classify only discrete features. So, preprocessing of those features is required.
GA based IDS	• It is used to select best features for detection. • Has better efficiency.	• It is complex method. • Used in specific manner rather than general.
Hybrid techniques	• It is an efficient approach to classify rules accurately.	• Computational cost is high.

Figure 12: Summary of IDS/IPS techniques [40]

4 Research Approach (Research Protocol)

This section is an introduction to the objective and approach of this case study. First, the purpose of research and research questions are briefed. Further subsections include an introduction to the research methodology and data collection approach.

4.1 Research Objective

The departments of GPS GmbH and J. Schmalz GmbH are working together on Digitalization projects to establish a connection and decrease gaps between physical and software components. There are different maintenance and monitoring methods of the physical components. Predictive maintenance via condition monitoring being the identified identical method for the cyber-physical systems with tightly coupled security as well as safety norms requires scientifically established knowledge.

The objective of this case study is to determine that what benefits can PdM and CM bring, how to get useful information from industrial components to integrate PdM and CM with coupled security and safety, what benefits can such a system bring, what are the challenges to build such a system and how to improve them.

4.2 Research Questions

As of now there has been a limited research been done on the integration of PdM and CM considering security and safety within the existing industries to enable them to digitalize. Industry 4.0 (I4O) [9] brings in the concept of Cyber-Physical Systems (CPS) [10]. CPS brings in the capability to enable the components within the Industry to communicate information they possess for PdM and CM. Open standards for communication includes protocols like OPC UA, Powerlink etc. Safety is the most important aspect for I4O and requires integrated safety standards like openSafety.

RQ1: How PdM and CM are integrated with cyber-physical systems?

RQ2: What kinds of benefits can CM and PdM bring?

RQ3: What are the security and safety analysis aspects of the ecosystem concerning PdM and CM?

RQ4: What are the challenges and how to improve them?

4.3 Research Methodology

The report of this thesis is a 7 months case study (September 2017 – March 2018). For this case study, different projects with their associated distinct processes and activities are evaluated. As each of the project has a unique role to develop a complete solution for the next generation monitoring and maintenance. Therefore, each of this project becomes a unit of analysis. For such setups, the most appropriate case study design is of type embedded. Predictive maintenance and condition monitoring with integrated security and safety mechanisms becomes the case for this case study. Set of units of analysis is formed for the mentioned case. Below figure presents the structure of case for the case study.

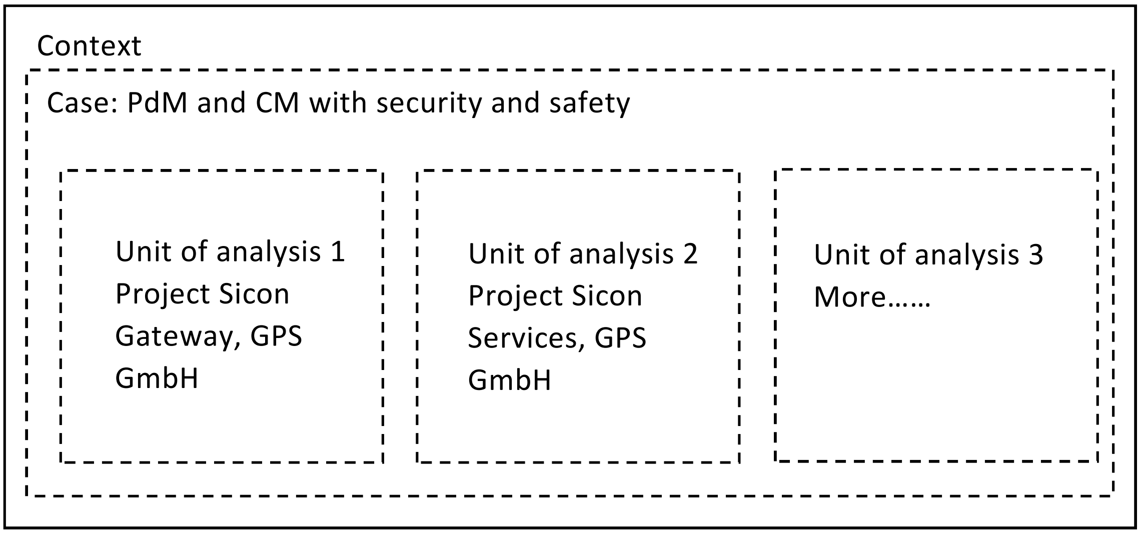


Figure 13: Structure of case for the case study

Various projects within GPS GmbH and J. Schmalz GmbH forms numerous units of analysis. Project Sicon Gateway is implementing a hardware solution for industries with the aim to reduce the gap between OT (Operational Technology) and IT (Information Technology) side of the organization. From the reference architecture (section 2.4) of this report, it is evident that there are different types of communication protocols used within the industries on the OT as well as IT side and there is high requirement for a solution which can connect both the sides effectively and securely. “Plug and Play” is the motivation behind Project Sicon Gateway.

Project Sicon Services is a set of services running on Sicon Gateway, which enables data collection from OT side, filtering, integration etc. Multiple services form the ecosystem for achieving predictive maintenance and condition monitoring with embedded safety and security mechanisms. Combination of gateway and services facilitates:

- Identification of machine, equipment and devices on the factory floor;
- Identification of communication protocol and connection with the equipment;
- Collection of data from equipment, data filtering, unification and integration;
- Data storage and manipulation;
- Algorithms for maintenance and monitoring activities;

Table 1: Units of analysis - Projects

Project / Organization Name	**Team Size**	**Tasks / Developed Product**	**Reason of Selection**
Project Sicon Gateway, GPS GmbH	About 10	Development of Industrial plug and play gateway	Effective data aggregation from industrial components
Project Sicon Services, GPS GmbH	About 10	Apps and services for management, monitoring and maintenance	Research platform for this thesis
Digitalization Department, J. Schmalz GmbH	About 5	Development of integrated smart solutions for existing and new Vacuum devices (Vacuum Technology)	Working closely with condition monitoring and Predictive maintenance

4.3.1 Research Strategy: Exploratory

Many research projects and solutions established the theory around different mechanisms for maintenance and monitoring. Different industries have deployed the mechanisms over the time based upon the individual requirement. Safety and security concepts have been always researched and thought around the complete ecosystem of CPS and Industry 4.0, but there had been a very limited or almost negligible research specifically for safety and security for predictive maintenance and condition monitoring. This case study initiates with the questions covering the current trend of maintenance and monitoring strategies being employed within the industries as a prelude. Later, the benefits of predictive maintenance and condition monitoring embedded with CPS and the safety and security aspects of the same are explored. Hypotheses and opinions would be the base for further optimization and research. There exist different research strategies and for this case study, *Exploratory* research strategy is relevant and hence practiced. Exploratory research strategy permits *"finding out what is happening, seeking new insights, and generating ideas and hypotheses for new research"* [41].

4.3.2 Research Design: Flexible

In a fixed design procedure all the parameters of the study are defined before the study initiates and these parameters do not change when the study is in progress. This thesis as the case study of type flexible because the parameters need to be adjusted during the course of the study.

4.3.3 Research Category: Inductive Enquiries

The adapted research strategy for this case study is of type Exploratory and observations is the initial stage in this process. Therefore, this case study is an *Inductive* research where *"the researcher first observes with an open mind, identifies patterns in the observations, sets up tentative hypotheses, and finally relates them to existing theory or develops new theory"* [41].

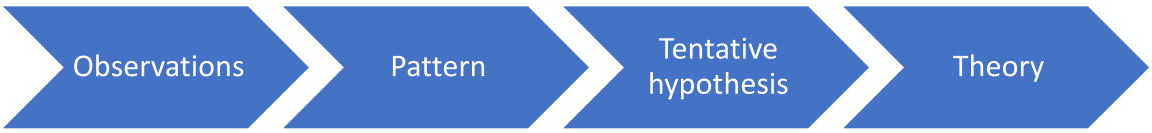


Figure 14: Inductive approach (adapted from [41])

4.3.4 Triangulation

Triangulation empowers to obtain numerous perspectives on the subject of study and extensive picture of the subject can be catered. With triangulation, precision of the case study has been extended as well as the credibility and validity of the case study has been strengthened. Denzin (1978) [42] identified and defined four different types of triangulation:

- Data (Source) Triangulation: Use of multiple data sources or collection of same data over different time and scenario.
- Observer or Investigator Triangulation: Multiple researchers for the same case study.
- Methodological Triangulation: Combination of different methods of data collection like interviews, group discussions, observations, questionnaires, and documents etc.
- Theory Triangulation: Use of multiple theoretical approach or viewpoints to explain and support data.

This case study practices Data (Source) Triangulation, Methodological Triangulation and Theory Triangulation for the research. For Data (Source) Triangulation group discussions and documents are included. Qualitative and quantitative methods are used for Methodological Triangulation. In theory triangulation, for alternative theory, different strategies of maintenance and monitoring are detailed and compared.

4.3.5 Replication

There are different types of replication for quantitative and qualitative case studies. Sampling logic is used for quantitative replication in which “an experiment is replicated with new subjects or artifacts, assuming the subjects and artifacts are sampled from a population” [41].

For qualitative replication, literal and theoretical replication methods are used. Literal replication is “selection of a replication case aimed at finding similar results, confirming earlier findings” [41]. Whereas theoretical replication is “aimed at finding contrasting results for predictable reasons” [41].

As this case study includes units of analysis which aims or implements predictive maintenance and condition monitoring, here the type of replication is literal because the replication cases are aligning towards finding similar results and confirming earlier findings.

Furthermore, there involves other maintenance and monitoring strategies in units of analysis and questionnaires are also part of this case study. Therefore, this case study is also theoretically replicated as well as quantitatively replicated in view of questionnaires.

4.4 Research Approach for Data Collection

The three different degrees of data collection defined by Lethbridge et al. [43] are:

- First Degree: Direct methods like interviews, focus group discussions (FGD) and questionnaire surveys.
- Second Degree: Indirect methods where the researcher records data from group discussions without focused interaction.
- Third Degree: Methods in which analysis of already available data or artifacts are analyzed.

In this case study, both the direct and indirect data collection methods are used. In direct collection methods first degree focus group discussions (FGD) and questionnaire surveys are used. Furthermore, for the indirect method, project group discussions are used. All the three different degrees of data collection have been executed to collect the data.

Data in this case study is the combination of quantitative and qualitative data. The data collected from the questionnaires and already available results from different surveys conducted by researchers and industries is quantitative data. Whereas, the data collected from focus and project group discussions as well as from the already available case studies becomes qualitative data.

Team members from the same department of the projects are part of the focus group discussions. Questions during the discussion were asked in a semi-structured way, in which the planned sequence of questions is not mandatorily followed. Semi-structured questions during FGD enhances the probability of better discussions and hence improvisation is achieved.

Time-glass model [41] is used in this case study to ask questions during focus group discussions (FGD). Time-glass model allows to combine both the open questions and specific questions during the course of the FGD.

Table 2: Summary of Research Approach

Research Strategy		Exploratory
Research Design		Flexible
Research Category		Inductive Research
Triangulation	Data Source	Focus and project group discussions and documents
	Methodological	Using qualitative (group discussions), quantitative (questionnaire) methods and documents
	Theory	-------------------
Replication		Literal, theoretical and sampling logic
Data Collection	Methods	Direct (Focus group discussions and questionnaire), Indirect (Project Reports) and independent (Documentation analysis)
	Data type	Qualitative and quantitative
	Type of questions	Open (Focus group discussions) / Closed (Questionnaire)
	Key parameters design	Flexible
	Way to conduct FGD	Semi-Structured
	Model to ask questions in FGD	Time-glass model
	Way to arrange FGD	Physical and video conference

5 Data Analysis Methods

After the phase of data collection, the next step is data analysis. This section details the different methods used for data analysis of quantitative and qualitative data. First the analysis strategy is briefed, and further subsection include techniques and concludes with tool support for the data analysis.

5.1 Data Analysis Strategy

Output of the data collection step becomes the input of data analysis step. There are different methods for different types of collected data. For the collected quantitative data, the questionnaire results are coded and presented in the form of table, charts and further findings are derived from the tables and charts. Moreover, for the collected qualitative data the process of analysis is entirely different and complexity level of analysis can increase or decrease based upon the available data.

The objective of data analysis is to establish generalization from the collected data regarding patterns, sequences, relationships etc. Generalization is achieved summarizing, coding, categorizing and commenting the data [41]. The data analysis strategy is an iterative process and the process can be visualized from the figure 15.

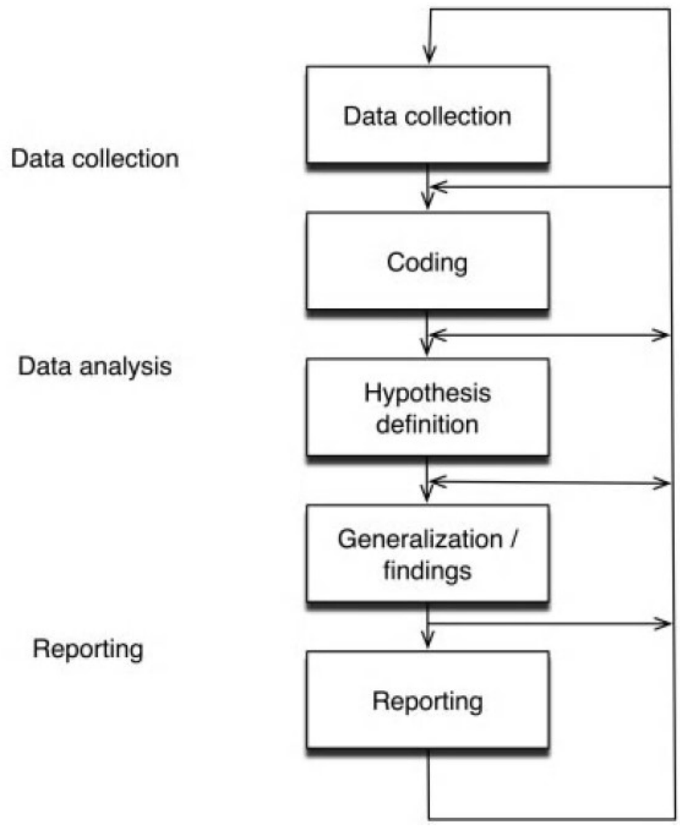


Figure 15: Maine steps and iterative process of data analysis [41]

5.1.1 Quantitative Data Analysis Strategy

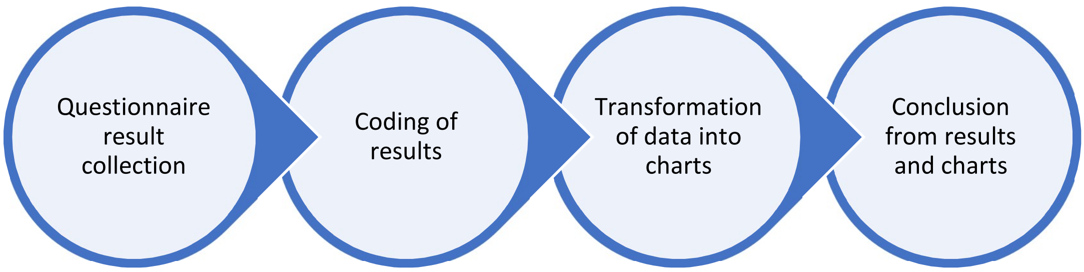


Figure 16: Quantitative data analysis steps

Questionnaire survey result collection

The inputs from all the participants of the questionnaire survey have been collected for every question from the Table 3 (Section 6.1) of this report. Online tool “kwiksurveys” [48] has been used to collect the response from participants. Participant has been presented with two different set of questions based upon the answer to the question “Does your organization have predictive maintenance and condition monitoring strategy in place?”.

Coding of results

First the data have been imported into spreadsheets for every questionnaire question, where the column heading represent the question and rows represent the input from survey participants. The data in the spreadsheet is further coded for the purpose of chart generation, analysis and generating conclusions.

Different types of charts are used like pie chart, bar chart etc. to present easily understandable visualization of data analysis. There are two types of participants, first type consisted of participants whose organization has predictive maintenance strategy as a part of the maintenance plan, second type consisted of participants whose organization has different maintenance strategy in place.

Transformation of data into charts

After the transformation of raw results in the tabular form and coded, the well formatted data from tables is used to generate different charts.

Conclusion from results and charts

Findings have been derived from the final transformed tabular data and charts. Findings are based on the two types of participants and further generalization is made.

5.1.2 Qualitative Data Analysis Strategy

In this case study, the researcher has conducted focus group discussions for the qualitative data collection. Further, archival data like project reports, analysis results and existing hypothesis from industries have been studied. Initially the codes for analysis have been defined and data collection process has been carried out based upon the codes. As the new insights has been found during the analysis process, the data collection process has been triggered again and new codes have been defined. This kind of approach is an iterative process [44] and is defined as grounded theory analysis [45] for qualitative data analysis. Kasurinen et al. [46] has defined the steps for grounded theory analysis and they are as following:

- Open Coding: From collected data, the categories and codes are generated.
- Axial Coding: Generated categories and codes are associated.
- Selective Coding: Identification of core category and description.

Based upon the iterative approach and steps of the grounded theory analysis, the qualitative data analysis process is defined as following:

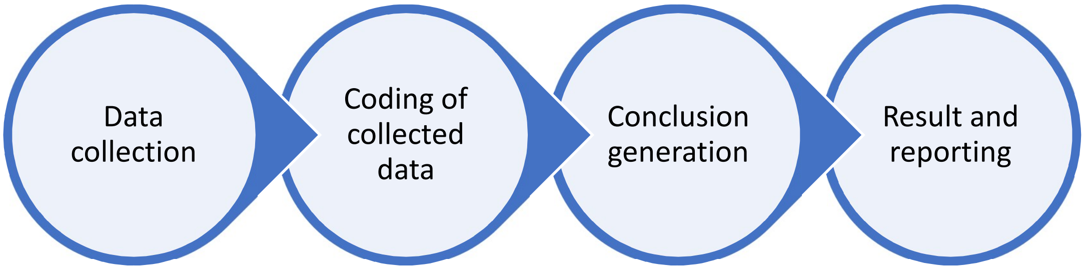


Figure 17: Qualitative data analysis steps

Data collection

Numerous sources for data has been considered by the researcher. Focus group discussions data has been recorded into notes, which is further transformed into a textual transcript. Archival data is also collected during the data collection process and as the per the requirement triggered from the iterative process.

Coding of collected data

Initially a set of codes has been defined and mapped to the collected data. Further the set of codes has been modified by defining new codes or removing defined codes on the basis of the collected data.

In the next step of coding, the text from the FGD and archival data or reports have been clustered together based upon the categories and codes for the analysis purpose.

Conclusion generation

In this phase of the qualitative analysis, hypothesis generation has been completed through continual assessments and comparison with the results of quantitative data analysis. Additionally, hypothesis confirmation has been accomplished from triangulation and replication as detailed in sections 4.3.4 and 4.3.5 respectively.

Result and reporting

The result of this case study is analysis report of findings and comparison with the results of the quantitative data analysis results.

5.2 Data Analysis Techniques

Different techniques have been used in this case study for the quantitative and qualitative data analysis.

5.2.1 Quantitative Data Analysis Techniques

Statistical Analysis

Calculations of the sum of the responses in numbers and percentage for available inputs of the questionnaire questions. Standard deviation and weighted average is also calculated based upon the question type. Univariate analysis has been achieved through the calculation of frequency distribution.

Comparison – Data from two participant types

As there are two participant types, defined in Section 6.2.1 (Table 5 – Type of participants), Comparison on the collected data from both the participant types has been done for similar or shared questions.

Multivariate Analysis

For this case study, there are questions types where the results can be compared with the result of another question, i.e. multiple variable can be analyzed together to get an outcome. Multivariate analysis technique/s have been applied for the quantitative data analysis.

5.2.2 Qualitative Data Analysis Techniques

As this case study includes focus group discussions and several other resources for the qualitative data analysis therefore there are various qualitative data analysis techniques have been used.

Content Analysis

This is the technique in which certain words or content from the collected data from different sources is coded and then the patterns are identified and concludes with interpretation.

Thematic Analysis

The collected data from different sources is first grouped into themes to answer the research questions. The theme can be preset before the data collection phase and based upon the research questions. Furthermore, a theme can emerge during the progression of the case study. A theme is basically a combination of codes which have been predefined or arise during any phase of the case study.

Logic Models

This is one of the analysis technique defined by Yin [47] where complex cause-effect relationships are analyzed. Theoretical predictions of the similar or related theme is compared with the practical observations.

5.3 Data Analysis – Tool Support

5.3.1 Quantitative Data Analysis – Tool Support

Online survey tool, "Kwiksurveys" [48] provided the platform for the questionnaire survey. The tool was supportive in terms of the type of questions required like multiple choice, matrix etc. Furthermore, it also provided the ability to skip the questions or navigate the participant to specific question based upon the previous answer. Further processing of the raw data has been done in excel.

5.3.2 Qualitative Data Analysis – Tool Support

In this case study, for the qualitative data analysis QDA Miner Lite [49] tool is used. QDA Miner Lite is a free version of the QDA Miner tool from company Provalis Research. QDA Miner Lite aided to organize the collected data from focus group discussions and several other archival data sources. Later, the data has been coded and analyzed with the same tool.

6 Case Study

This section is an introduction to the objective and approach of this case study. First, the purpose of research and research questions are briefed. Further subsections include an introduction to the research methodology and data collection approach.

6.1 Case Study Design

This case study is executed to collect quantitative and qualitative data. Quantitative data is collected from the questionnaire survey. The questionnaire survey is based upon the four research questions mentioned in Section 4.2 Research questions. All the four research questions are further divided into sub-questions respectively. Qualitative data is collected from the FGD's (Focus group discussions). Each FGD corresponds to one unit of analysis from the Table 1. All the research questions from questionnaire survey and FGD's are assigned with a code for the analysis purpose.

Table 3: Case Study Questions – Questionnaire Survey

Research / General Question	Survey Questions	Assigned Code
Information about participant	1. Does your organization have predictive maintenance and condition monitoring strategy in place?	About participant
Maintenance and monitoring strategies	2. Which condition-based monitoring methods are currently being applied in your organization?	Maintenance Strategy
Maintenance and monitoring strategies	20. Which maintenance strategies are currently being in use in your organization?	Monitoring Strategy
RQ1: How PdM and CM are integrated with cyber-physical systems?	3. On which tiers of the CPS ecosystem, PdM and CM systems are in place in your organization?	CPS Ecosystem

	4. Does your organization allows remote maintenance?	E-maintenance
	5. Does your organization allows remote monitoring?	E-monitoring
RQ2: What kinds of benefits can PdM and CM bring?	6. How do you rate effect of CM on equipment in your organization? In terms of: Machine availability and reliability, profitability	Effect of CM
	7. How do you rate effect of PdM on equipment in your organization? In terms of: Machine availability and reliability, profitability	Effect of PdM
	8. Any other maintenance strategy in place with PdM?	Maintenance Strategy
RQ3: What are the security and safety analysis aspects of the ecosystem concerning PdM and CM?	9. Who is provider of PdM and CM systems for your organization? Internal systems, third party systems	PdM and CM system provider
	10. Who manages the PdM and CM systems for your organization? Internal team, outsourced	PdM and CM system manager
	11. Which components in your organization contributes for PdM and CM?	PdM and CM components
	12. Where do you store the generated data from machines for PdM and CM?	Data storage
	13. Which communication protocol/s are in use currently on the OT side?	Communication protocols

	14. Which communication protocol/s are in use currently on the IT side?	Communication protocols
	15. How does the PdM and CM systems access the data? From: Machines, PLCs, gateways, storage, cloud	Data access
	16. Does your organization have network segmentation policy in place? Between: OT, IT and IIoT networks	Network
	17. How critical is the security and safety for the components involved for PdM and CM? Network, communication, data, machines	Criticality of PdM and CM component's security and safety
	18. Which of the following security and safety mechanism/s are in place for the components involved for PdM and CM? In terms of: Risk assessment, security and safety objectives, threat identification, access management, breach detection	Security and safety mechanisms for components of PdM and CM
RQ4: What are the challenges and how to improve them?	19. Which of the following needs improvement or optimization in terms of PdM and CM? Security and safety mechanisms, PdM and CM systems improvement	Requires improvement

Additional Question if question 1 is answered "no"	21. What are the main reasons for not making Predictive maintenance as a part of your organizational maintenance plans? Eg. Cost, effectiveness, knowledge etc.	PdM hurdles
	22. Does your organization have any plans to adapt to the Predictive Maintenance strategy for maintenance?	Probability for implementation of PdM solution

Table 4: Case Study Questions – Focus Group Discussions

Research Question	**FGD Questions**	**Assigned Code**
RQ2: What kinds of benefits can PdM and CM bring?	1. How condition monitoring is beneficial?	Effect of CM
	2. How predictive maintenance is beneficial?	Effect of PM
	3. Do you have or in future planned other maintenance strategies?	Maintenance Strategy
RQ1: How PdM and CM are integrated with cyber-physical systems?	4. On which tiers of the CPS ecosystem, PdM and CM systems are currently in place?	CPS Ecosystem
	5. What about e-monitoring?	E-monitoring
	6. What about e-maintenance?	E-maintenance
RQ3: What are the security and safety analysis aspects of	7. Who manages the PdM and CM systems for the organization?	PdM and CM system manager

the ecosystem concerning PdM and CM?	8. Which components in the Industry contribute for PdM and CM?	PdM and CM components
	9. Where do you store the data generated and collected from machines?	Data storage
	10. Which communication protocol/s your system supports currently on the OT and IT side?	Communication protocols
	11. How does the PdM and CM systems access the data? From: machines, PLCs, gateways, storage, cloud	Data access
	12. How is the system connected to network?	Network
	13. How can external components connect to our system?	Network
	14. How critical is the security and safety for the components involved for PdM and CM? Network, communication, data, machines	Criticality of PdM and CM component's security and safety
	15. Which of the following security and safety mechanism/s are in place or planned for the components involved for PdM and CM?	Security and safety mechanisms for components of PdM and CM

	16. How are the services and applications running on gateway for PdM and CM are safe and secure?	Security and safety of PdM and CM system
RQ4: What are the challenges and how to improve them?	17. For the complete ecosystem of PdM and CM systems: 17.1 What are the current challenges? 17.2 What are the possible improvements and how we can bring them to the system?	Challenges and improvements for PdM and CM system
	18. For the safety and security of PdM and CM systems: 18.1. What are the current challenges? 18.2 What are the possible improvements and how we can bring them to the system?	Challenges and improvements for security and safety of PdM and CM system

6.2 Case Study Implementation

6.2.1 Questionnaire Survey

With the help of online tool “kwiksurveys”, a survey has been created. Survey consists of all the questions from the Table 3. The hyperlink to survey has been shared in different groups on websites like LinkedIn and Facebook. Also, the link has been shared with known personnel across different industries and countries. The type of participants and summary of the questionnaire survey is listed in the below Table 5 and Table 6 respectively.

Table 5: Type of Participants

Participant Type	Description
1	Participants from the organization where predictive maintenance strategy is the part of the organizational maintenance plan/s.
2	Participants from the organization where predictive maintenance strategy is not part of the organizational maintenance plans.

Table 6: Summary of Questionnaire Survey

Number of questions	22
Start date of questionnaire	14.12.2017
End date of questionnaire	15.02.2018
Total participants	28
Participants type 1	11
Participants type 2	17
Questionnaire published on or shared with	Social media websites and known personnel

6.2.2 Focus Group Discussion

A combined FGD (Focus Group Discussion) has been executed to discuss the questions mentioned in Table 4 for the units of analysis Project Sicon Gateway and Project Sicon Services. Total 6 participants have been part of the discussion. Each participant alone or together with other team members takes care of the different aspects of the ecosystem. Another FGD is further conducted to discuss the same questions with 3 participants from J. Schmalz GmbH. The summary of the FGDs is listed in the Table 6.

Table 7: Summary of Focus Group Discussion

Focus Group Discussion	Unit of Analysis	Total Participants	Conducted on
FGD 1.1	Project Sicon Gateway	6	15.02.2018
FGD 1.2	Project Sicon Services	6	15.02.2018
FGD 2	Digitalization Team	3	16.02.2018

6.3 Collected Data – Data coding

6.3.1 Coding Procedure for Questionnaire Survey Result

The questionnaire survey has been created for two participant types as described in Table 5, Type of Participants. As per the quantitative analysis strategy and techniques mentioned in Sections 5.1.1 and 5.2.1 respectively, the raw data has been coded. Participant type 2 is color coded as red.

There are different coding techniques followed in this case study for questionnaire data. The coding technique is based upon the type of question, available inputs for the user and the user input. Coding process is further described with each of the tables in this section. First the questions for participant type 1 are coded and then followed by type 2.

Table 8: Coding result for question 1 and 2 from Table 3, Case Study Questions – Questionnaire Survey

Participant	**1. Does your organization have predictive maintenance and condition monitoring strategy in place?**	**2. Which condition-based monitoring methods are currently being applied in your organization?**									
	Yes (1) or No (2)	A	B	C	D	E	F	G	H	I	J
1	1	-	-	-	-	1	-	1	-	1	-
2	2	-	-	1	-	-	1	-	-	1	-
3	1	-	-	1	1	-	1	-	1	1	1
4	1	-	-	-	-	-	-	-	-	1	-
5	2	-	-	-	-	-	-	-	-	-	1
6	1	1	-	-	-	-	1	-	-	1	-
7	2	-	-	-	-	-	1	-	-	-	-
8	2	-	-	1	-	-	1	-	-	-	-
9	1	1	-	-	-	1	1	-	-	1	1
10	1	-	-	1	-	-	1	-	-	1	-
11	2	-	-	-	-	-	1	-	-	-	1
12	2	-	-	-	-	-	1	-	-	-	1
13	1	-	-	1	-	-	-	-	-	1	1
14	1	-	-	-	-	-	-	-	-	1	1
15	1	1	-	-	-	-	-	-	-	-	-
16	2	-	-	-	-	-	1	-	-	-	-
17	2	-	-	-	-	-	-	-	-	-	1
18	2	-	-	-	-	-	-	-	-	-	-
19	2	-	-	-	-	-	-	-	-	-	1
20	2	1	1	1	1	-	1	1	1	1	1
21	1	1	-	-	-	-	1	-	-	-	1
22	2	-	-	-	-	-	-	-	-	-	1
23	2	-	-	-	-	-	1	-	-	-	1
24	2	-	-	1	-	-	1	-	-	-	1
25	2	-	-	-	-	-	-	-	-	-	1
26	2	-	-	-	-	-	-	-	-	-	1
27	2	-	-	-	-	-	1	-	-	-	-
28	1	-	-	-	-	-	-	-	-	1	1
Participant type 1 (Yes)	**11**	**4**	**0**	**3**	**1**	**2**	**5**	**1**	**1**	**9**	**6**
Participant type 2 (No)	**17**	**1**	**1**	**4**	**1**	**0**	**10**	**1**	**1**	**2**	**11**

For question 1 in the Table 8, the answers yes and no are coded as ”1” and “2” respectively. For question 2, the available inputs are given codes from letters A to J, where each letter corresponds to a single available input for the user. The letter to the available input mapping is listed in the below Table 9. For statistical analysis, every user input type is assigned a number and the sum of the participant types are calculated as well.

Table 9: Question – 2, Letter to available input mapping

A	Vibration analysis and diagnostics
B	Wear debris analysis
C	Noise monitoring
D	Lubricant analysis
E	Infrared thermography
F	Visual inspection
G	Acoustic based analysis
H	Oil analysis
I	Energy consumption monitoring
J	Other

Question 1 and 2 are generic questions for both participant type and based upon the answer to the Question 1, the next set of questions have been presented to the participant. If the answer to Question is “Yes” then the participant has answered set of questions ranging from Question 3 to Question 19. If the answer is “No” to Question 1 then the participant has been presented with only questions from Question 20 to Question 22. First the coding process for the questions of participant type 1 is described and are then followed by questions of participant type 2.

Table 10: Coding result for question 20 from Table 3, Case Study Questions – Questionnaire Survey

Participant	20. Which maintenance strategies are currently being in use in your organization?			
	Corrective Maintenance (run-to-failure)	Preventive Maintenance	Reliability-centered Maintenance	Other
2	1	1	-	-
5	-	-	1	-
7	1	1	1	-
8	1	1	-	1
11	1	1	-	-
12	1	1	-	-
16	1	1	-	-
17	-	1	-	-
18	-	1	-	1
19	1	1	1	-
20	-	1	1	-
22	-	1	-	-
23	-	-	1	1
24	-	1	1	-
25	1	1	-	-
26	1	1	-	-
27	-	1	1	1
Participants type 2	**9**	**15**	**7**	**4**

Table 11: Coding result for question 21 from Table 3, Case Study Questions – Questionnaire Survey

Participant	**21. What are the main reasons for not making Predictive maintenance as a part of your organizational maintenance plans?**						
	Benefits not clear	Limited knowledge	Cost factor	Effectiveness factor	Existing ecosystem not ready	Security and safety concerns	Other
2	-	-	1	-	1	1	-
5	-	1	-	-	-	-	-
7	1	1	1	1	1	1	1
8	-	-	-	1	-	1	1
11	-	-	1	1	1	1	-
12	-	-	-	-	1	1	1
16	-	-	1	1	1	1	1
17	-	-	-	-	1	1	1
18	-	-	1	-	1	-	1
19	-	-	1	1	-	1	-
20	1	1	1	1	1	1	1
22	-	-	-	-	1	1	-
23	-	-	-	1	-	1	1
24	-	-	1	-	1	1	1
25	-	-	1	-	1	1	1
26	-	-	-	-	1	-	1
27	-	-	-	1	1	1	-
Participants type 2	**2**	**3**	**9**	**8**	**13**	**14**	**11**

Table 12: Coding result for question 22 from Table 3, Case Study Questions – Questionnaire Survey

Participant	22. Does your organization have any plans to adapt to the Predictive Maintenance strategy for maintenance?				
	Already started	Within 1 year	In next 3 years	No plans	Do not know
2	-	-	-	-	1
5	-	-	-	1	-
7	-	-	-	-	1
8	-	1	-	-	-
11	-	-	-	-	1
12	-	-	-	1	-
16	-	-	-	-	1
17	-	-	-	-	1
18	-	-	1	-	-
19	1	-	-	-	-
20	-	-	-	-	1
22	-	1	-	-	-
23	-	-	-	-	1
24	-	-	-	-	1
25	-	-	-	-	1
26	-	-	-	-	1
27	-	-	-	-	1
Participants type 2	1	2	1	2	11

In Tables 10 to 12, all the selected inputs from the participant corresponding to a question is coded as “1”, whereas the not selected are coded as “-”. Sum of the responses to a particular input is highlighted with green in last row of each table.

Table 13: Coding result for question 3 from Table 3, Case Study Questions – Questionnaire Survey

Participant	**3. On which tiers of the CPS ecosystem, PdM and CM systems are in place in your organization?**		
	Edge Tier	Platform Tier	Enterprise Tier
1	1	1	1
3	1	-	-
4	-	-	1
6	1	1	-
9	1	-	-
10	1	-	-
13	1	-	-
14	1	-	-
15	-	-	1
21	1	-	-
28	1	1	-
Participants Type 1	**9**	**3**	**3**

Table 14: Coding result for question 4 and 5 from Table 3, Case Study Questions – Questionnaire Survey

Participant	**4. Does your organization allows remote maintenance?**	**5. Does your organization allows remote monitoring?**
	Yes (1) or No (2)	Yes (1) or No (2)
1	1	1
3	2	2
4	2	1
6	2	2
9	2	1
10	2	2
13	2	2
14	2	2
15	1	1
21	2	2
28	1	1
Participants type 1	Yes = **3** No = **8**	Yes = **5** No = **6**

Table 15: Collected raw data about the effectiveness of condition monitoring

Participant	6. How do you rate effect of CM on equipment in your organization?		
	Availability	Reliability	Overall Equipment Effectiveness
1	Neutral	Neutral	Neutral
3	Very Effective	Very Effective	Very Effective
4	Effective	Very Effective	Effective
6	Very Effective	Very Effective	Very Effective
9	Neutral	Neutral	Needs some improvement
10	Very Effective	Neutral	Effective
13	-	Needs some improvement	Needs some improvement
14	Effective	Effective	Effective
15	Effective	Neutral	Effective
21	Effective	Effective	Effective
28	Effective	Effective	Effective

Table 16: Coded data for effectiveness of condition monitoring

Participant	6. How do you rate effect of CM on equipment in your organization?		
	Availability	Reliability	Overall Equipment Effectiveness
1	3	3	3
3	5	5	5
4	4	5	4
6	5	5	5
9	3	3	2
10	5	3	4
13	-	2	2
14	4	4	4
15	4	3	4
21	4	4	4
28	4	4	4

Table 17: Summary and coding table for effectiveness of condition monitoring

	Ineffec-tive (1)	Needs some improvement (2)	Neu-tral (3)	Effective (4)	Very Effec-tive (5)	Do not know (6)
Availability	0	0	2	5	3	0
Reliability	0	1	4	3	3	0
Overall Equipment Effectiveness	0	2	1	6	2	0

Table 15 represents the collected raw data in the tabular form and further this data is coded. The sum of responses on the scale from 1 to 6 (Ineffective to Do not know) is listed in Table 17 and the scale codes are assigned to each participant input in the Table 16. Further, for the effectiveness of the predictive maintenance questionnaire survey similar approach has been applied to convert the raw collected data in coded form.

Table 18: Coded data for effectiveness of predictive maintenance

Partici-pant	**7. How do you rate effect of PdM on equipment in your organization?**					
	Availability	Reliability	Reduction in Operational Risk	Reduction in Maintenance Cost	Reduction in Operational Cost	Overall Equip-ment Effective-ness
1	3	3	4	4	4	3
3	3	3	3	2	3	2
4	4	3	5	5	5	4
6	4	4	4	4	4	4
9	2	2	3	2	2	2
10	2	2	1	1	1	2
13	2	2	3	1	1	2
14	4	4	4	4	4	4
15	5	5	3	3	3	4
21	3	3	3	2	2	3
28	4	4	4	4	4	4

Table 19: Summary and coding table for effectiveness of predictive maintenance

	Ineffective (0)	Needs some improvement (1)	Neutral (2)	Effective (3)	Very Effective (4)	Do not know (5)
Availability	0	3	3	4	1	0
Reliability	0	3	4	3	1	0
Reduction in Operational Risk	1	0	5	4	1	0
Reduction in Maintenance Cost	2	3	1	4	1	0
Reduction in Operational Cost	2	2	2	4	1	0
Overall Equipment Effectiveness	0	4	2	5	0	0

The response to the Questions 8 and 20 from Table 3, Questionnaire Survey are aggregated and coded for the two participant types to get a better understanding that what is the current trend in organizations regarding the maintenance plans.

Table 20: Aggregated summary and coded table for organizational maintenance plans

Participant	8. Any other maintenance strategy in place with PdM? 20. Which maintenance strategies are currently being in use in your organization?			
	Corrective Maintenance (run-to-failure)	Preventive Maintenance	Reliability-centered Maintenance	Other
1	1	1	-	-
2	1	1	-	-
3	1	1	-	-
4	1	-	-	-
5	-	-	1	-
6	-	1	1	1
7	1	1	1	-
8	1	1	-	1
9	1	1	1	1
10	1	1	-	-
11	1	1	-	-
12	1	1	-	-
13	-	1	1	1
14	-	1	-	-
15	-	-	-	1
16	1	1	-	-
17	-	1	-	-
18	-	1	-	1
19	1	1	1	-
20	-	1	1	-
21	1	1	1	-
22	-	1	-	-
23	-	-	1	1
24	-	1	1	-
25	1	1	-	-
26	1	1	-	-
27	-	1	1	1
28	-	-	-	1
Participants type 1	**6**	**8**	**4**	**5**
Participants type 2	**9**	**15**	**7**	**4**

For the questions about provider and manager of the PdM and CM systems for an organization, the available inputs for the participant has been assigned a number from the range 1 to 3 for the both the questions 9 and 10 respectively. The last row of the table lists the sum of all the user inputs for a particular available input.

Table 21: Coded table for provider and manager of PdM and CM systems in an organization

Participant	**9. Who is provider of PdM and CM systems for your organization?** Internal Developed Systems (1) Third Party Developed (2) Hybrid - Internal and third party (3)	**10. Who manages the PdM and CM systems for your organization?** Internal Team (1) Internal Team from different location (2) Outsourced (3)
1	1	1
3	3	1
4	1	1
6	1	1
9	1	1
10	1	1
13	2	1
14	1	1
15	1	
21	1	1
28	3	1
Participants type 1	**Internal Developed Systems = 8** **Third Party Developed = 1** **Hybrid - Internal and third party = 2**	**Internal Team = 10** **Internal Team from different location = 2** **Outsourced = 1**

Table 22: Coded table for the PdM and CM components

Participant	11. Which components in your organization contributes for PdM and CM?										
	OT Wired Network	OT Wireless Network	IT Wired Network	IT Wireless Network	IIoT Gateways	Data Storage	Private Cloud	Public Cloud	Edge computing	Fog computing	Others
1	1	-	1	1	1	1	-	-	1	1	-
3	1	-	1	-	-	1	-	-	-	-	1
4	-	-	-	-	-	-	1	-	-	-	-
6	1	-	1	1	-	1	1	-	-	-	1
9	1	-	1	1	1	1	1	1	1	-	1
10	1	-	1	-	1	-	-	-	-	-	1
13	1	-	-	1	-	1	-	1	1	-	1
14	-	-	1	-	1	-	-	-	1	-	-
15	-	-	1	-	-	-	-	-	-	-	-
21	1	-	1	1	1	1	1	-	1	-	1
28	1	-	1	-	-	1	-	-	-	-	-
Participants type 1	8	0	9	5	5	7	4	2	5	1	6

Table 23: Data Storage for PdM and CM – Coded table

Participant	12. Where do you store the generated data from machines for PdM and CM?					
	IIoT Gateways	Private Cloud	Public Cloud	Internal Data Storage Server	Remote Data Storage Server	Others
1	1	-	-	-	-	-
3	-	-	-	1	-	1
4	-	-	-	1	-	-
6	-	-	-	1	-	1
9	1	-	1	1	-	1
10	1	-	-	1	-	1
13	-	-	1	1	-	1
14	1	1	-	-	-	-
15	-	-	-	-	1	-
21	1	1	-	1	-	1
28	-	-	-	1	-	-
Participants type 1	5	2	2	8	1	6

Table 24: Coded inputs for the communication protocols on the OT side

Participant	13. Which communication protocol/s are in use currently on the OT side?							
	OPC UA	Modbus	PROFINET	PROFIBUS	IO-Link	EtherNet/IP	CAN bus	Others
1	1	-	-	-	-	1	-	-
3	1	-	-	-	1	-	-	1
4	1	-	-	-	-	-	1	-
6	1	-	1	-	1	-	1	-
9	1	-	1	-	1	1	-	-
10	-	1	1	-	1	1	-	1
13	-	-	-	-	1	-	-	1
14	1	-	1	-	1	-	-	-
15	-	-	-	-	-	-	1	-
21	1	-	1	1	1	1	-	1
28	1	1	1	-	1	1	1	1
Participants type 1	8	2	6	1	8	5	4	5

Table 25: Coded inputs for the communication protocols on the IT side

Participant	14. Which communication protocol/s are in use currently on the IT side?							
	SNMP	HTTP	SOAP	XML	MQTT	AMQP	CoAP	Others
1	-	1	-	-	1	-	-	-
3	-	1	-	-	1	-	-	1
4	-	-	-	-	1	-	-	-
6	-	1	-	-	1	-	1	1
9	1	1	-	-	1	1	-	1
10	-	1	-	-	1	-	-	1
13	-	1	-	-	1	-	-	1
14	-	1	-	-	1	-	-	-
15	-	1	-	-	1	-	-	-
21	-	1	-	-	1	1	1	1
28	-	1	-	-	-	-	-	-
Participants type 1	**1**	**10**	**0**	**0**	**10**	**2**	**2**	**6**

Table 26: Data access for PdM and CM – Coded table

Participant	15. How does the PdM and CM systems access the data?					
	Directly from machines	PLCs	IIoT Gateways	Persistent Storage	Private Cloud	Public Cloud
1	1	1	1	-	-	-
3	1	1	-	-	-	-
4	-	-	-	1	-	-
6	1	1	-	1	-	-
9	1	1	1	1	-	1
10	1	1	1	1	-	-
13	1	1	-	1	-	1
14	-	-	1	-	-	-
15	-	-	1	1	-	-
21	1	1	1	1	1	-
28	-	-	-	1	-	-
Participants type 1	**7**	**7**	**6**	**8**	**1**	**2**

Table 27: Coded table for network segmentation policy

Participant	16. Does your organization have network segmentation policy in place for the OT, IT and IIoT network? Between:			
	OT - IT - IIoT	OT - IT	IT - IIoT	OT - IIoT
1	1	-	-	-
3	-	1	-	-
4	-	-	1	-
6	-	1	-	-
9	1	-	-	-
10	1	-	-	-
13	-	1	-	-
14	-	1	-	-
15	-	-	-	1
21	1	-	-	-
28	-	1	-	-
Participants type 1	**4**	**5**	**1**	**1**

Table 28: Coding table for the criticality of security and safety mechanisms of PdM and CM components

	Very Unimportant (1)	Unim-portant (2)	Neutral (3)	Im-portant (4)	Very Im-portant (5)	Not sure (6)	Not Applica-ble (7)
Communica-tion Network	0	0	1	2	8	0	0
Communica-tion Protocols	0	0	0	4	7	0	0
Software, Services and Applications	0	0	2	2	7	0	0
Data Storage	0	0	1	2	8	0	0
Machines	0	1	2	1	7	0	0
Computing Units	0	1	1	2	6	1	0
IIoT gateways	0	0	1	1	5	0	4
Private Cloud	0	0	0	3	2	0	6
Public Cloud	0	0	0	3	2	1	5

Table 29: Coded data for the criticality of security and safety mechanisms of PdM and CM components

Participant	17. How critical is the security and safety mechanisms for the components involved for PdM and CM?								
	Communication Network	Communication Protocols	Software, Services and Applications	Data Storage	Machines	Computing Units	IIoT gateways	Private Cloud	Public Cloud
1	5	4	5	3	2	3	5	4	4
3	5	4	4	4	5	4	7	7	7
4	4	4	3	5	3	2	4	5	4
6	5	5	5	5	5	5	7	7	7
9	5	5	5	5	5	5	5	7	5
10	5	5	5	5	5	5	5	7	7
13	5	5	5	5	5	6	7	7	5
14	4	5	4	5	4	4	5	4	6
15	3	4	3	4	3	5	3	4	4
21	5	5	5	5	5	5	5	5	7
28	1	1	1	1	1	1	1	1	1

Table 30: Coded data for security and safety mechanisms of PdM and CM components

Participant	18. Which of the following security and safety mechanism/s are in place for the components involved for PdM and CM?					
	Risk Assessment	Security and Safety Objectives	Threat Identifica-tion	Access Management	Breach Detection	Others
1	1	1	-	1	-	-
3	-	1	-	1	-	1
4	-	-	1	1	-	-
6	1	1	-	1	1	1
9	1	1	1	1	1	1
10	-	1	-	1	-	1
13	-	1	-	1	-	1
14	-	1	-	1	-	-
15	1	-	1	-	1	-
21	1	1	-	1	-	1
28	1	1	1	-	1	-
Participants type 1	**6**	**9**	**4**	**9**	**4**	**6**

Table 31: Coding table – Required improvements for the PdM and CM systems

	Not Required (1)	Neutral (2)	Required (3)	Highly Required (4)	Do not know (5)
Security and Safety Mechanisms	0	1	4	6	0
PdM and CM Systems Improve-ment	0	1	6	4	0
Understanding of Benefits of PdM and CM	0	3	3	5	0
Cost for Implementation	0	3	5	1	2
Time for Implementation	0	3	5	2	1
Time to Success	0	2	2	6	1
Ease of Adaptation to existing ecosystem	0	1	2	8	0

Table 32: Coded table – Required improvements for the PdM and CM systems

Participant	19. Which of the following needs improvement or optimization in terms of PdM and CM?						
	Security and Safety Mechanisms	PdM and CM Systems Improvement	Understanding of Benefits of PdM and CM	Cost for Implementation	Time for Implementation	Time to Success	Ease of Adaptation to existing ecosystem
1	4	4	2	5	3	4	4
3	3	3	3	3	2	4	4
4	4	3	4	4	3	2	4
6	4	3	4	3	3	3	4
9	3	3	4	3	3	2	4
10	4	4	4	2	2	3	3
13	2	3	2	5	5	5	4
14	4	3	3	3	4	4	3
15	3	2	3	2	2	4	2
21	3	4	2	3	3	4	4
28	4	4	4	2	4	4	4

6.3.2 Coding Procedure for FGD Result and Archival Data

Two FGDs have been conducted for the qualitative data collection.

Step 1: Mapping, rearranging and transformation of the transcript data

To make the coding process easy and less complex, the researcher has rearranged the text from transcripts according to the individual questions. Inputs from the participants are then mapped to the questions.

Step 2: The FGD transcripts and project report have been added to the coding tool – QDA Miner Lite

Step 3: Categories, sub-categories and codes have been created

Based upon the four research questions, four categories have been created. Each category consisted of a set of codes.

- Category1: RQ1, PdM and CM in cyber-physical systems
- Category2: RQ2, Benefits of PdM and CM
- Category3: RQ3, Security and safety aspects of PdM and CM
- Category4: RQ4, Challenges and improvements

Additional sub-categories are created for Category3 and they are as following:

- Category3.1: Network
- Category3.2: Communication Protocols

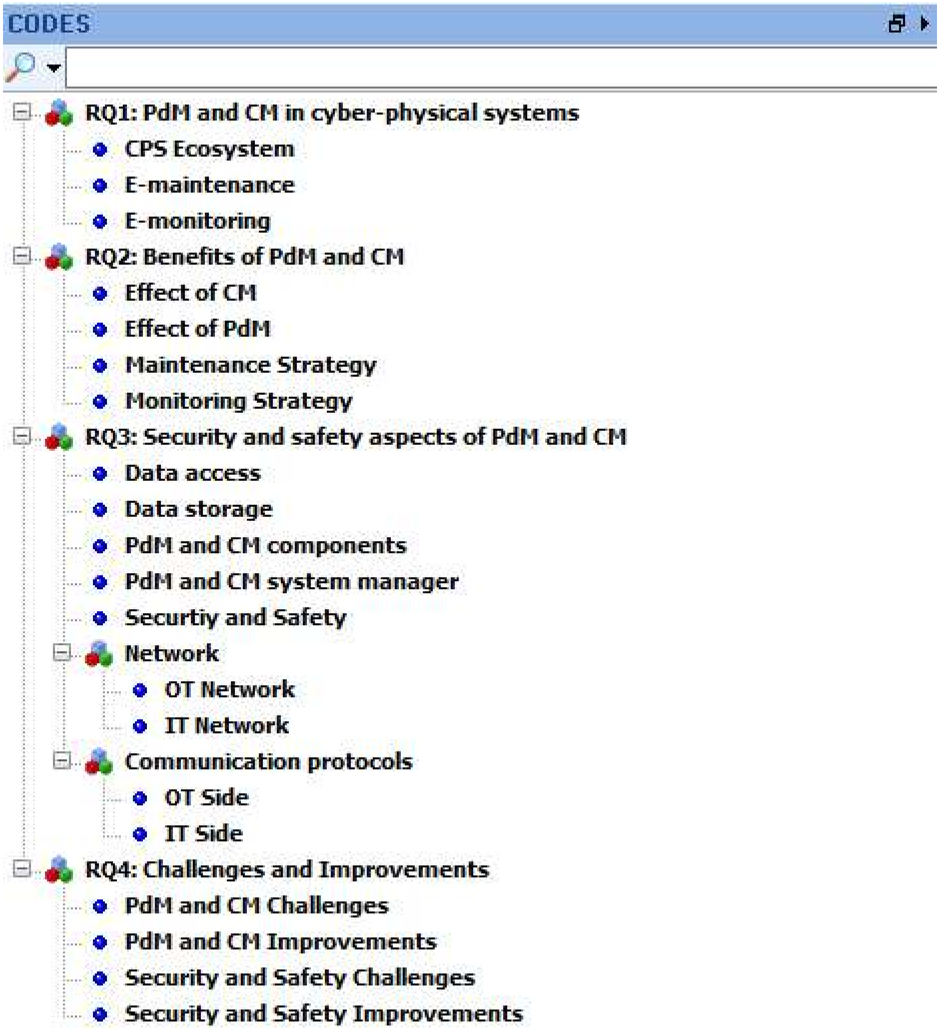


Figure 18: Coding hierarchy in QDA Miner Lite

Step 4: Transcript and report are then assigned corresponding categories and codes

There have been several questions discussed during the FGDs and some participants presented their viewpoints in sentences and some answered to the point. For example, for the question: “Benefits of PdM and CM”, answers have been given as “cost effectiveness” and “As you already know that currently …”. Such answers are differentiated as direct and indirect answers. The response which gives clear idea that to which code they belong are coded within direct coding technique and others in indirect coding technique.

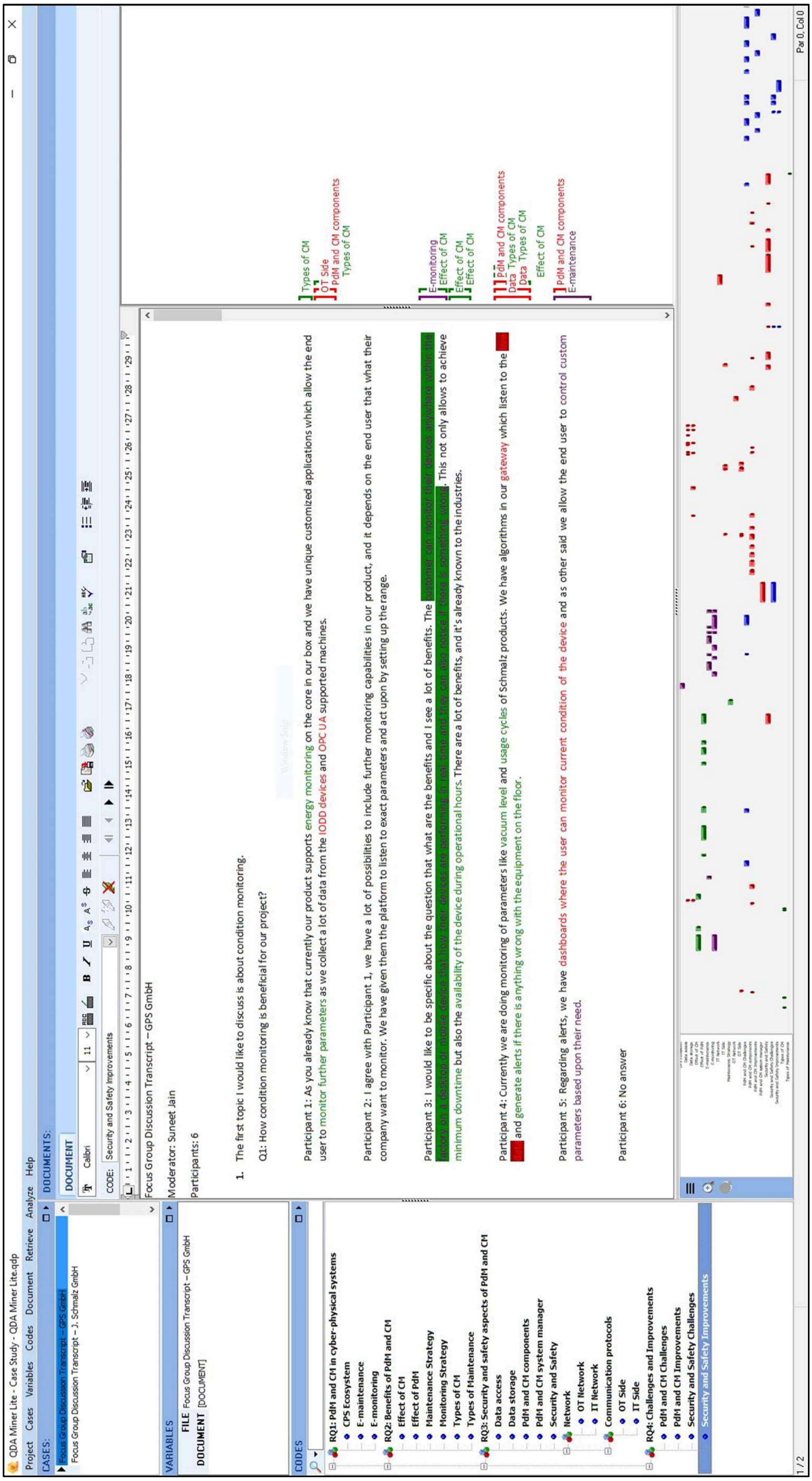


Figure 19: Coding process in QDA Miner Lite

During the coding process, multiple codes have been identified from different research questions to a specific answer. Hence, part of the answer is assigned with multiple codes wherever necessary.

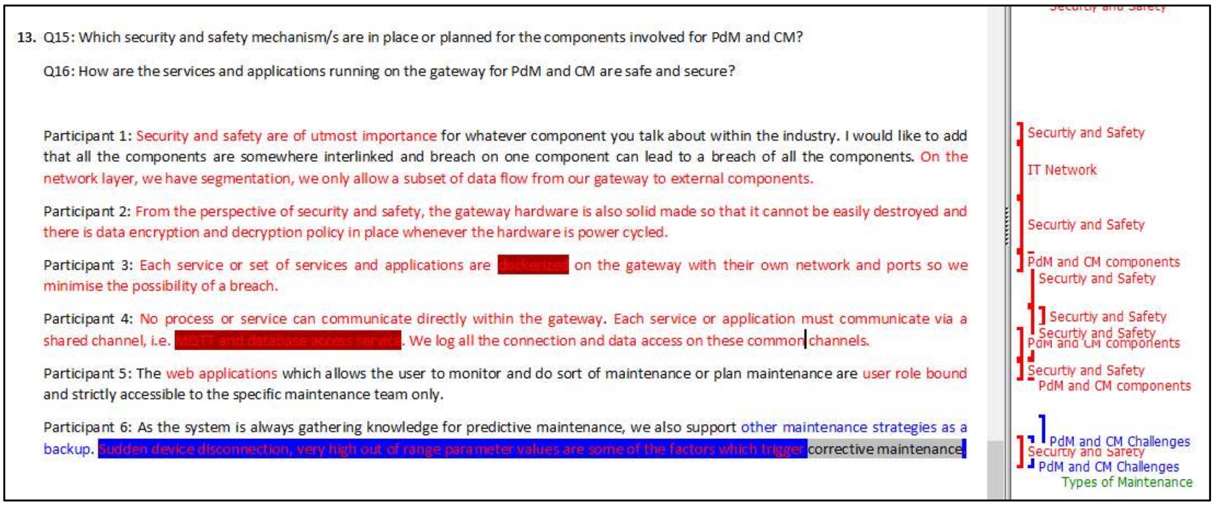


Figure 20: Example of multiple code assignment

Coding frequency has been generated with the help of QDA Minor Lite. Table 33 gives an overview of the coding frequency in terms of number and percentage of words and cases coded for each individual code. Also, on the category level, the code frequency is calculated.

Table 33: Overview of coding frequency

Category	Code	Count	% Codes	Cases	% Cases	Nb Words	% Words
RQ1: PdM and CM in cyber-physical systems	CPS Ecosystem	5	2.30%	2	66.70%	43	1.50%
RQ1: PdM and CM in cyber-physical systems	E-maintenance	8	3.60%	2	66.70%	86	3.00%
RQ1: PdM and CM in cyber-physical systems	E-monitoring	8	3.60%	2	66.70%	126	4.30%
RQ2: Benefits of PdM and CM	Effect of CM	11	5.00%	2	66.70%	110	3.80%
RQ2: Benefits of PdM and CM	Effect of PdM	11	5.00%	2	66.70%	115	3.90%
RQ2: Benefits of PdM and CM	Maintenance Strategy	2	0.90%	1	33.30%	5	0.20%
RQ2: Benefits of PdM and CM	Monitoring Strategy	4	1.80%	1	33.30%	22	0.80%
RQ2: Benefits of PdM and CM	Types of CM	4	1.80%	1	33.30%	9	0.30%
RQ2: Benefits of PdM and CM	Types of Maintenance	3	1.40%	2	66.70%	6	0.20%
RQ3: Security and safety aspects of PdM and CM	Data access	13	5.90%	2	66.70%	50	1.70%
RQ3: Security and safety aspects of PdM and CM	Data storage	10	4.50%	2	66.70%	62	2.10%
RQ3: Security and safety aspects of PdM and CM	PdM and CM components	38	17.10%	2	66.70%	135	4.60%
RQ3: Security and safety aspects of PdM and CM	PdM and CM system manager	4	1.80%	2	66.70%	55	1.90%
RQ3: Security and safety aspects of PdM and CM	Security and Safety	20	9.00%	2	66.70%	278	9.50%
RQ3: Security and safety aspects of PdM and CM\Network	OT Network	5	2.30%	2	66.70%	21	0.70%
RQ3: Security and safety aspects of PdM and CM\Network	IT Network	3	1.40%	2	66.70%	29	1.00%
RQ3: Security and safety aspects of PdM and CM\Communication protocols	OT Side	16	7.20%	2	66.70%	34	1.20%
RQ3: Security and safety aspects of PdM and CM\Communication protocols	IT Side	11	5.00%	2	66.70%	23	0.80%
RQ4: Challenges and Improvements	PdM and CM Challenges	21	9.50%	2	66.70%	301	10.30%
RQ4: Challenges and Improvements	PdM and CM Improvements	7	3.20%	2	66.70%	74	2.50%
RQ4: Challenges and Improvements	Security and Safety Challenges	13	5.90%	2	66.70%	187	6.40%
RQ4: Challenges and Improvements	Security and Safety Improvements	5	2.30%	2	66.70%	64	2.20%

6.4 Generation of Hypotheses and Confirmation

In the iterative approach, data collection and data analysis process has been repeated in parallel. A set of hypotheses has been generated from the literature review and project experience, which can be confirmed subsequently the coding process. During the coding process of quantitative and qualitative data, new set of hypotheses is generated. This new set of hypotheses can only be confirmed by further data collection.

Hypotheses	Description
H1	PdM and CM strategy benefits the manufacturing industry
H2	Security and safety is inherited from CPS ecosystem
H3	PdM strategy is not the best suitable strategy for every manufacturing industry
H4	Lot of improvements are required for more effectiveness of PdM. Security and safety fear is the limiting factor.

Table 34: Overview of the generated hypotheses during case study

Hypotheses H1 and H2 have been generated during literature review. Whereas hypotheses H3 and H3 have been generate during data collection and data analysis phase of this case study. Hypotheses confirmation has been established through triangulation and replication during the data analysis phase.

6.5 Validity Process

To be sure that the generated results from the case study are not biased by the researcher, the trustworthiness of the results from the case study is denoted by validity of the subject of the case study. The types of validity identified by Yin [47] to categorize characteristics of validity and threats are construct validity, internal validity, external validity and reliability.

During this case study, many measures have been taken into consideration to discard the threats to the validity types.

7 Results

In this section the results and findings of the quantitative and qualitative data analysis process have been presented.

7.1 Quantitative Data Analysis Results

Quantitative data analysis is executed into 4 different steps, which is described in the Section 5.1.1. Quantitative data has been collected for all the four research questions of this case study. After the data collection and data coding phase this section presents the next two phases of the quantitative data analysis strategy.

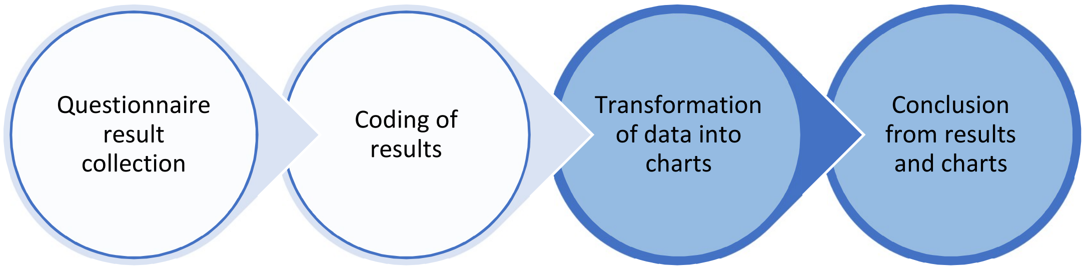


Figure 21: Active phases of quantitative data analysis to generate results and findings

The coded data for each research question has been transformed into charts. Further, the findings from tables and charts are presented as results.

Questionnaire survey – Participant type

Total 28 participants completed the questionnaire survey. 11 participant's organization have predictive maintenance and condition monitoring strategy as the part of organizational maintenance and monitoring strategy. Based upon the participant input to this question different set of questions have been presented to the participant to analyze the benefits and limitations of acceptance of the PdM strategy.

Does your organization have predictive maintenance and condition monitoring strategy in place?

	Yes	No	Standard Deviation	Responses
All Data	11 (39%)	17 (61%)	3	28

Figure 22: Overview of questionnaire survey participant types

Which condition-based monitoring methods are currently being applied in your organization?

	Vibration analysis and diagnostics	Wear debris analysis	Noise monitoring	Lubricant analysis	Infrared thermography	Visual inspection	Acoustic based analysis	Oil analysis	Energy consumption monitoring	Other	Responses
All Data	5 (19%)	1 (4%)	7 (26%)	2 (7%)	2 (7%)	15 (56%)	2 (7%)	2 (7%)	11 (41%)	17 (63%)	27

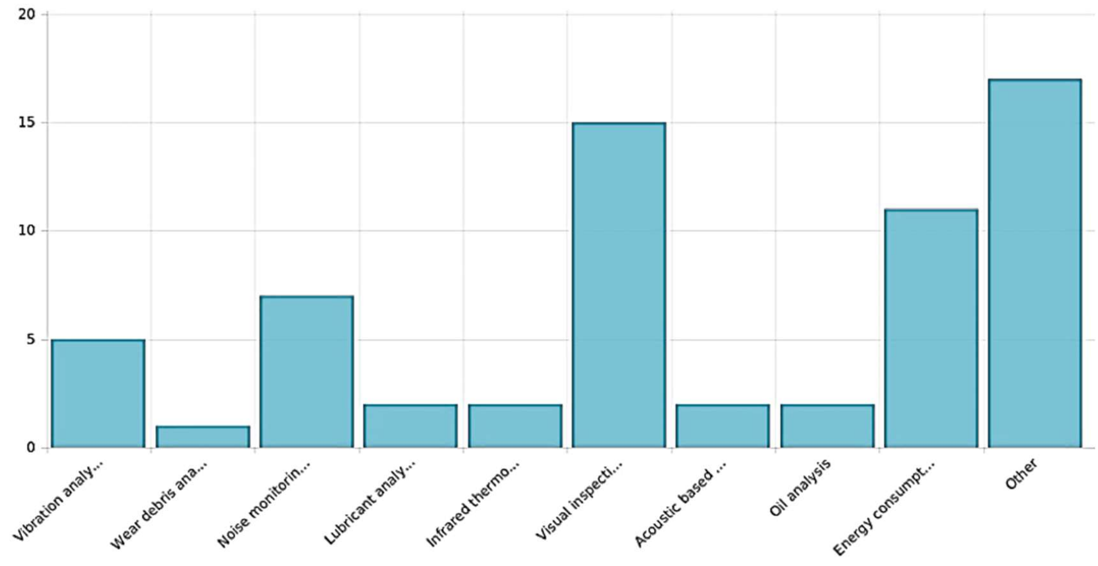


Figure 23: Condition monitoring methods

7.1.1 Result of RQ1: How PdM and CM are integrated with cyber-physical systems

For this research question, 3 questions have been presented to the participants type 1 (Section 6.2.1, Table 5, Type of Participants) of the questionnaire survey to find out the maturity of the PdM and CM systems in context of Industry 4.0 and IIoT.

Chart Generation and description

1. Integration with cyber-physical systems:

Out of 13 participants, only 1 participant's organization has PdM and CM system integrated on all the three tiers and 2 have answered both Edge as well as Platform Tier. Most of the organizations have PdM and CM systems integrated on the edge tier only (Section 2.4.2, Figure 6).

On which tiers of the Cyber Physical System ecosystem, Predictive Maintenance and Condition Monitoring systems are in place in your organization?CPS - Cyber Physical SystemPlease refer to this image: ibb.co/n8uFnH

	Edge Tier	Platform Tier	Enterprise Tier	Responses
All Data	9 (82%)	3 (27%)	3 (27%)	11

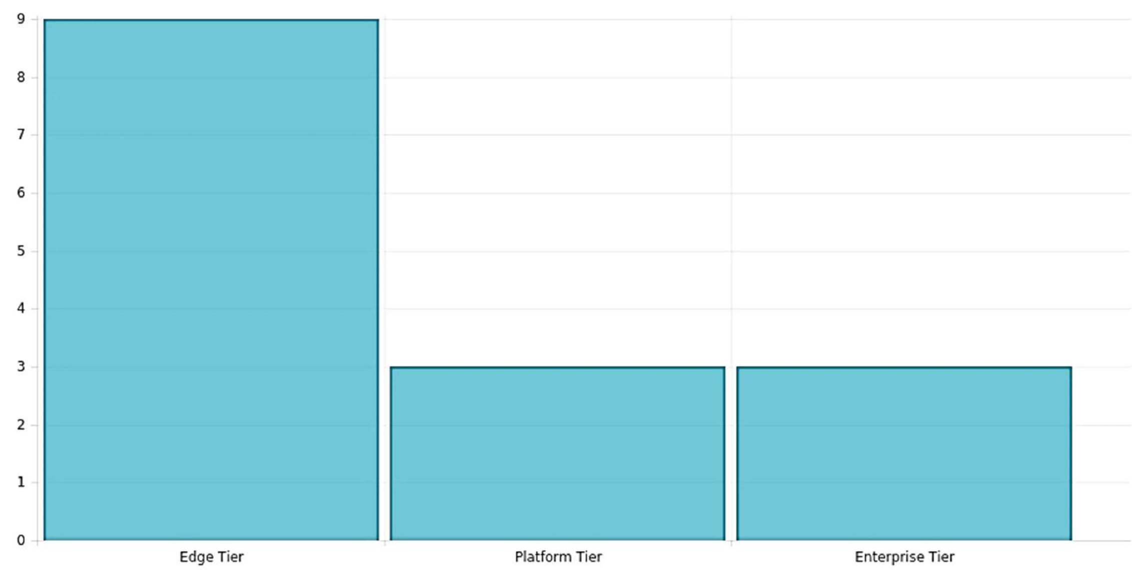


Figure 24: PdM and CM systems integrated with CPS ecosystem

1. E-Maintenance:

   Only 27 percent (3 out of 11) have responded “Yes” and 73 percent (8 out of 11) have responded “No”.

Does your organization allows remote maintenance?

	Yes	No	Standard Deviation	Responses
All Data	3 (27%)	8 (73%)	2.5	11

Figure 25: Acceptance level of e-maintenance in organizations

2. E-Monitoring:

The change in trend of the acceptance level of e-monitoring can be variably observed from the below table and chart. 45 percent participant's organizations have enabled e-monitoring as a part of the monitoring strategy. Still there is a decline level of 55 percent, which is higher than the acceptance level.

Does your organization allows remote monitoring?

	Yes	No	Standard Deviation	Responses
All Data	5 (45%)	6 (55%)	0.5	11

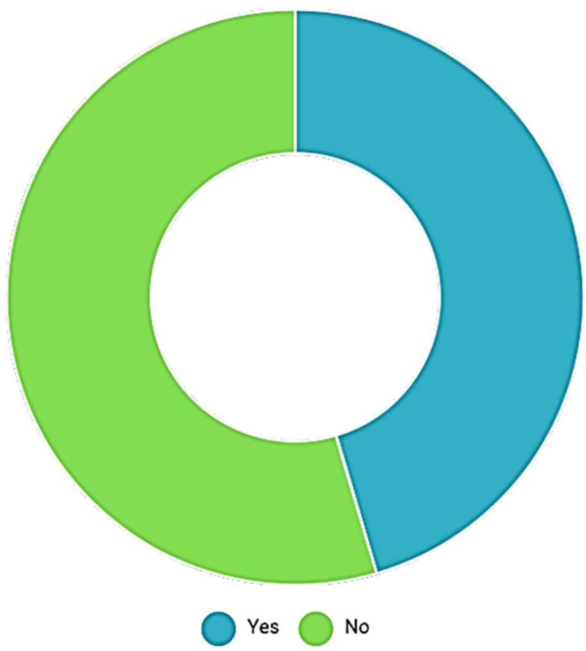


Figure 26: Acceptance level of e-monitoring in organizations

Results and findings

It can be concluded that most of the integration of the PdM and CM systems with the CPS ecosystem is limited to the edge and platform tier. Further, the interest in remote monitoring and maintenance is also not observed. There are certain reasons behind the problem of not moving to higher levels like existing ecosystem is not completely ready. There are safety and security concerns, strong results have not been achieved from such systems etc., which have been confirmed with further questions in Section 7.1

7.1.2 Result of RQ2: What kinds of benefits can CM and PdM bring

In research question 2, several sub-questions have been included in the data collection and analysis process to identify the benefits of the PdM and CM systems and their effects for the industries.

Chart Generation and description

1. Benefits and effect of CM on equipment

In terms of availability, reliability and overall equipment effectiveness, availability has a weighted average of 4.1 out of 5. For equipment availability, no ineffectiveness and improvement requirement has been marked. Additionally, overall equipment effectiveness is close to effective.

How do you rate effect of CM on equipment in your organization?CM - Condition Monitoring

	Ineffective	Needs some improvement	Neutral	Effective	Very Effective	Do not know	Standard Deviation	Responses	Weighted Average
Availability	0 (0%)	0 (0%)	2 (20%)	**5 (50%)**	3 (30%)	0 (0%)	1.89	10	4.1 / 5
Reliability	0 (0%)	1 (9%)	**4 (36%)**	3 (27%)	3 (27%)	0 (0%)	1.57	11	3.73 / 5
Overall Equipment Effectiveness	0 (0%)	2 (18%)	1 (9%)	**6 (55%)**	2 (18%)	0 (0%)	2.03	11	3.73 / 5
									3.84 / 5

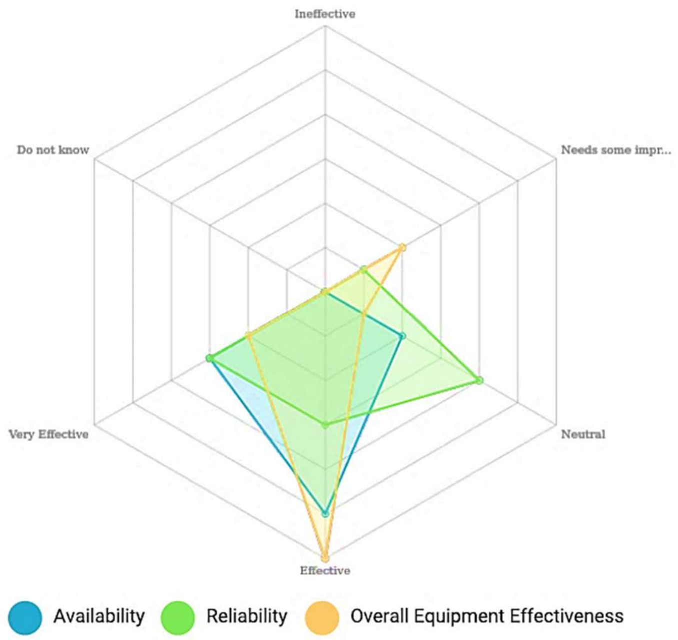


Figure 27: CM system – Benefits and their effects

2. Benefits and effect of PdM on equipment:

The effectiveness of the benefits of PdM lies in the range from ineffective to very effective. Taking weighted average into consideration, overall the result can be summarized as neutral.

How do you rate effect of PdM on equipment in your organization?PdM - Predictive Maintenance

	Ineffective	Needs some improvement	Neutral	Effective	Very Effective	Do not know	Standard Deviation	Responses	Weighted Average
Availability	0 (0%)	3 (27%)	3 (27%)	**4 (36%)**	1 (9%)	0 (0%)	1.57	11	3.27 / 5
Reliability	0 (0%)	3 (27%)	**4 (36%)**	3 (27%)	1 (9%)	0 (0%)	1.57	11	3.18 / 5
Reduction in Operational Risk	1 (9%)	0 (0%)	**5 (45%)**	4 (36%)	1 (9%)	0 (0%)	1.95	11	3.36 / 5
Reduction in Maintenance Cost	2 (18%)	3 (27%)	1 (9%)	**4 (36%)**	1 (9%)	0 (0%)	1.34	11	2.91 / 5
Reduction in Operational Cost	2 (18%)	2 (18%)	2 (18%)	**4 (36%)**	1 (9%)	0 (0%)	1.21	11	3 / 5
Overall Equipment Effectiveness	0 (0%)	4 (36%)	2 (18%)	**5 (45%)**	0 (0%)	0 (0%)	2.03	11	3.09 / 5
									3.14 / 5

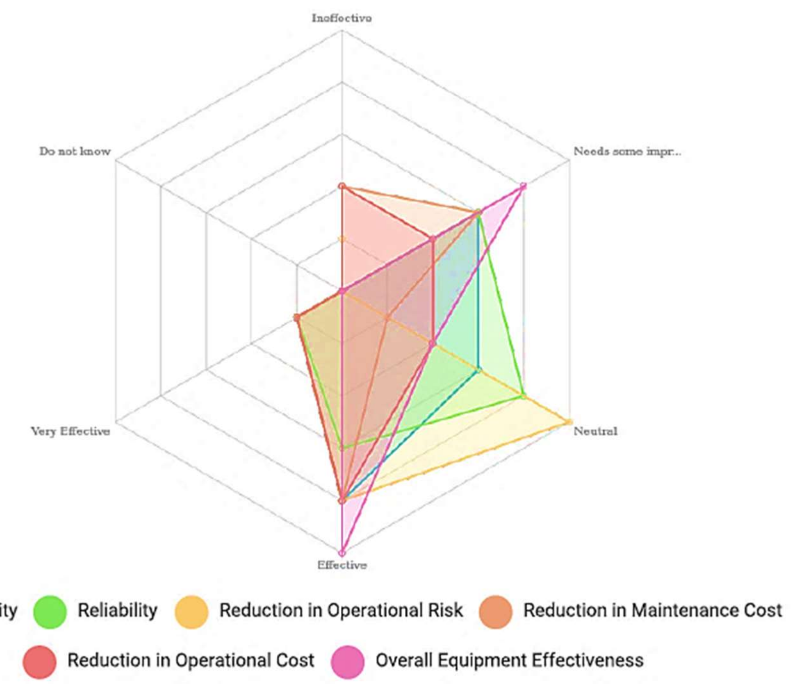
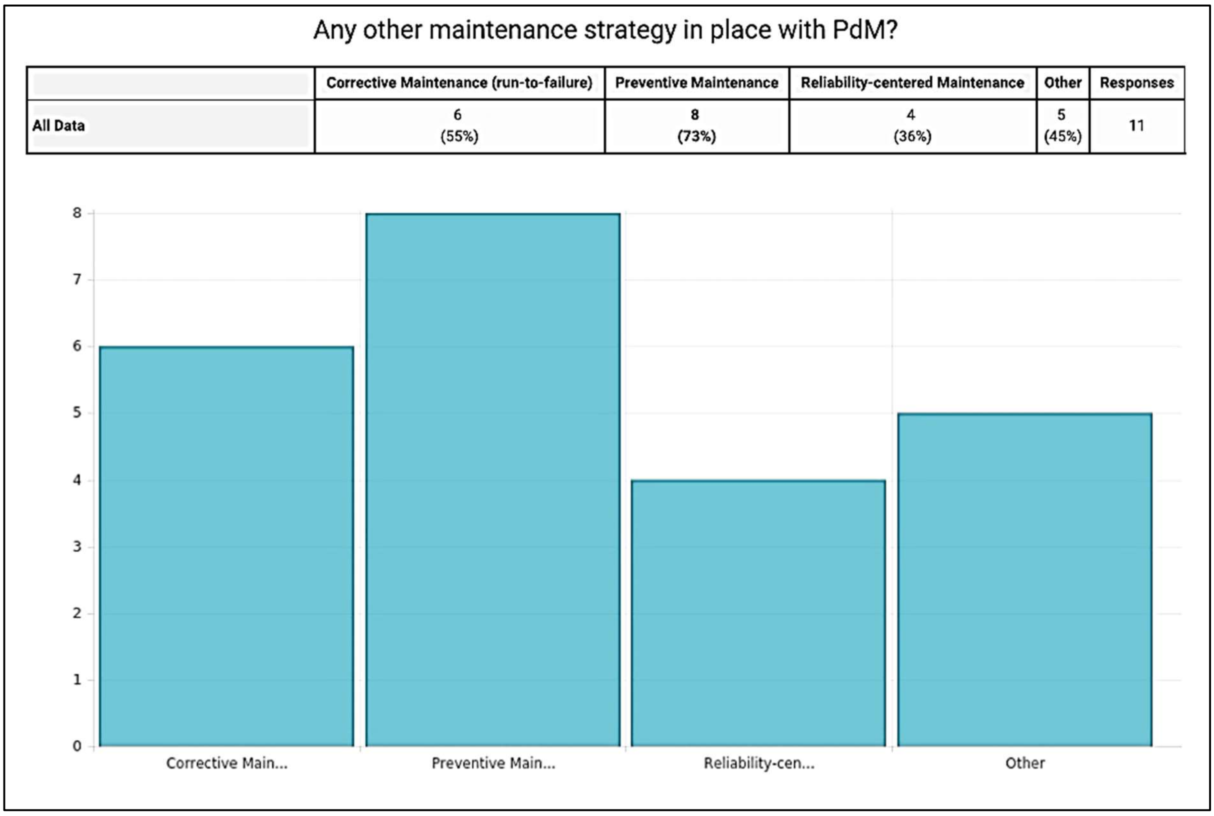


Figure 28: PdM system – Benefits and their effects

3. Additional maintenance strategy with PdM:

Organizations have other maintenance strategies like corrective maintenance, preventive maintenance, reliability-centered maintenance in combination with PdM. Preventive maintenance is the highest in comparison to others.



	Corrective Maintenance (run-to-failure)	Preventive Maintenance	Reliability-centered Maintenance	Other	Responses
All Data	6 (55%)	8 (73%)	4 (36%)	5 (45%)	11

Figure 29: Maintenance strategies in parallel with PdM

Results and findings

Machine availability can be seen as the major benefit of the condition monitoring. Many factors influence the availability and reliability of the machine, what are the parameters that are being monitored, are all the parameters monitored, how well the input functions to the CM system is defined. For the evaluation of the effectiveness of the predictive maintenance system, several benefits exist in the theory. But in practical the response from the industry is neutral and demanding.

With PdM the equipment availability is increased. The expected results like reduction in maintenance cost and operational cost are not achieved. Furthermore, industries have other maintenance strategies in parallel to PdM. Industries cannot solely rely on predictive maintenance strategy as it is yet to reach the maturity level. In conclusion, there are many limiting factors for the PdM and CM systems, most important is the availability of the data, connectivity with the old physical ecosystem.

7.1.3 Result of RQ3: What are the security and safety analysis aspects of the ecosystem concerning PdM and CM

Numerous direct and indirect questions have been part of the questionnaire survey for research questions 3. Direct questions, where the participants have been asked the importance of security and safety mechanisms of PdM and CM systems. Indirect questions, about the components involved for the PdM and CM have been asked to identify the security and safety aspects of such ecosystem.

Chart generation and description

1. Provider of PdM and CM systems:

   Majority of the systems are developed by the internal team of the organization. Hybrid systems are the combination of organizational developed systems and procured from other solution providers in the market.

Who is provider of PdM and CM systems for your organization?

	Internal Developed Systems	Third Party Developed	Hybrid - Internal and third party	Standard Deviation	Responses
All Data	8 (73%)	1 (9%)	2 (18%)	3.09	11

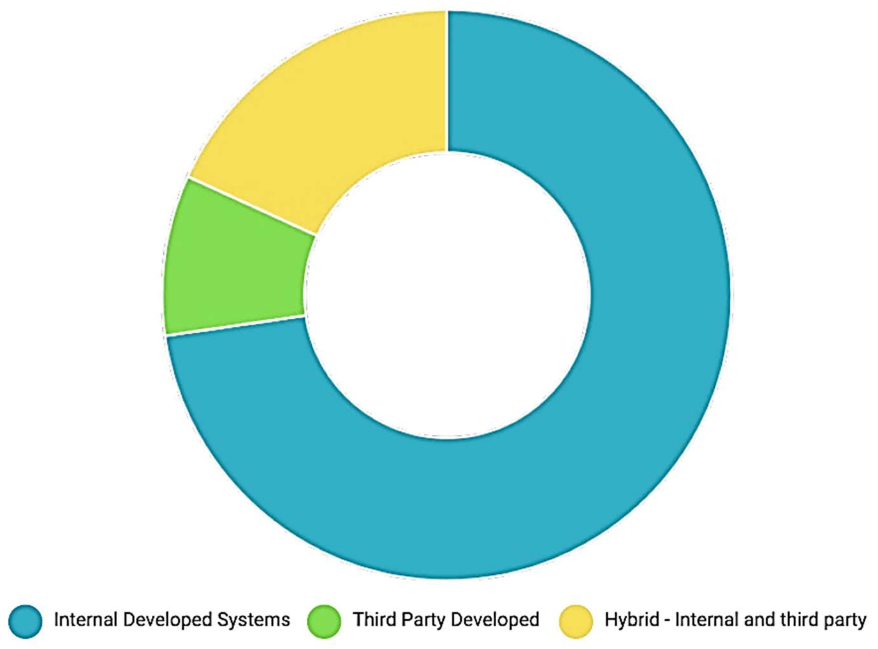


Figure 30: Providers of PdM and CM systems

2. Management of PdM and CM systems:

Management tasks include optimization of algorithms, parameterization, asset management etc. PdM and CM systems are managed by internal teams as observed from the response from participants.

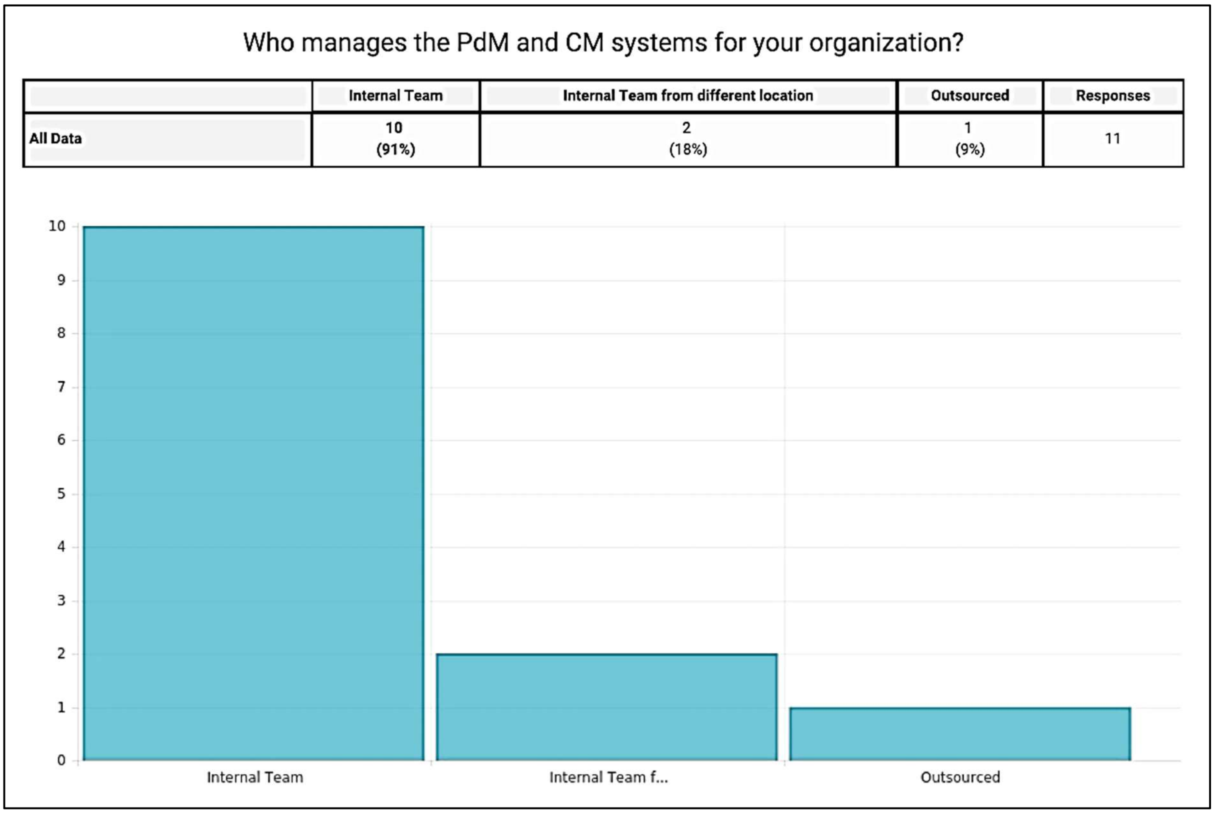


Figure 31: Management of PdM and CM systems

3. Components for PdM and CM:

Components from the CPS ecosystem serve for the PdM and CM systems. OT and IT wired network and data storage are selected by 73%, 82% and 64% of the participants respectively.

Which components in your organization contributes for PdM and CM?

	OT Wired Network	OT Wireless Network	IT Wired Network	IT Wireless Network	IIoT Gateways	Data Storage	Private Cloud	Public Cloud	Edge computing	Fog computing	Others	Responses
All Data	8 (73%)	0 (0%)	9 (82%)	5 (45%)	5 (45%)	7 (64%)	4 (36%)	2 (18%)	5 (45%)	1 (9%)	6 (55%)	11

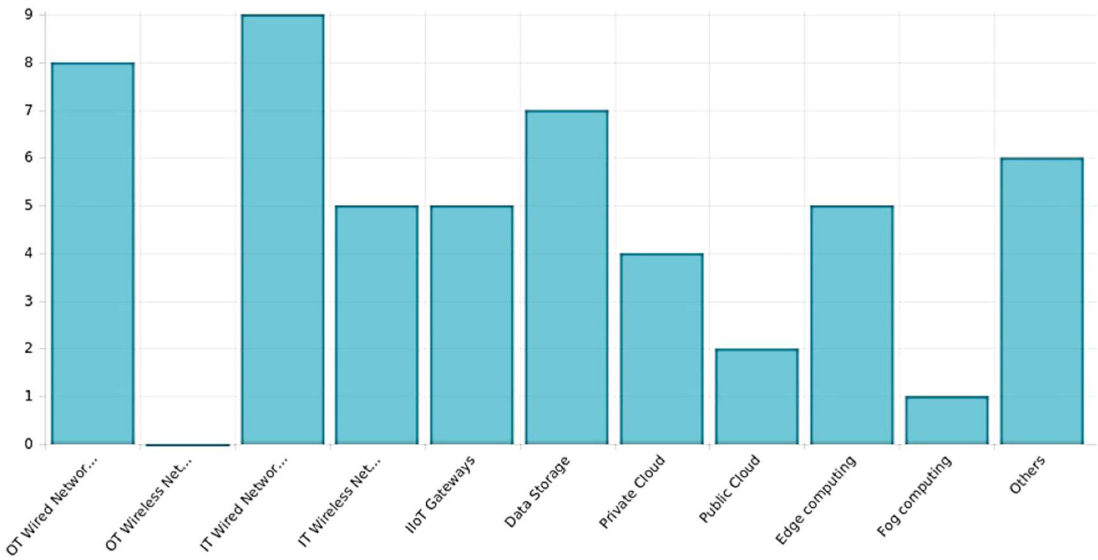


Figure 32: Components of PdM and CM ecosystem

4. Data storage for PdM and CM:

The real-time and historical data is vital for the effectiveness of the PdM systems. Organizations have internal data storage servers to store the data. They also store the data on IIoT gateways, which enables Predictive Maintenance 4.0.

Where do you store the generated data from machines for PdM and CM?

	IIoT Gateways	Private Cloud	Public Cloud	Internal Data Storage Server	Remote Data Storage Server	Others	Responses
All Data	5 (45%)	2 (18%)	2 (18%)	8 (73%)	1 (9%)	6 (55%)	11

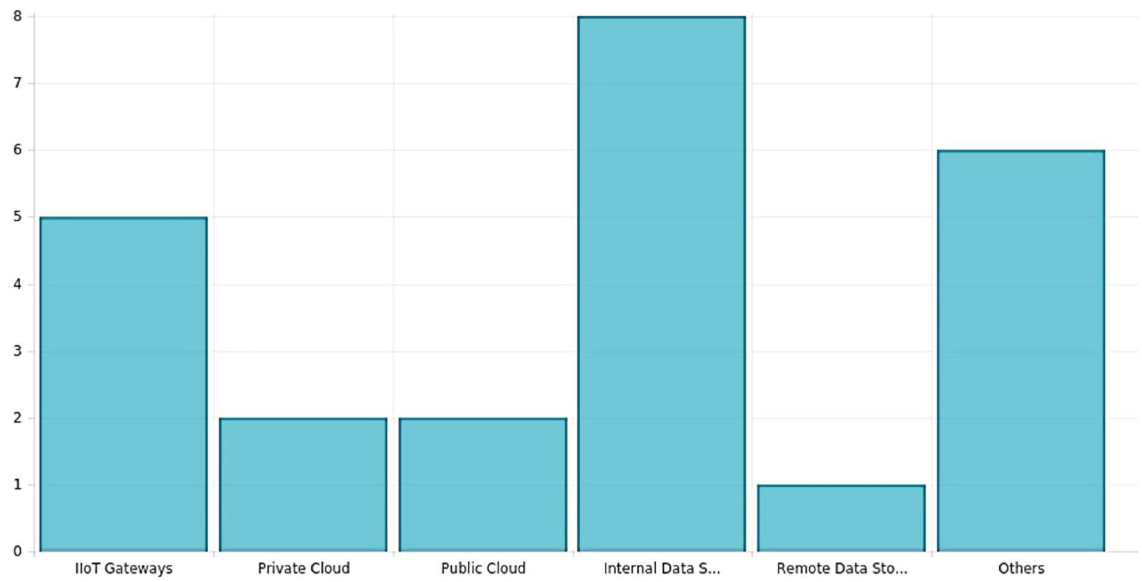


Figure 33: Data storage for PdM and CM

5. Operational Technology – Communication Protocols:

The results show protocols from the CPS systems, industrial messaging bus and new protocols such as OPC UA. IO-Link and OPC UA are the protocols which are currently trending in the context of Industry 4.0 and IIoT.

Which communication protocol/s are in use currently on the OT side?

	OPC UA	Modbus	PROFINET	PROFIBUS	IO-Link	EtherNet/IP	CAN bus	Others	Responses
All Data	8 (73%)	2 (18%)	6 (55%)	1 (9%)	8 (73%)	5 (45%)	4 (36%)	5 (45%)	11

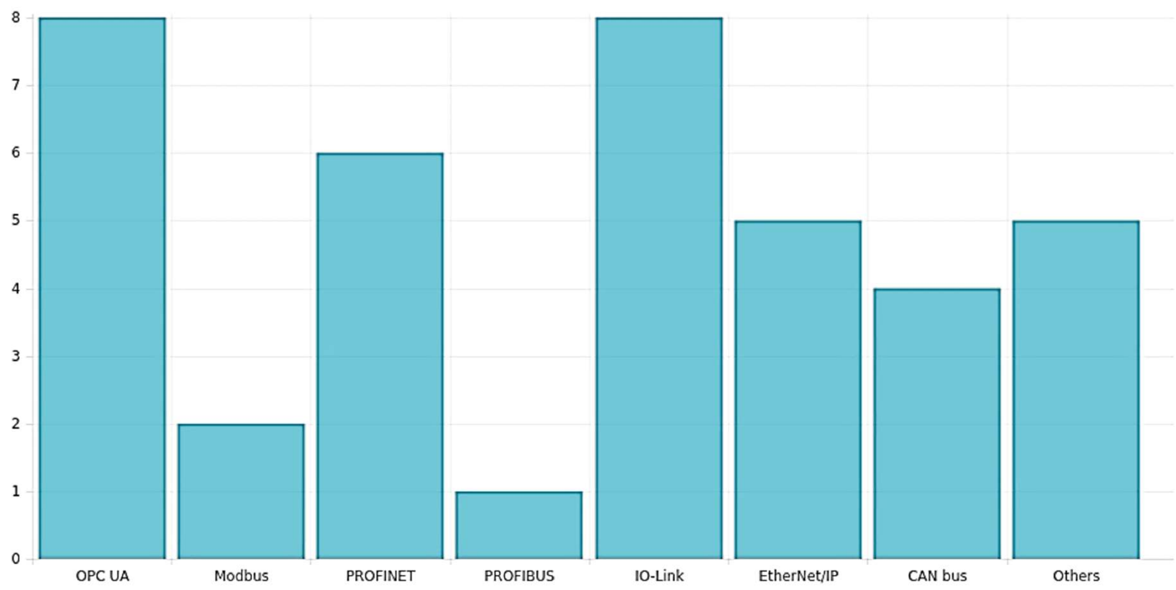
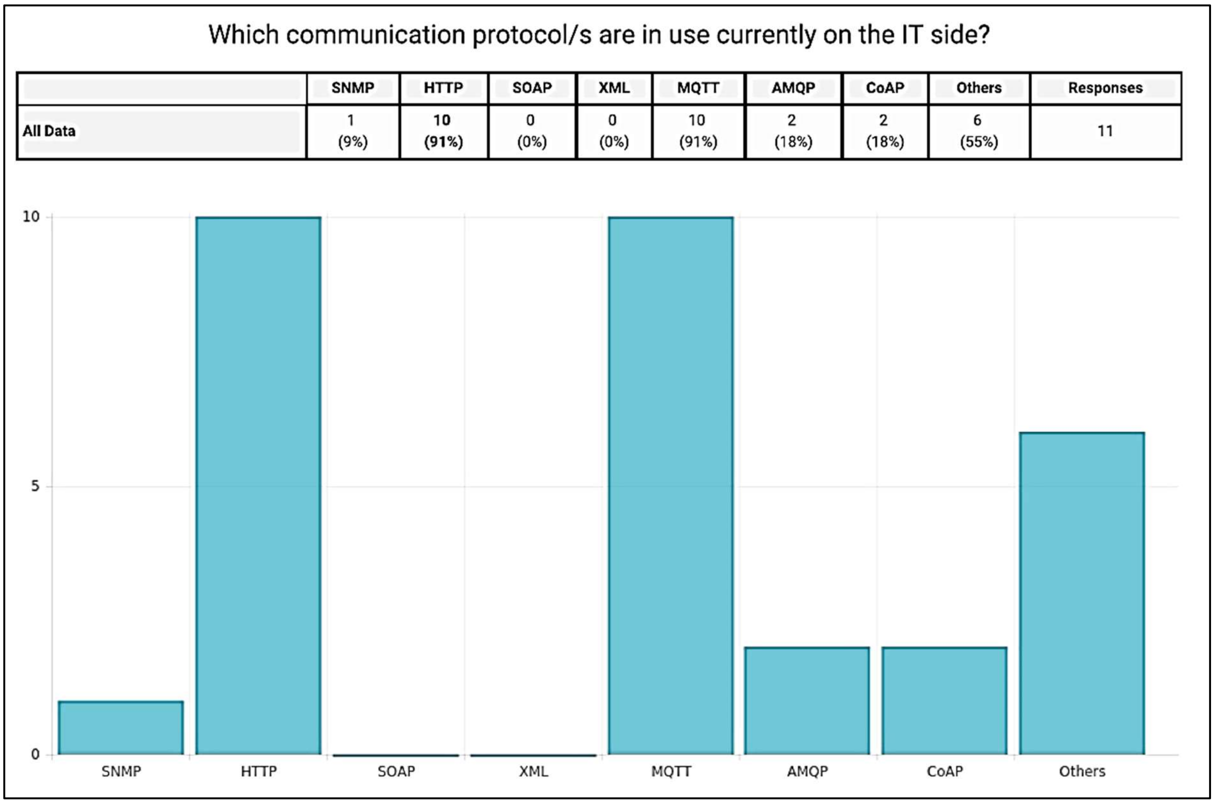


Figure 34: OT – Communication Protocols

6. Information Technology – Communication Protocols

On the IT side of the industrial network, HTTP and MQTT empowers data exchange with applications and services enabling PdM and CM. HTTP interface is used to access the historical data and MQTT for real-time data.



	SNMP	HTTP	SOAP	XML	MQTT	AMQP	CoAP	Others	Responses
All Data	1 (9%)	10 (91%)	0 (0%)	0 (0%)	10 (91%)	2 (18%)	2 (18%)	6 (55%)	11

Figure 35: IT – Communication Protocols

7. Data access for PdM and CM:

For effective PdM and CM, data availability is important. As per the survey participants, combination of sources is utilized to access the data. Persistent storage provides only historical data, whereas data from machines, PLCs is the real-time data. IIoT gateways delivers both historical and real-time data.

How does the PdM and CM systems access the data?

	Directly from machines	PLCs	IIoT Gateways	Persistent Storage	Private Cloud	Public Cloud	Responses
All Data	7 (64%)	7 (64%)	6 (55%)	8 (73%)	1 (9%)	2 (18%)	11

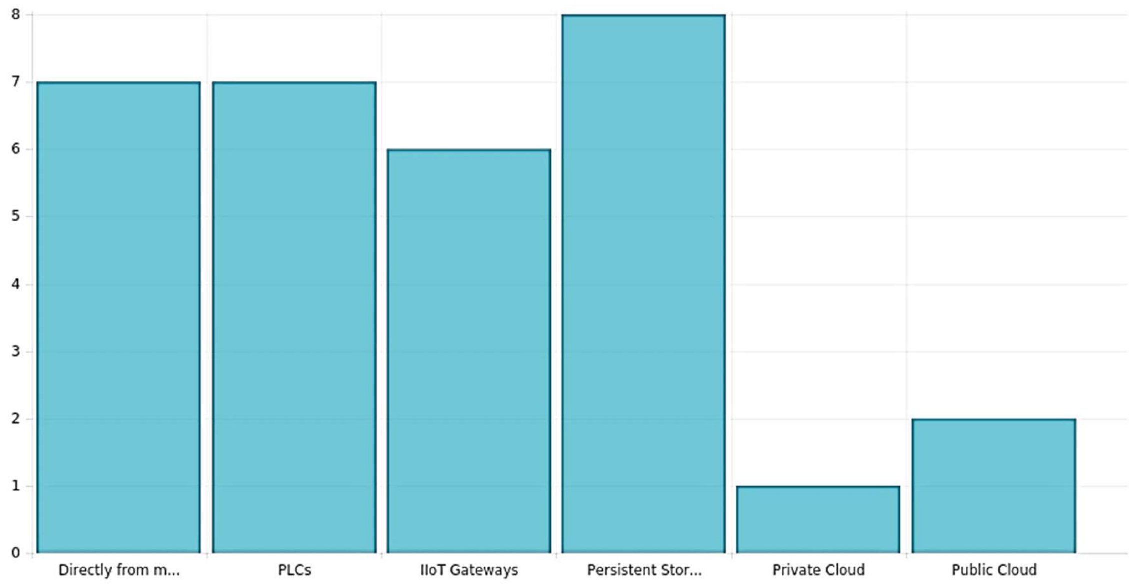


Figure 36: Interfaces for Data Access

8. Network Segmentation Policy:

In Section 3.3, Network Security, high level network segmentation is the policy which evolved in the industrial network with the era of industrial digitalization. 45% percent of the response from the survey indicates that they have network segmentation in place between OT and IT network.

Does your organization have network segmentation policy in place for the OT, IT and IIoT network? Between:

	OT - IT - IIoT	OT - IT	IT - IIoT	OT - IIoT	Responses
All Data	4 (36%)	5 (45%)	1 (9%)	1 (9%)	11

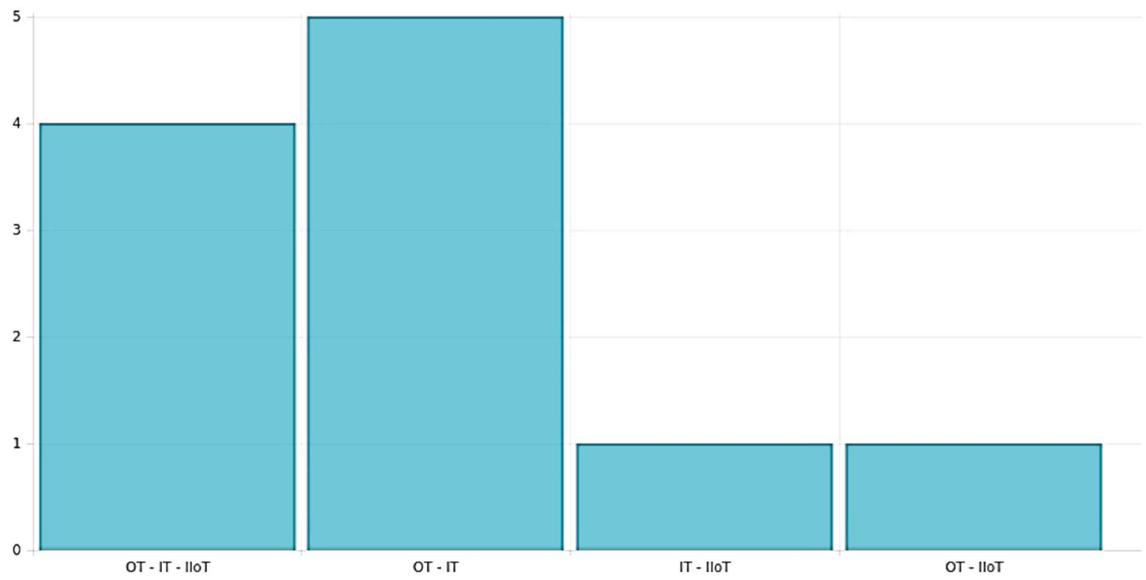


Figure 37: Network Segmentation – OT, IT, IIoT

9. Security and safety of PdM and CM components:

It can be seen from the below Figure 37 that majority of the participants agrees that security and safety mechanisms are very important for the components which serves PdM and CM ecosystem.

How critical is the security and safety mechanisms for the components involved for PdM and CM?

	Very Unimportant	Unimportant	Neutral	Important	Very Important	Not sure	Not Applicable	Standard Deviation	Responses	Weighted Average
Communication Network	0 (0%)	0 (0%)	1 (9%)	2 (18%)	**8 (73%)**	0 (0%)	0 (0%)	2.72	11	4.64 / 7
Communication Protocols	0 (0%)	0 (0%)	0 (0%)	4 (36%)	**7 (64%)**	0 (0%)	0 (0%)	2.61	11	4.64 / 7
Software, Services and Applications	0 (0%)	0 (0%)	2 (18%)	2 (18%)	**7 (64%)**	0 (0%)	0 (0%)	2.38	11	4.45 / 7
Data Storage	0 (0%)	0 (0%)	1 (9%)	2 (18%)	**8 (73%)**	0 (0%)	0 (0%)	2.72	11	4.64 / 7
Machines	0 (0%)	1 (9%)	2 (18%)	1 (9%)	**7 (64%)**	0 (0%)	0 (0%)	2.32	11	4.27 / 7
Computing Units	0 (0%)	1 (9%)	1 (9%)	2 (18%)	**6 (55%)**	1 (9%)	0 (0%)	1.92	11	4.45 / 7
IIoT gateways	0 (0%)	0 (0%)	1 (9%)	1 (9%)	**5 (45%)**	0 (0%)	4 (36%)	1.92	11	5.45 / 7
Private Cloud	0 (0%)	0 (0%)	0 (0%)	3 (27%)	2 (18%)	0 (0%)	**6 (55%)**	2.13	11	5.82 / 7
Public Cloud	0 (0%)	0 (0%)	0 (0%)	3 (27%)	2 (18%)	1 (9%)	**5 (45%)**	1.76	11	5.73 / 7
										4.9 / 7

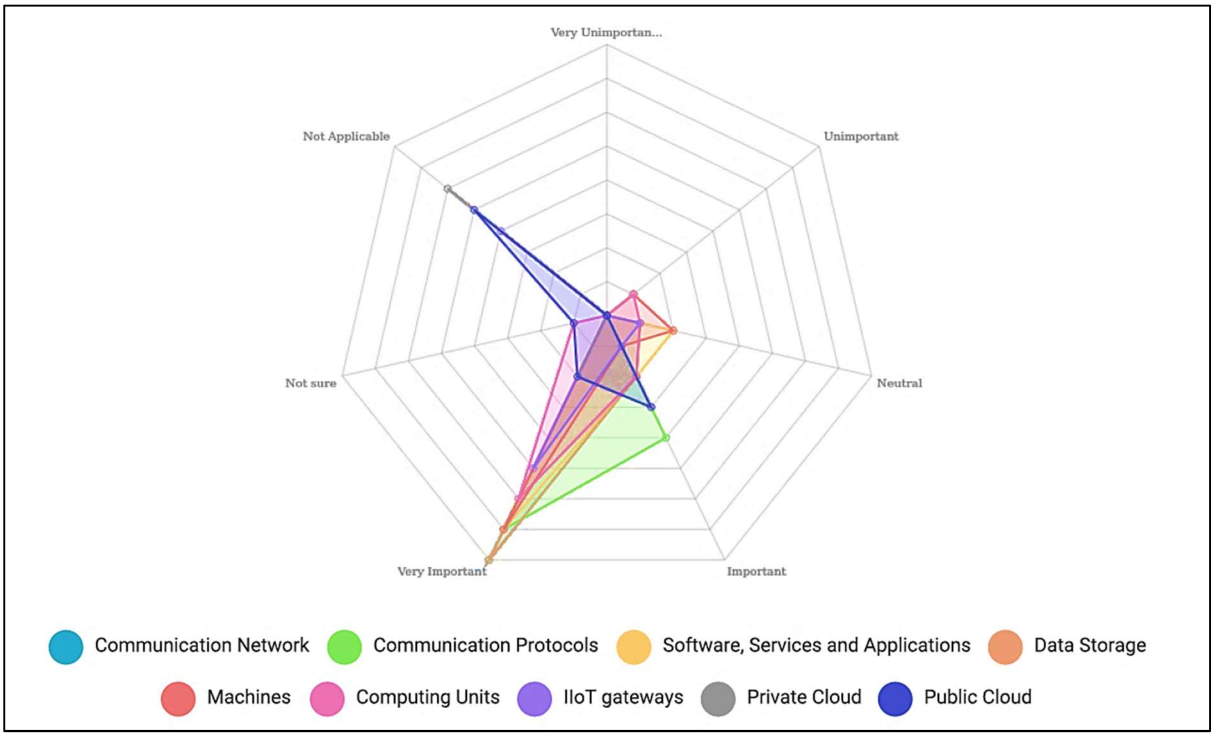


Figure 38: Network Segmentation – OT, IT, IIoT

10. Security and safety mechanisms:

For the security and safety of the ecosystem, security and safety objects, access management and risk assessment are the security and safety are some of the mechanisms which industries put in practice.

Which of the following security and safety mechanism/s are in place for the components involved for PdM and CM?

	Risk Assessment	Security and Safety Objectives	Threat Identification	Access Management	Breach Detection	Others	Responses
All Data	6 (55%)	9 (82%)	4 (36%)	9 (82%)	4 (36%)	6 (55%)	11

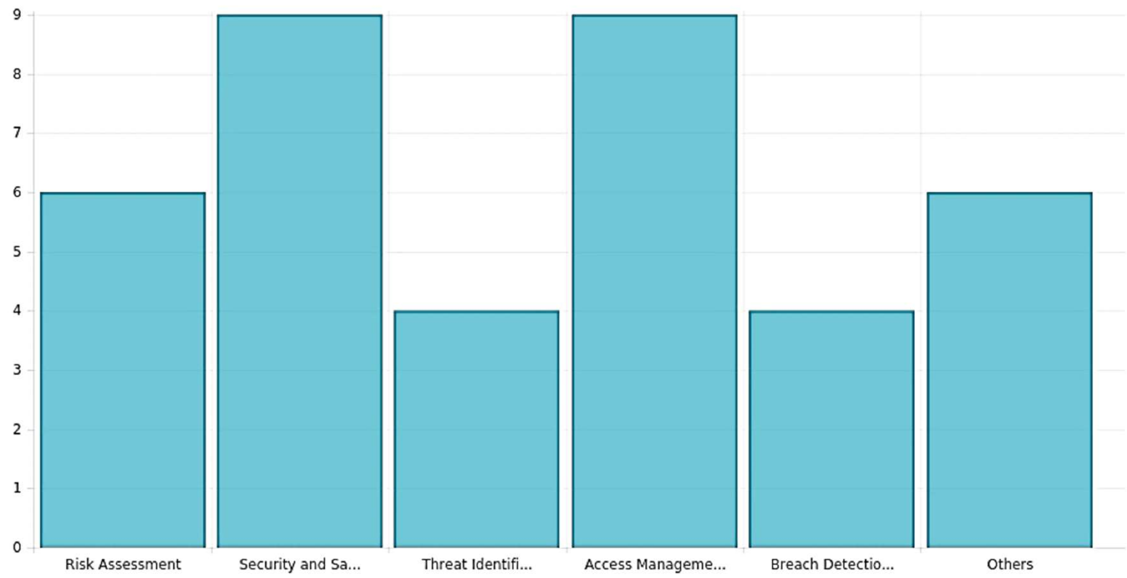


Figure 39: PdM and CM Components – Security and Safety Mechanisms

Results and findings

From ages, organizations are procuring solutions from market. Specialized machines, ERP systems, networking and database solutions etc. But in case of PdM and CM solutions, industry is not showing interest. The main reason behind is the fear of exposing their crucial data to the external solution providers. The trust factor is limited when it comes to the real process data from the machines because any leak of such confidential data can create highly adverse situation for the organization.

When organizations are limiting themselves from procuring external systems then it is understandable that there are very rare cases where the PdM and CM systems are managed by external teams or third party.

There are many components from the CPS ecosystem which are part of the PdM and CM ecosystem. Security and safety mechanisms are already enforced on the components of the CPS ecosystem but as the ecosystem is growing with the need of industrial digitalization, there are new components evolving. Components like OT wireless network, IIoT gateways, Edge and fog computing are very new to the industry. Lot of research has been done on the safety and security aspects of such new components but still there is a lack of confidence within the industries. As the new components become part of the ecosystem, change in security and safety mechanisms are required. Changes in the existing ecosystem regarding security and safety is a very crucial step because addition of one unsafe functionality can lead to exposure of the complete ecosystem.

For effective PdM and CM, the real-time data from the machines and historical data from persistent storage is very important. Condition monitoring systems rely on the real-time process data received from machines. The data flow can be directly from the machines or from other components. Predictive maintenance requires real-time data, stored data and knowledge base of the machine process to provide efficient maintenance schedule. Secure access to the data, exposing only required data to the PdM and CM systems and continuous data access logs are some of the safety and security mechanisms for PdM and CM ecosystem.

Some of the communication protocols used in the industry before industrial digitalization are not ready to be integrated to new IT and IIoT protocols. Security and safety aspects need to be reconsidered before the integration planning in such situations. When there are different protocols on each side of the network then it is complex procedure to put security and safety mechanisms in place. Evolved protocols like OPC UA, provides a seamless solution with integrated security and safety for communication from OT to the IT side and vice versa because it is the same protocol that can be used on both OT and IT side.

In conclusion, there are several safety and security mechanisms defined specifically for the PdM and CM ecosystem. Participants of the questionnaire approve that the security and safety mechanisms are very crucial for all the components which caters for PdM and CM ecosystem.

7.1.4 Result of RQ4: What are the challenges and how to improve them?

Chart generation and description

Which of the following needs improvement or optimization in terms of PdM and CM?

	Not Required	Neutral	Required	Highly Required	Do not know	Standard Deviation	Responses	Weighted Average
Security and Safety Mechanisms	0 (0%)	1 (9%)	4 (36%)	**6 (55%)**	0 (0%)	2.4	11	3.45 / 5
PdM and CM Systems Improvement	0 (0%)	1 (9%)	**6 (55%)**	4 (36%)	0 (0%)	2.4	11	3.27 / 5
Understanding of Benefits of PdM and CM	0 (0%)	3 (27%)	3 (27%)	**5 (45%)**	0 (0%)	1.94	11	3.18 / 5
Cost for Implementation	0 (0%)	3 (27%)	**5 (45%)**	1 (9%)	2 (18%)	1.72	11	3.18 / 5
Time for Implementation	0 (0%)	3 (27%)	**5 (45%)**	2 (18%)	1 (9%)	1.72	11	3.09 / 5
Time to Success	0 (0%)	2 (18%)	2 (18%)	**6 (55%)**	1 (9%)	2.04	11	3.55 / 5
Ease of Adaptation to existing ecosystem	0 (0%)	1 (9%)	2 (18%)	**8 (73%)**	0 (0%)	2.99	11	3.64 / 5
								3.34 / 5

Figure 40: Challenges and possible improvements 1

What are the main reasons for not making Predictive maintenance as a part of your organizational maintenance plans?

	Benefits not clear	Limited knowledge	Cost factor	Effectiveness factor	Existing ecosystem not ready	Security and safety concerns	Other	Responses
All Data	2 (12%)	3 (18%)	9 (53%)	8 (47%)	13 (76%)	**14 (82%)**	11 (65%)	17

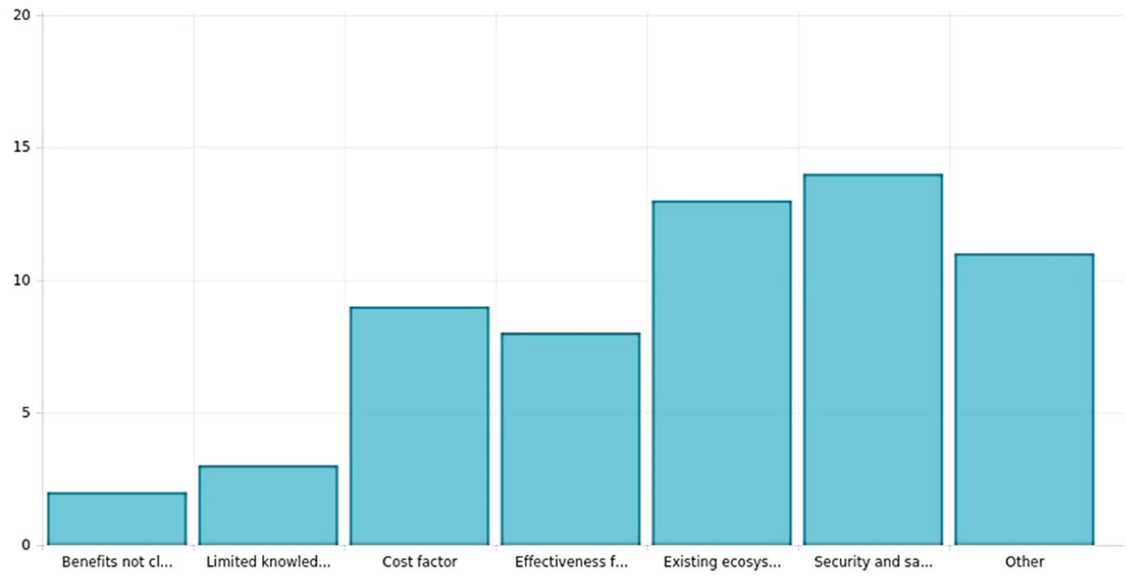


Figure 41: Challenges and possible improvements 2

Results and findings

PdM system cannot be used as standalone maintenance strategy in any organization. The reasons behind this are the maturity level of the PdM and CM system. Without the required process data, the PdM and CM systems cannot train themselves. As per the response from participants, the cost and time required for the implementation of the system need to be reduced so that it can be adapted earlier by the industries. The topmost problem is how to integrate such new systems in the old ecosystem, where a single bit of data is not sent by the machine. In rescue, there are multiple solutions from market but the reach to the actual process data is still far behind for such solutions. Security and safety is again highlighted in this research questions as the issue.

7.2 Qualitative Data Analysis Results

Qualitative data analysis is also executed into 4 different steps, which is described in the Section 5.1.2. Qualitative data has been collected for all the four research questions of this case study. After the data collection and data coding phase this section presents the next two phases of the qualitative data analysis strategy.

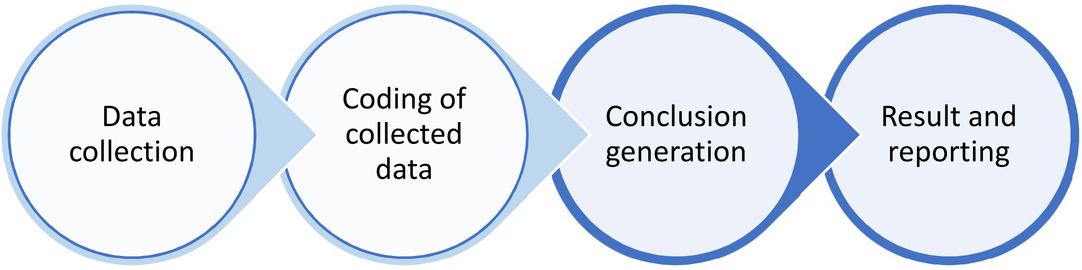


Figure 42: Active phases of qualitative data analysis to generate results and findings

The coded data from QDA Miner lite is further analyzed together with all the categories, sub-categories, codes and research questions.

7.2.1 Result of RQ1: How PdM and CM are integrated with cyber-physical systems

For this research question, three questions from the Table 4 (Section 6.1) have been asked during the focus group discussions.

Coded data with corresponding unit of analysis

1. Integration with cyber-physical systems:

Table 35: PdM and CM systems integrated with CPS ecosystem: FGDs

Code	Coded Text	Unit of Analysis
CPS Ecosystem	Edge tier and platform tier. We are already working on enterprise tier.	Project Sicon Gateway and Services
	employee can monitor the condition physically with a NFC reader	J. Schmalz GmbH
	PdM systems are with maintenance team in the production area.	J. Schmalz GmbH
	Monitoring from HMIs	J. Schmalz GmbH
	System applications in different areas of the factory	J. Schmalz GmbH

2. E-Maintenance:

Table 36: Acceptance level of E-Maintenance: FGDs

Code	Coded Text	Unit of Analysis
E-maintenance	control custom parameters based upon their need	Project Sicon Gateway and Services
	Maintenance is also limited from our applications like calibration of some sensors or change of parameters.	Project Sicon Gateway and Services
	E-maintenance not at all planned	J. Schmalz GmbH
	About remote maintenance, it is a thing of future because of security and safety of the machines.	J. Schmalz GmbH
	yes, if the Io-link master is connected to the IT network then it can be enabled	J. Schmalz GmbH

3. E-Monitoring:

Table 37: Acceptance level of E-Monitoring: FGDs

Code	Coded Text	Unit of Analysis
E-Monitoring	customer can monitor their devices anywhere within the factory on a desktop or mobile device that how their devices are performing in real time and they can also notice if there is something wrong	Project Sicon Gateway and Services
	We only allow monitoring on the production floor and one level above	Project Sicon Gateway and Services
	E-monitoring is planned but can't say when	Project Sicon Gateway and Services
	E-monitoring capability is sort of implemented in the system but not enabled	Project Sicon Gateway and Services
	We have monitoring in external cloud applications plan in the pipeline, but there is no definite response from customers.	Project Sicon Gateway and Services
	yes, if the Io-link master is connected to the IT network then it can be enabled	J. Schmalz GmbH

Results and findings

Similar to the findings from the quantitative analysis, in qualitative analysis for the RQ1, the outcome from both the FGDs about the integration in the CPS system is on the edge tier and platform tier. On the edge tier, NFC reader and devices, HMIs are mentioned. For the platform tier, system applications in different areas of the factory are mentioned.

Remote maintenance can be done but due to the limited control over the devices from remote location only certain parameters can be changes from the factory premises. Remote maintenance can be understood as a second level once the confidence level of security and safety is achieved. Also, the underlying systems need to be upgraded to enable remote maintenance.

Remote monitoring is enabled in many industries but up to certain level, like monitoring anywhere within the company premises etc.

7.2.2 Result of RQ2: What kinds of benefits can CM and PdM bring

For this research question, three questions from the Table 4 (Section 6.1) have been asked during the focus group discussions.

Coded data with corresponding unit of analysis

1. Benefits and effect of CM on equipment:

Table 38: CM system – Benefits and their effects: FGDs

Code	Coded Text	Unit of Analysis
Effect of CM	customer can monitor their devices anywhere within the factory on a desktop or mobile device that how their devices are performing in real time and they can also notice if there is something wrong	Project Sicon Gateway and Services
	minimum downtime	Project Sicon Gateway and Services
	availability of the device during operational hours	Project Sicon Gateway and Services
	generate alerts if there is anything wrong with the equipment on the floor.	Project Sicon Gateway and Services
	system operator can access the status information of the device anytime	J. Schmalz GmbH
	Process faults recognized earlier	J. Schmalz GmbH
	Optimizations can be planned according to the existing status of the device	J. Schmalz GmbH
	smaller issue can be identified at earlier stage to avoid bigger issues	J. Schmalz GmbH
	measurement of device parameters	J. Schmalz GmbH
	leakage triggers received from devices	J. Schmalz GmbH
	similar to the benefits of CM	J. Schmalz GmbH

2. Benefits and effect of PdM on equipment:

Table 39: PdM system – Benefits and their effects: FGDs

Code	Coded Text	Unit of Analysis
Effect of PdM	less downtime and more production time	Project Sicon Gateway and Services
	I would like to give is that a customer never wants his machine gets repaired during the operation time. If we can give him an alert that their machine will soon need maintenance	Project Sicon Gateway and Services
	profitable maintenance	Project Sicon Gateway and Services
	less inventory of the parts	Project Sicon Gateway and Services
	reduce labor cost and sudden machine downtime	Project Sicon Gateway and Services
	maintenance team can plan the maintenance more precisely with advance maintenance plans	Project Sicon Gateway and Services
	reduce their efforts to find a solution to the problem	Project Sicon Gateway and Services
	safety of the on-field employee is also increased because potential issues can be identified and fixed before they occur	Project Sicon Gateway and Services
	most efficient, cost effective	J. Schmalz GmbH
	like the benefits of CM	J. Schmalz GmbH
	maintenance and repairs proactively planned, avoid costly downtime, increase availability	J. Schmalz GmbH

3. Additional maintenance strategy with PdM:

Table 40: Maintenance strategies in parallel with PdM: FGDs

Code	Coded Text	Unit of Analysis
Maintenance Strategies	Corrective maintenance	Project Sicon Gateway and Services
	Reliability-centered maintenance	Project Sicon Gateway and Services

Results and findings

The benefits which are observed in the FGDs are close to the mentioned in literatures and industrial reports. Some of the common verbs are minimum downtime, maximum availability, anywhere anytime monitoring and earlier fault detection.

There are benefits from the device lifetime perspective and from the organizational profitability as well. Important point has been noticed that one of the benefit also states that the employee safety on the production floor is also increased because potential issues can be identified earlier and fixed before they occur.

7.2.3 Result of RQ3: What are the security and safety analysis aspects of the ecosystem concerning PdM and CM

For this research question, several questions from the Table 4 (Section 6.1) have been asked during the focus group discussions.

Coded data with corresponding unit of analysis

1. Management of PdM and CM systems:

Table 41: Management of PdM and CM systems: FGDs

Code	Coded Text	Unit of Analysis
PdM and CM system manager	We only provide system software updates and provide customized applications as per the customer need. But we do not have any control over the system in production in the customer premise. So, it is managed by the organization itself.	Project Sicon Gateway and Services
	Maintenance team	J. Schmalz GmbH
	IT team	J. Schmalz GmbH

2. Data storage for PdM and CM:

Table 42: Data storage for PdM and CM: FGDs

Code	Coded Text	Unit of Analysis
Data Storage	database on the gateway	Project Sicon Gateway & Services
	internal server for the backup and archival purpose	Project Sicon Gateway & Services
	SQLite database	Project Sicon Gateway & Services
	stored data from the database	Project Sicon Gateway & Services
	persistent storage	Project Sicon Gateway & Services
	devices have some inbuilt memory where the data from last use cycle is stored and replaced by next cycle.	J. Schmalz GmbH
	total cycles data is also stored on device, device management system	J. Schmalz GmbH
	systems on the production floor, database servers	J. Schmalz GmbH

3. Operational Technology – Communication Protocols:

Table 43: OT – Communication Protocols: FGDs

Code	Coded Text	Unit of Analysis
OT – Communication Protocols	OPC UA, IO-Link, MQTT, Rest API, HTTP, CAN BUS, EtherNet/IP, PROFINET, Modbus	Project Sicon Gateway & Services
	IO-Link, OPC UA, PROFIBUS, http, EtherCAT, PROFINET, Fieldbus	J. Schmalz GmbH

4. Information Technology – Communication Protocols

Table 44: OT – Communication Protocols: FGDs

Code	Coded Text	Unit of Analysis
IT – Communication Protocols	OPC UA, MQTT, Rest API, HTTP, WebSocket, Socket.IO	Project Sicon Gateway & Services
	OPC UA, http, MQTT	J. Schmalz GmbH

5. Data access for PdM and CM:

Table 45: IT – Communication Protocols: FGDs

Code	Coded Text	Unit of Analysis
Data Access	Real-time data	Project Sicon Gateway & Services
	SQLite database	Project Sicon Gateway & Services
	IODD files	Project Sicon Gateway & Services
	live data from IO-Link masters	J. Schmalz GmbH
	OPC UA enabled devices	J. Schmalz GmbH
	from devices directly using NFC reader	J. Schmalz GmbH
	device management system, SPS	J. Schmalz GmbH
	systems on the production floor, data storage servers	J. Schmalz GmbH

6. Security and safety of PdM and CM components:

Table 46: Security and safety of PdM and CM components: FGDs

Code	Coded Text	Unit of Analysis
Security and Safety	Each service or set of services and applications are dockerized on the gateway with their own network and ports so we minimize the possibility of a breach.	Project Sicon Gateway & Services
	No process or service can communicate directly within the gateway	Project Sicon Gateway & Services
	Each service or application must communicate via a shared channel, i.e. MQTT and database access service. We log all the connection and data access on these common channels.	Project Sicon Gateway & Services
	user role bound	Project Sicon Gateway & Services
	only limited device parameters can be changed like device calibration and vacuum modes	J. Schmalz GmbH
	this is the area where most of the research work is done, extremely critical	J. Schmalz GmbH
	All the industrial level mechanisms are in place, control events are possible only from production floor	J. Schmalz GmbH
	Extra security of the data, only authorized entities can access the data till certain extent	J. Schmalz GmbH
	no singleton application, hardware has the full access rights of complete data or network.	J. Schmalz GmbH

Results and findings

Somehow similar results to the quantitative data analysis results. Additional aspects are some other IT protocols like Socket.IO, Websockets and on the OT side IO-Link has been given a lot of space. Another important finding is that defining a common channel for the data exchange, so the data access logs can be generated on the channel and regular monitoring of such logs can prevent potential threats.

Further, all the security and safety mechanisms need to be rethought and reapplied from base for the PdM and CM systems, as such systems are integrating with the CPS ecosystem and any potential security issue can arise.

7.2.4 Result of RQ4: What are the challenges and how to improve them

For this research question, several questions from the Table 4 (Section 6.1) have been asked during the focus group discussions.

Coded data with corresponding unit of analysis

1. PdM and CM challenges

Table 47: PdM and CM Challenges: FGDs

Code	Coded Text	Unit of Analysis
PdM and CM Challenges	If we can predict something correctly then this is the best case	Project Sicon Gateway & Services
	profitable maintenance if the prediction is correct	Project Sicon Gateway & Services
	E-maintenance not at all planned	Project Sicon Gateway & Services
	We have monitoring in external cloud applications plan in the pipeline, but there is no definite response from customers	Project Sicon Gateway & Services
	challenge for the PdM systems is the maturity level and cost factor	Project Sicon Gateway & Services
	Costly + Existing ecosystem of most of the companies worldwide is not ready to be digitalized	Project Sicon Gateway & Services
	fear is regarding the safety of the production machines	Project Sicon Gateway & Services
	They do not want to allow any activities to be performed virtually	Project Sicon Gateway & Services
	PdM is not made for every industry or organization	Project Sicon Gateway & Services
	Some organizations are very small that a PdM solution is a significant burden on their financial backbone	Project Sicon Gateway & Services
	For some organizations other maintenance solutions are more fruitful	Project Sicon Gateway & Services
	PdM and CM systems cannot be successful without correct data and learning	Project Sicon Gateway & Services
	Manual methods like Visual inspection, noise monitoring etc. by an employee on the production floor cannot be replaced by strategies like PdM	Project Sicon Gateway & Services
	Cost + Effectiveness + Adaptability + Safety are the most vital challenges out of other problems	Project Sicon Gateway & Services
	asset management and device condition cannot be completely monitored from remote location	J. Schmalz GmbH
	Wireless technology is missing on the production floor, where a worker can roam around with wireless handheld device and monitor the condition of devices	J. Schmalz GmbH

2. PdM and CM possible improvements

Table 48: PdM and CM possible improvements: FGDs

Code	Coded Text	Unit of Analysis
PdM and CM Improvements	dynamic knowledge capturing and improvement of algorithms.	Project Sicon Gateway & Services
	Improvement is less time to success, less costly and highly secure	Project Sicon Gateway & Services
	Improvement is a mixed maintenance strategy from my perspective	Project Sicon Gateway & Services
	Improvement is only knowledge gathering over time and making the systems more mature	Project Sicon Gateway & Services
	speed of data analysis	Project Sicon Gateway & Services
	The less learning time for PdM systems can be a improvement	J. Schmalz GmbH
	More intelligence embedded on the device is a possible improvement and this will also minimize the concern of safety.	J. Schmalz GmbH

3. Security and safety challenges

Table 49: Security and safety Challenges: FGDs

Code	Coded Text	Unit of Analysis
Security and safety challenges	fear is regarding the safety of the production machines	Project Sicon Gateway & Services
	They do not want to allow any activities to be performed virtually	Project Sicon Gateway & Services
	Safety is highly crucial as relying on only PdM can lead to severe issues	Project Sicon Gateway & Services
	only limited device parameters can be changed like device calibration and vacuum modes	J. Schmalz GmbH
	this is the area where most of the research work is done, extremely critical	J. Schmalz GmbH
	All the process and production data are stored in company premise, this needs lot of hardware resources and energy. Today, in the era of cloud solutions when we can store data and run applications without owning the hardware, we still cannot be assured of data security.	J. Schmalz GmbH
	Wireless technology is missing on the production floor, where a worker can roam around with wireless handheld device and monitor the condition of devices	J. Schmalz GmbH

Security and safety possible improvements:

Table 50: Security and safety possible improvements: FGDs

Code	Coded Text	Unit of Analysis
Safety and security Improvements	solutions which give industries confidence about the safety of their equipment and embedded security solutions at each part of the system.	Project Sicon Gateway & Services
	Improvement maybe optimization of the system from different viewpoints like data flow encryption, restricted access to the system, algorithms improvement	Project Sicon Gateway & Services
	More intelligence embedded on the device is a possible improvement and this will also minimize the concern of safety.	J. Schmalz GmbH

Results and findings

As the complete process data is not available or accessible in most of the industries, it is difficult to train the PdM systems and also only certain parameters can be monitored. This leads to the ineffectiveness of the complete PdM systems. Cost factor cannot be neglected because lot of equipment need to be upgraded on factory floor to connect every equipment to the industrial network to achieve effective PdM and CM.

PdM is also not adaptable for every industry because of numerous reasons. Industries where maintenance activities are performed rarely have no plans to invest in something which they do not use. Smaller industries where only limited maintenance work is done are also denying the extra burden of cost. Not only the cost but also such industries refrain themselves to expose their data to systems which are not profitable for them. It can be concluded that PdM strategy is not optimal for every industry and multiple factors need to be considered before implementing such solutions.

8 Conclusion and Future Work

This case study is aimed to research the benefits of the PdM and CM systems for the manufacturing industry and the security and safety aspects of such systems. Through an embedded case study, 2 semi-structured FGDs and 1 questionnaire survey were conducted to study the subject of this case study. To answer the 4 RQs (Section 4.2), both quantitative and qualitative analysis haven been completed.

RQ1, RQ2, RQ,3, RQ4: Both quantitative and qualitative data have been analyzed. For quantitative data analysis, questionnaire survey has been conducted and the data is transformed in to coded tables as well as charts to explain the results of the data analysis. Qualitative data has been coded and analyzed to present more details about the outcome of this case study.

There has been a very limited research done about the security and safety aspects for the predictive maintenance and condition monitoring. In conclusion, Predictive maintenance strategy and condition monitoring methodology has been studied from the literature, project reports and available case studies. This case study has been conducted to generate finding about the benefits of methodologies like predictive maintenance and condition monitoring and how security and safety aspects influence such systems.

8.1 Implication for Practitioners

This study presented the benefits of the predictive maintenance and condition monitoring methods. The benefits, effects and limitations can be used to optimize the systems further for smart industries.

This study also investigated the security and safety aspects of predictive maintenance and condition monitoring. The challenges and improvements are also presented. Till now very limited research has been done, specially on the security and safety of predictive maintenance and condition monitoring systems. The investigation can be further taken as reference to understand the current standing problems and what are the viewpoints need to be considered before integration or adaptation of PdM and CM systems.

8.2 Contribution to Academic Research

The lack of research for the security and safety aspects of PdM and CM systems has been the motivation behind this case study. This study has presented a whole new picture of the PdM and CM ecosystem that how important is to consider every component's security and safety.

Though previous studies and research on benefits of predictive maintenance and condition monitoring has presented a lot of positive factors. This case study investigated on the negative factors as well. The conclusion from this case study, that predictive maintenance is not for every industry will be a viewpoint to research further.

8.3 Future Work

This case study included quantitative and qualitative data analysis on the data collected from questionnaire survey and focus group discussions. It would be interesting to take this research through practical analysis from the industries. Measurement like time, cost and efforts to make the PdM and CM system successful. Furthermore, the security and safety aspects of such systems need to be investigated in depth.

New methods like PdM 4.0 have evolved and there are more security and safety aspects need to be considered for the industry. Advancements in the data flow and industrial connectivity has already triggered a lot of research in the field of security and safety of Industry 4.0 ecosystem. PdM and CM are a crucial part of the new industrial revolution. Future work also requires making the PdM and CM system much more flexible and remote monitoring can be achieved securely.

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Appendix A.1: Questionnaire Survey

In this section the questionnaire survey questions are presented with their available input options.

1* Does your organization have predictive maintenance and condition monitoring strategy in place?

- [ ] Yes
- [ ] No

2 Which condition-based monitoring methods are currently being applied in your organization?

- [ ] Vibration analysis and diagnostics
- [ ] Wear debris analysis
- [ ] Noise monitoring
- [ ] Lubricant analysis
- [ ] Infrared thermography
- [ ] Visual inspection
- [ ] Acoustic based analysis
- [ ] Oil analysis
- [ ] Energy consumption monitoring
- [ ] Other

3 On which tiers of the Cyber Physical System ecosystem, Predictive Maintenance and Condition Monitoring systems are in place in your organization?
CPS – Cyber Physical System
Please refer to this image: ibb.co/n8uFnH

- [ ] Edge Tier
- [ ] Platform Tier
- [ ] Enterprise Tier

4 Does your organization allows remote maintenance?

- [ ] Yes
- [ ] No

5 Does your organization allows remote monitoring?

- [ ] Yes
- [ ] No

6 How do you rate effect of CM on equipment in your organization?

CM – Condition Monitoring

	Ineffective	Needs some improvement	Neutral	Effective	Very Effective	Do not know
Availability	1	2	3	4	5	-
Reliability	1	2	3	4	5	-
Overall Equipment Effectiveness	1	2	3	4	5	-

7 How do you rate effect of PdM on equipment in your organization?

PdM – Predictive Maintenance

	Ineffective	Needs some improvement	Neutral	Effective	Very Effective	Do not know
Availability	1	2	3	4	5	-
Reliability	1	2	3	4	5	-
Reduction in Operational Risk	1	2	3	4	5	-
Reduction in Maintenance Cost	1	2	3	4	5	-
Reduction in Operational Cost	1	2	3	4	5	-
Overall Equipment Effectiveness	1	2	3	4	5	-

8* Any other maintenance strategy in place with PdM?

- ☐ Corrective Maintenance (run-to-failure)
- ☐ Preventive Maintenance
- ☐ Reliability-centered Maintenance
- ☐ Other

9 Who is provider of PdM and CM systems for your organization?

- ☐ Internal Developed Systems
- ☐ Third Party Developed
- ☐ Hybrid - Internal and third party

10 Who manages the PdM and CM systems for your organization?

- ☐ Internal Team
- ☐ Internal Team from different location
- ☐ Outsourced

11 Which components in your organization contributes for PdM and CM?
OT – Operational Technology
IT – Information Technology

- ☐ OT Wired Network
- ☐ OT Wireless Network
- ☐ IT Wired Network
- ☐ IT Wireless Network
- ☐ IIoT Gateways
- ☐ Data Storage
- ☐ Private Cloud
- ☐ Public Cloud
- ☐ Edge computing
- ☐ Fog computing
- ☐ Others

12 Where do you store the generated data from machines for PdM and CM?

- ☐ IIoT Gateways
- ☐ Private Cloud
- ☐ Public Cloud
- ☐ Internal Data Storage Server
- ☐ Remote Data Storage Server
- ☐ Others

13 Which communication protocol/s are in use currently on the OT side?

- ☐ OPC UA
- ☐ Modbus
- ☐ PROFINET
- ☐ PROFIBUS
- ☐ IO-Link
- ☐ EtherNet/IP
- ☐ CAN bus
- ☐ Others

14 Which communication protocol/s are in use currently on the IT side?

- ☐ SNMP
- ☐ HTTP
- ☐ SOAP
- ☐ XML
- ☐ MQTT
- ☐ AMQP
- ☐ CoAP
- ☐ Others

15 How does the PdM and CM systems access the data?

- ☐ Directly from machines
- ☐ PLCs
- ☐ IIoT Gateways
- ☐ Persistent Storage
- ☐ Private Cloud
- ☐ Public Cloud

16 Does your organization have network segmentation policy in place for the OT, IT and IIoT network?

Between:

☐ OT - IT - IIoT ☐ OT - IT ☐ IT - IIoT ☐ OT - IIoT

17 How critical is the security and safety mechanisms for the components involved for PdM and CM?

	Very Unimportant	Unimportant	Neutral	Important	Very Important	Not sure	Not Applicable
Communication Network	1	2	3	4	5	6	7
Communication Protocols	1	2	3	4	5	6	7
Software, Services and Applications	1	2	3	4	5	6	7
Data Storage	1	2	3	4	5	6	7
Machines	1	2	3	4	5	6	7
Computing Units	1	2	3	4	5	6	7
IIoT gateways	1	2	3	4	5	6	7
Private Cloud	1	2	3	4	5	6	7
Public Cloud	1	2	3	4	5	6	7

18 Which of the following security and safety mechanism/s are in place for the components involved for PdM and CM?

- ☐ Risk Assessment
- ☐ Security and Safety Objectives
- ☐ Threat Identification
- ☐ Access Management
- ☐ Breach Detection
- ☐ Others

19 Which of the following needs improvement or optimization in terms of PdM and CM?

	Not Required	Neutral	Required	Highly Required	Do not know
Security and Safety Mechanisms	1	2	3	4	5
PdM and CM Systems Improvement	1	2	3	4	5
Understanding of Benefits of PdM and CM	1	2	3	4	5
Cost for Implementation	1	2	3	4	5
Time for Implementation	1	2	3	4	5
Time to Success	1	2	3	4	5
Ease of Adaptation to existing ecosystem	1	2	3	4	5

20* Which maintenance strategies are currently being in use in your organization?

- ☐ Corrective Maintenance (run-to-failure)
- ☐ Preventive Maintenance
- ☐ Reliability-centered Maintenance
- ☐ Other

21 What are the main reasons for not making Predictive maintenance as a part of your organizational maintenance plans?

- ☐ Benefits not clear
- ☐ Limited knowledge
- ☐ Cost factor
- ☐ Effectiveness factor
- ☐ Existing ecosystem not ready
- ☐ Security and safety concerns
- ☐ Other

22 Does your organization have any plans to adapt to the Predictive Maintenance strategy for maintenance?

- ☐ Already started
- ☐ Within 1 year
- ☐ In next 3 years
- ☐ No plans
- ☐ Do not know

Appendix A.2: Focus Group Discussion Questions

1. How condition monitoring is beneficial?
2. How predictive maintenance is beneficial?
3. Do you have or in future planned other maintenance strategies?
4. On which tiers of the CPS ecosystem, PdM and CM systems are currently in place?
5. What about e-monitoring?
6. What about e-maintenance?
7. Who manages the PdM and CM systems for the organization?
8. Which components in the Industry contribute for PdM and CM?
9. Where do you store the data generated and collected from machines?
10. Do the organization has any other possibility to store the data somewhere else?
11. Which communication protocol/s our system supports currently on the OT and IT side?
12. How does the PdM and CM systems access the data?
13. How is the system connected to network and how can external components connect to the system?
14. How critical is the security and safety for the components involved for PdM and CM?
15. Which security and safety mechanism/s are in place or planned for the components involved for PdM and CM?
16. How are the services and applications running on gateway for PdM and CM are safe and secure?
17. For the complete ecosystem of PdM and CM systems:
    What are the current challenges?
    What are the possible improvements and how we can bring them to the system?

18. For the safety and security of PdM and CM systems:
    What are the current challenges?
    What are the possible improvements and how we can bring them to the system?

Appendix B: Raw Data, Coding Tables and Coded Tables

After coding process for the qualitative and quantitative data analysis, the coded results are demonstrated in the form of coding table, which has been extensively used to analyze the research questions.

The collected data for the analysis process is in the form of transcript, excel tables and in QDA miner tool.

1. Case Study - QDA Miner Lite.qdp
2. RQ1.xls
3. RQ2.xls
4. RQ3.xls
5. RQ4.xls

All collected data and coded data can be found in the attachment of the master thesis.