Architecture of the Data Collecting System of Figueira da Foz Mill

Mário Filipe Batalha Reis

Thesis to obtain the Master of Science Degree in

Information Systems and Computer Engineering

Supervisors: Prof. José Luís Brinquete Borbinha

Eng. Duarte Miguel Filipe

Examination Committee

Chairperson: Paolo Romano

Supervisor: Prof. José Luís Brinquete Borbinha

Member of the committee: Paulo Miguel Nogueira Peças

September 2020

Acknowledgments

I would like to thank The Navigator Company and Instituto Superior Técnico for the opportunity given.

To Eng.º Duarte Filipe, my sincerest thank you for always being available to my questions and for the support you had given me. Without your contribution and shared knowledge, I would not have been able to develop this investigation.

To my Parents, Margarida and Mário, and my sister, Joana, for all the support, patience and encouragement given to me throughout the years.

To Maria, my girlfriend, for all the unconditional support since I can remember, and for always believing in me even when I did not. I cannot thank her enough for all the motivation and kindness.

Lastly, to all my friends who have helped and supported me, both in the good and bad times.

To each and every one of you, thank you.

Abstract

In a world that is becoming utterly technologic and innovative, the need to update traditional industries is crucial in order to minimize losses while maximizing their market value.

Being the Pulp and Paper Industry one of the largest in the world, and considering all environmental and governance issues, this work focuses on the identification of data that is being collected and stored, having as background the case study of The Navigator Company – not only using the potential of the industry 4.0 (the latest revolutionary path that involves a decentralisation of the control for a more effective production), but also taking into account their goal to achieve predictive maintenance by preventing asset failure, as it analyses production data to identify patterns and potential risks.

Considering that the Company does not have the information organized and available to the people who need it to work, a data collecting system architecture was designed, containing all subsystems that are crucial to better assess the mill's relevant data and gaps which were found throughout the production process.

Therefore, and bearing in mind the Company's familiarity with SAP PowerDesigner, this tool was used and an UML visual modeling profile was created to model the architecture of the data collecting system of the Figueira da Foz mill.

Keywords

Industry 4.0, Predictive Maintenance, Pulp and Paper, Data Collecting System

Resumo

Num mundo que se está a tornar cada vez mais tecnológico e inovador, a necessidade de atualização das indústrias tradicionais é fundamental para minimizar perdas e maximizar o seu valor de mercado.

Sendo a Indústria da Pasta e do Papel uma das maiores do mundo, e tendo presente todas as questões ambientais e de Governança, este trabalho versa a identificação dos dados que são coletados e armazenados, tendo como pano de fundo o caso de estudo da The Navigator Company – que não só frui do potencial da indústria 4.0 (o mais recente caminho revolucionário que tem por base a descentralização do controlo para uma produção mais efetiva), mas também tem em conta o seu objetivo de alcançar a manutenção preditiva através da prevenção de falhas de ativos, uma vez que analisa os dados de produção a fim de identificar padrões e riscos potenciais.

Considerando que a Empresa não possui informação organizada nem acessível às pessoas que necessitam dela para trabalhar, foi concebida uma arquitetura do sistema de coleta de dados contendo todos os subsistemas essenciais para melhor avaliar as lacunas da fábrica que foram encontradas ao longo do processo de produção.

Assim, e tendo presente a familiarização da Empresa com o SAP PowerDesigner, esta ferramenta foi utilizada e um perfil de modelação visual UML foi criado de modo a modelar a arquitetura do sistema de recolha de dados da fábrica da Figueira da Foz.

Palavras Chave

Indústria 4.0, Manutenção Preditiva, Pasta e Papel, Sistema de Recolha de Dados

Contents

List of Figures

List of Tables

List of Acronyms

LABET – Laboratório de Ensaios de Termodinâmica e Aeroespaciais

MES – Manufacturing Execution System

MIS – Mill Information System

PROFIBUS-DP – Process Field Bus-Decentralized Peripherals

RAMI4.0 – Reference Architectural Model for Industry 4.0

SCADA – Supervisory Control and Data Acquisition

SysML – Systems Modelling Language

1 Introduction

The pulp and paper industry is one of the largest and most vital industries Worldwide. Through its supply chains, this Industry reaches more than 5 billion customers' needs. Pulp and papermaking are intricate processes which encompass several, and often very distinct processing areas, such as wood preparation and those regarding the conversion of pulp, chemical improvement, whitening, and papermaking to finally convert wood into paper or another desirable product [1].

In order to face the Industrial needs, the fourth industrial revolution brought the concept of decentralized control and sophisticated connectivity (Internet of Things features), which lead to the reorganization of industrial production systems, and the flexibility of mass customed production and quality enhancement. Consequently, big Industries and Enterprises felt the need to keep up with the demands of this entirely technological World, and The Navigator Company, one of the world's largest companies in the paper industry, was no exception.

The Navigator Company is an integrated producer of forest, pulp and paper, tissue and energy, and whose activity is based on modern large-scale factories with state-of-the-art technology and a benchmark of quality in the industry. The Company's business model is developed based on an excellent raw material - Eucalyptus globulus - whose intrinsic characteristics allow the development of a strategy of differentiation, based on high quality products, which are now an international reference in this sector.

Considering that both equipment conditions and production process are equally important for the good function of the mill, Predictive Maintenance (PdM) techniques were brought to attention, due to predicting future failures in assets and ultimately prescribing the most effective preventive measures by applying advanced analytic techniques on big data about technical aspects such as condition, usage, environment, or maintenance history.

This way not only appropriate maintenance is given, but also the consumption of resources and energy are optimized, leading to continuous improvement.

1.1 The Problem and Objectives

In a globalized, technological World (where the need to keep up with the latest developments is vital), big companies and industries have the need to reinvent themselves in order to correctly deliver their products in a fast, effective way. The Navigator Company is no exception, and, through this work, the goal is to conceive a way to help this Enterprise achieving predictive maintenance and thus improving the production process with reduce costs and waste of resources.

The Navigator Company plans to implement an Asset Performance Management (APM) - a system that is intended to help optimise the performance of its assets by connecting different data sources and using advanced analytics to turn data into actionable insights. This system will integrate the Company's existing plant systems to collect data but they do not have the information regarding the identification of the assets and data that was being collected, how it was being collected and where it was stored, organized and available to the people who need it to work, which not only limits it to its innovation objectives based on the potential of the Industry 4.0 vision, but can also help them change the way their maintenance works, and consequently the production and management of the mill.

Considering what was previously said, this work aims to contribute to the solution of this problem, which involves the identification of all data sources, the creation of a catalog with the different systems that collect data and what data is retrieved, and the modelling of the data collecting systems architectures', in order to understand what useful data is being collected and what other sets of data collection would be of interest for further analysis.

1.2 Structure of the Document

Apart from this introductive chapter, this document is organised as follows: Chapter 2 covers the Related Work regarding the Pulp and Paper Industry, Industry 4.0, the Internet of Things and the Automation Pyramid. Chapter 3 centres its core in the Analysis of the Problem and specifies The Navigator Company's case both when contextualizing the Pulp and Paper Industry applied to this Company, and regarding how is maintenance done within the mill. It also focuses on the Visual Modelling Profile, and an overview of the system is established. Chapter 4 aims to cover the main aspects that constitute the Process and Quality Data Subsystems. Chapter 5 enumerates the existing specialized data subsystems, regarding vibration, maintenance, inspection, and lubrication – which are vital to keep the production process running in the most efficient and effective way. Finally, chapter 6 will show the conclusions regarding this case analysis, as well as what needs to be done after this study.

2 Related Work

In this chapter is present the research done in the context of the work.

2.1 Pulp and Paper Industry

The pulp and paper industries supply an essential product – paper - to over 5 billion consumers worldwide. Papermaking started off as a slow, labour-intensive activity. Currently however, pulping and papermaking are driven by capital-intensive technical equipment and high-tech and high-speed machines which are able to produce paper rolls at speeds that may reach 2 000 miles per minute and with a web width that may exceed eight metres [1].

The official definition of the ISO 4046 (2002), 'Paper, board, pulps and related terms', matches mainly with the definition of the CEPI list: on a wider sense, the term 'paper' could also be used to describe both paper and board. They are, however, different, and primarily distinguished based on thickness or grammage, although in some cases the differentiation considers other characteristics and/or end use. Illustratively, some materials of lower grammage, such as grades of folding boxboard and corrugating raw materials, are generally referred to as 'board', while other materials of higher grammage, in addition, grades of blotting paper, felt paper and drawing paper, are mainly denominated as 'paper' [2].

The pulp for papermaking may be produced from virgin fibre by chemical or mechanical means or by the repulping of paper for recycling (RCF). In Europe, wood is the foremost raw material - paper for recycling has a quota of about 50% of all the fibres used - but in exceptional cases grass, cotton, hemp, amongst other cellulose-bearing materials may also be used. Figure 2.1 depicts a run-through of the pulping and papermaking processes.

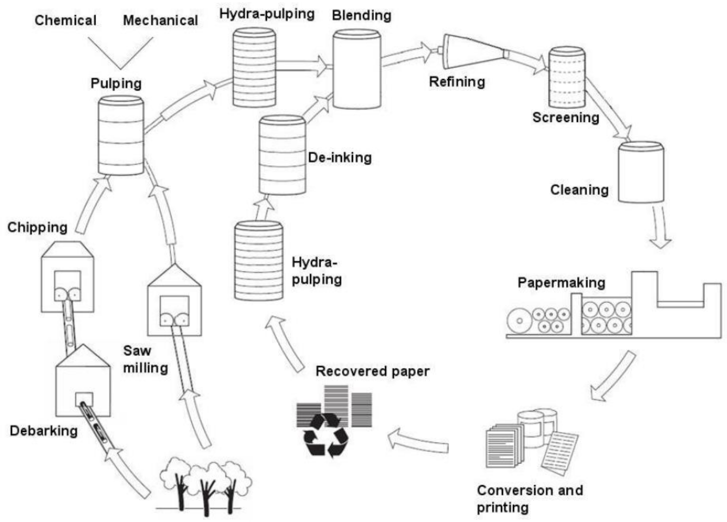


Figure 2.1: The papermaking process

The precise composition of wood varies according to the type and species used, but the most important components are cellulose, hemicellulose and lignin.

Wood naturally contains around 50% water and the solid fraction is typically about 45% cellulose, 25% hemicelluloses, 25% lignin and 5% other organic and inorganic materials. In chemical pulping, chemicals are employed to dissolve the lignin and free the fibres.

The lignin and many other organic substances are therefore placed into a solution from which the chemicals and the energy content of the lignin and other organics are recovered. The extent of this recovery is reliant upon the chemical base used and the process configuration. In mechanical pulping processes, mechanical shear forces are used to pull the fibres apart and most of the lignin remains with the fibres although there is still dissolution of some organics.

Pulp and paper mills may exist independently or as integrated operations. An integrated paper mill conducts pulp manufacturing on-site. Pulp can be generated by mechanical or chemical methods. In mechanical pulping, wood is pressed against a grinder which destroys the wood matrix splitting the fibres from each other. This type of pulping preserves the main part of the lignin, achieving high yield (≈95%) with tolerable strength properties and brightness. However, it is linked with a low resistance in aging which tends to discolour. This technique is used for softer paper materials such as newspapers, paperbacked books and magazines. Chemical pulping eliminates non cellulose wood components leaving the cellulose fibres intact throughout the cooking of raw materials with a solution of chemicals under a higher pressure, employing kraft (sulphate), sulphite or soda procedures. Chemical pulping yields approximately 50% but offers higher strength properties and the fibres are more easily bleached. This type of pulping is used on most papers produced commercially in the world today.

In Europe, more than 50% of the fibres from the paper industry come from paper through recycling. The fibres can be reused numerous times depending on the condition of the recycled material and the function of the end product. The paper product may also comprise up to 45% of its weight in fillers, coatings and other non-fibrous substances. Collection and sorting are essential steps, which establish to a great extent the quality of the paper for recycling. Separate assortment contributes to high levels of recycling [3].

However, pulp and paper industry is one of the largest polluting productions. The effluent of a pulp and paper mill contains an abundance of different substances, both organic and inorganic. The particulate material is mainly made up of wood fibres while soluble pollutants become part of the wastewater through various rejected flows from purification and separation processes within the pulp and paper mill [4]. The German industry has documented high growth levels for the past 20 years resulting in a rise of paper production by 75% from 1991 to 2008 [5].

2.2 Industry 4.0

2.2.1 Background and Definition

The first industrial revolution began with the mechanization that was introduced to manufacturing in 1800s. It brought the shift from manual work to the first manufacturing processes, mainly in textile industry. An improved quality of life was the most pursuing goal.

The second industrial revolution was caused by the electricity adaptation in factories which started to experience the birth of mass production.

The third industrial revolution is illustrated by the digitalization with the introduction of microelectronics and automation which facilitates flexible production as a variety of products manufactured on flexible production lines with programmable machines.

The fourth industrial revolution began with the development of Information and Communications Technologies (ICT). Its technological basis is smart automation of Cyber-Physical Systems (CPS) with decentralized control and advanced connectivity (Internet of Things functionalities). The effect of this new technology for industrial production systems is the restructuring of classical hierarchical automation systems to self-organizing cyber physical production system that allows flexible mass custom production and flexibility in production quantity [6].

Figure 2.2 shows the evolution from Industry 1.0 to Industry 4.0.

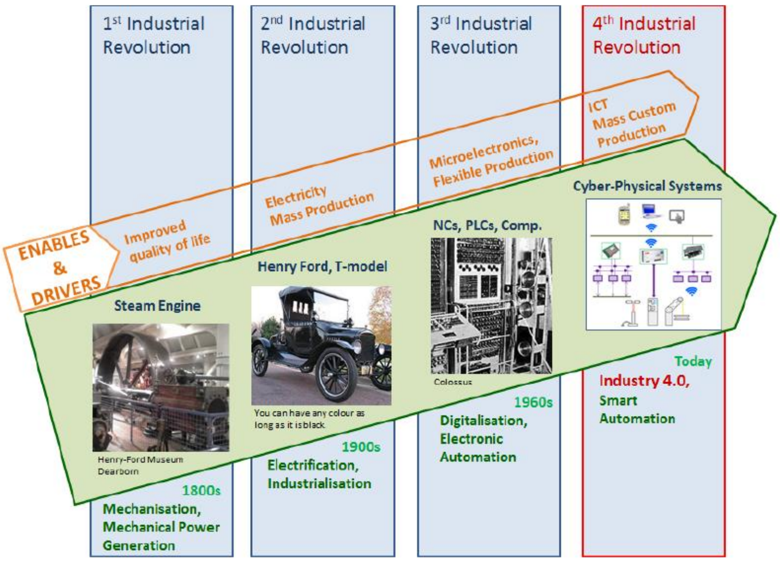


Figure 2.2: Industrial Revolutions

The 4.0 industry was initially introduced during the Hannover Fair in 2011.

Furthermore, it was officially announced in 2013 as a German strategic initiative to take a ground-breaking role in industries which are revolutionizing the manufacturing sector [7] at the moment.

The term Industry 4.0 stands for the fourth industrial revolution [8] and its vision is that in the future, industrial businesses will build global networks to connect their machinery, factories, and warehousing facilities as cyber-physical systems, connecting and controlling each other intelligently by sharing information which will not only generate autonomous but also easily adaptable improved machines, factories and facilities, allowing smart supply-chains to emerge [9].

Cyber-physical system (CPS) seeks the integration of computation and physical processes. This implies that computers and networks can monitor the physical process of manufacturing a certain process. On the other hand, Internet of Things (IoT) is what enables objects and machines such as mobile phones and sensors to “communicate" with each other as well as human beings to present solutions.

The incorporation of such technology allows objects to work and solve problems independently. The Internet of Services (IoS) aims at designing a wrapper that simplifies all connected devices to make the most out of them by shortening the process. It is the customer's gateway to the manufacturer. Industry 4.0 is a collective term for technologies and concepts of value-chain organizations. Within the modular structured smart factories of Industry 4.0, CPS monitor physical process generates a virtual copy of the physical world and makes decentralized decisions. Over the IoT, CPS communicates and cooperates with each other and humans in real time. Via the IoS, both internal and cross organizational services are offered and utilized by participants of the value chain.

2.2.2 Design Principles of Industry 4.0

According to Herman, there are four design principles for Industry 4.0 that support companies in identifying possible Industry 4.0 pilots, which then can be implemented [10]:

1. **Interconnection:** with the Internet of Everything (IoE), machines, devices, sensors and people are interconnected and can share information. There are three types of collaboration: human-human collaboration, human-machine collaboration and machine-machine collaboration. To make interconnection seamless, common communication standards are very important. This also makes it so that smart factories of Industry 4.0 are able to adapt to fluctuating market demands or personalized orders.
2. **Information transparency:** With the increase in the interconnected objects and people in the IoE, a new form of information transparency is enabled. Context aware information is essential to make correct decisions. Context-aware systems use information from both the virtual and physical world to accomplish their tasks. Raw sensor data needs to be aggregated to higher-value context information and analysed. This analysis needs to be embedded in assistance systems accessible to all IoE participants, including real-time information when needed.
3. **Decentralized decisions:** Using the interconnected objects and people and the transparency of information, decentralized decision-making becomes possible which also increases overall productivity. Tasks are usually performed autonomously and are only escalated in some exceptions, such as interferences or conflicting goals. Decentralized decisions are enabled by CPS.
4. **Technical assistance:** Humans can operate machines as well as make strategic decisions and problem solve when necessary. However, where CPS form complex networks and make decentralized decisions, humans are supported by assistance systems. Currently, smartphones and tablets are essential in connecting humans with the Internet of Things (IoT). Furthermore, these types of wearable technology should become increasingly important. Robots are another important aspect of technical assistance as they enable a range of tasks that are unpleasant, too exhausting or unsafe for humans. It is important that people are properly trained for such interactions and that robots can perform them as smoothly and intuitively as possible.

2.2.3 Key Technologies of Industry 4.0

This section describes eight technology trends that are the building blocks of Industry 4.0 and explores their potential:

- **Cloud Computing (The Cloud):** The large datasets involved in Industry 4.0 mean that data sharing will be not only desirable but imperative to leverage the full possibilities within the value chain. The Cloud is a way of storing and accessing data and programs over the internet. Cloud services that deliver real-time information and scalability can sustain a multitude of devices and sensors, along with all the data they generate [8].

- **Industrial Internet of Things (IIoT):** Describes a way to connect digital and physical systems with the goal to improve devices. The IIoT will bring improvements on equipment and unfinished products, such as embedded computing, whilst still using traditional technologies to link devices. Therefore, field appliances/devices/apparatuses are enabled to communicate and work as it fits, either with each other or with more unified controllers. [11].
- **Big Data and Analytics:** There is a need to gather data from many different sources, organize it in a cohesive way, and use the analytics supplied by the datasets to support management's decision-making. Their analysis will not only improve production quality but also save energy, improve services and allow real-time decision-making [10].
- **Augmented Reality:** The aim of Augmented reality is to increase the user's perception of reality. It incorporates 3D virtual objects into real environment in real-time. Manufacturers are turning to augmented-realitybased systems to enhance their maintenance procedures while lowering the costs of having experts on site [12].
- **Autonomous Robots:** The use of robots in the manufacturing process is no longer new; however, robots are also subject to improvements and evolution. Cooperation and automation are two vital features which will enable machines to work alongside humans with safety and the capacity to learn. [11].
- **Simulation:** Computer simulations have been used for years to determine the best possible design for production and distribution systems. However, future simulations will be used more extensively in plant operations as well. These mock-ups will leverage real-time data to reflect the physical world in a virtual model, which can include machines, products and humans [13].
- **Cyber-security:** With the increased connectivity and use of standard communication protocols brought by Industry 4.0 (there is also and increasing necessity to safeguard vital parts of the production process and industrial systems. Therefore, safe and reliable communications, management access, and identification are vital to shield organizations from growing cyber-security risks [11].
- **Additive Manufacturing:** It is also known as 3D printing and is a technology that has been around for at least three decades. Additive manufacturing enables manufacturers to come up with prototypes and proof of concept designs, which greatly lowers design time and effort. It also enables production of small batches of customized products that offer more value to customers or end users, while reducing cost and time inefficiencies for the manufacturer [14].

2.2.4 Reference Architectural Model for Industry 4.0 (RAMI4.0)

Identifying and structuring an architecture or model can be a long, tedious process with much negotiation to abstract from specific needs and technologies. Reference Architecture can serve as an overall generic guideline. However, not all domain applications will require each detail for real-life implementation.

RAMI4.0 is a reference architecture for smart factories which started in Germany and today is driven by all major companies and foundations in the relevant industry sectors [15]. This reference architecture seeks to focus on four aspects, including horizontal integration through value networks, vertical integration within a factory, lifecycle management and end-to-end engineering, and human beings orchestrating the value stream [15]. The reference architecture model RAMI4.0 is a three-dimensional layer model that shows how to approach the deployment of Industry 4.0 in a structured manner and has been put forward for standardization as DIN SPEC 91345 [16].

The first dimension consists of the hierarchy levels, the second the life cycle and value stream, and the third and final dimension covers the layers [16]. Figure 2.3 shows the Reference Architecture Model of Industry 4.0 (RAMI4.0).

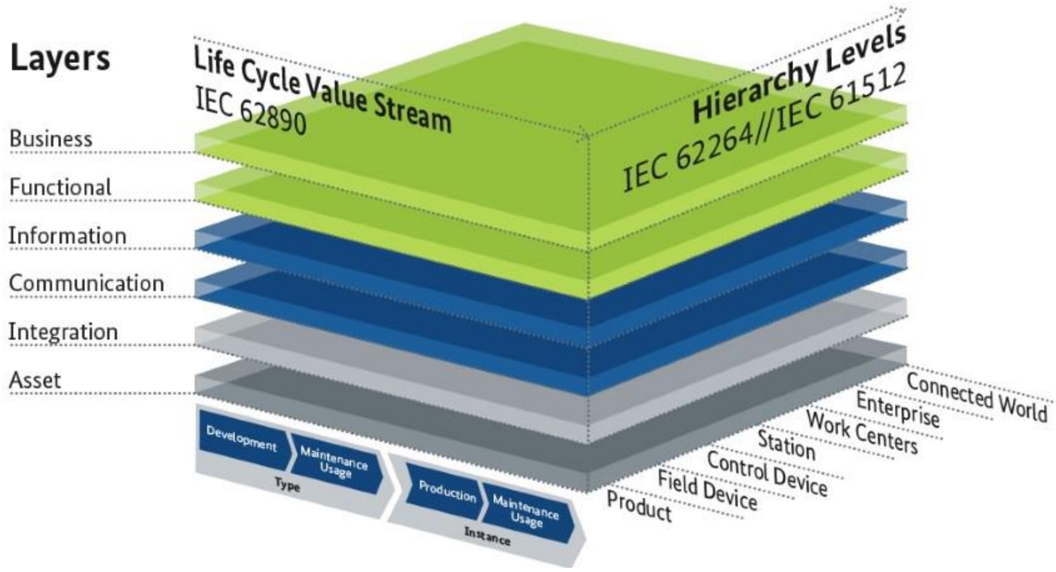


Figure 2.3: Reference Architecture Model of Industry 4.0 (RAMI4.0)

2.2.4.1 Hierarchy Levels

The first dimension exemplifies a functional hierarchy, and not the equipment classes or hierarchical levels of the classical automation pyramid. The right horizontal axis of the reference architecture model illustrates the functional classification of various circumstances within Industry 4.0. The issue here is not the implementation, but solely functional assignment. For classification within a factory, this axis of the architecture reference follows the IEC 62264 and IEC 61512 standards (For a uniform consideration covering as many sectors as possible from process industry to factory automation, the terms “Enterprise", “Work Unit", “Station" and “Control Device" were chosen from the options enumerated and used). For Industry 4.0, not only the control device (e. g. head controller) is decisive, but also considerations about a machine or system. Subsequently, the “Field Device" has been added below the Control Device. This represents the functional level of an intelligent field device (e. g. a smart sensor).

Furthermore, not only the plant and machinery for the manufacture of products is important in Industry 4.0, but also the product to be manufactured itself.

It has therefore been added as “Product" in the bottom level. As a result, the reference architecture model allows homogeneous consideration of the product to be manufactured and the production facility, with their interdependencies. An addition has also been made at the upper end of the hierarchy levels. The two IEC standards mentioned only the levels represented within a factory. Industry 4.0, however, goes a step further and describes the group of factories, and the cooperation with external engineering firms and component providers and customers. Therefore, and beyond the Enterprise level, the “Connected World" has been added [17].

2.2.4.2 Life Cycle and Value Stream

This dimension represents the product life cycle with the value streams it contains. This is displayed along the left-hand horizontal axis. Dependencies, including constant data acquisition throughout the life cycle, can also be well represented in the reference architecture model. Industry 4.0 offers great potential for improvement throughout the life cycle of products, machines, factories, and so on. The draft of IEC 62890 is a good guideline for consideration of the life cycle. The fundamental distinction between type and instance is utterly important in those considerations [18].

- **Type:** It is always created with the initial idea, as a product comes into the development phase. This covers the placing of design orders, development and testing up to the first sample and prototype production. The type of the product or machine is thus created in this phase. When all tests and validation are concluded, the type is released for series production.
- **Instance:** Products are industrially manufactured based on the general type. Each manufactured product then represents an instance of that type and has a unique serial number. The instances are then sold and delivered to customers. For the customer, the products are initially once again only types. They become instances when they are installed in a particular system. The change from type to instance may be repeated several times.

The product improvements report back to the manufacturer from the sales phase can lead to an adjustment of the type documents. The newly created type can then be used to manufacture new instances. Like any other individual instance, then, the type is also subject of use and updating. The digitization and linking of value streams in Industry 4.0 provides huge potential for improvement. Links spanning various functions are of absolute importance in this connection. Logistics data can be used in assembly and intralogistics organizing themselves based on the order backlog. Purchasing sees inventories in real time and knows where parts from suppliers are at any given moment. The customer sees the product completion status ordered during production, and so on. The linking of purchasing, order planning, assembly, logistics, maintenance, the customer and suppliers provides great improvement potential. The life cycle therefore has to be viewed together with the value-adding processes it contains, and not just a view to a single factory, but rather in the collective of all the factories and all the parties involved, from engineering through component suppliers to the customer.

2.2.4.3 Layers

Layers are used in the vertical axis to represent various perspectives, such as data maps, functional descriptions, communications behaviour, hardware/ assets or business processes. This corresponds to IT thinking where complex projects are split up into clusters of manageable parts.

This last dimension consists of six layers [17,18]:

- **Asset Layer:** The layer represents not only physical components such as robots, PLCs, metal parts, documents and archives, but also non-physical objects such as software and ideas. Human beings are also included in the Asset Layer and are linked to the virtual world via the Integration Layer.
- **Integration Layer:** Provides information on the assets (physical components, hardware, documents, software, etc.) in a form which can be digitally processed. It includes elements connected to IT such as sensors, RFID readers, integration to HMI and computer-aided control of technical processes. Interaction with humans also takes place on this level, for instance via the Human Machine Interface (HMI).
- **Communication Layer:** This layer provides standardized communication using uniform data format and predefined protocols between the integration and information layers. For example, the role of communication is to transmit and receive data using TCP/IP, HTTP/ FTP protocols, transmission through LAN or WAN, and interface through BLE (Bluetooth Low Energy) or Wi-Fi devices.
- **Information Layer:** Describes the rules of how data is represented and transformed into useful information. The main goal of this layer is to give information about the total number of sales, purchase orders information, suppliers and location. It carries information about all products and materials that are manufactured in the industry. It also gives information on the machines and components that are used to build products. It provides information to customers and saves their feedback. Information is software based as it might be in the form of application or data facts, figures, and files.
- **Functional Layer:** The layer is responsible for production rules, actions, processing and system control. It also includes the functionality of virtualized asset operations and a formal description of functions. ERP functions also belong to this layer. Furthermore, it involves various other activities like coordination of components, system power on/off, testing elements, delivery channels, user inputs, and functions including (but not limited to) alert lights, snapshots, and touch screen and fingerprint authentication.

- **Business Layer:** It represents the commercial view on the information exchange related to industrial processes. It deals with promotions and offers, target locations, advertisements, CRM, Budget and Pricing Model, and Manufacturing and Cost Analysis. It also maps out the business models and the resulting overall process. Legal and regulatory framework conditions are provided and includes links between different business processes.

2.2.5 Predictive Maintenance

Predictive maintenance is a method of avoiding asset failure by analysing production data in order to detect patterns and foresee issues before they happen. By spotting deterioration earlier than it could be detected by manual means, reliability increases. This earlier detection provides the maintenance workers more time to intervene - hopefully enough to avoid failure [19]. These projections are based on the equipment's condition which is assessed based on the data gathered using numerous condition monitoring sensors and techniques.

A predictive maintenance program can reduce unscheduled breakdowns of all mechanical and electrical equipment in the plant and make sure that repaired equipment is in appropriate conditions.

For years to come, and as a result of more automation and new technologies, maintenance will gradually be more important for improving availability, product quality, fulfilment of safety requirements, and plant cost-effectiveness [20].

According to Haarman et al. [21], PdM 4.0 focuses on forecasting future failures in assets and ultimately suggesting the most effective precautionary measure by applying advanced analytic techniques on big data about technical condition, usage, environment, maintenance history, similar equipment elsewhere and, in fact, anything possibly relating to the performance of an asset. A PdM Maturity Matrix is illustrated in Figure 2.4, where four "maintenance revolutions" show the increased level of reliability and need for data and statistics [21].

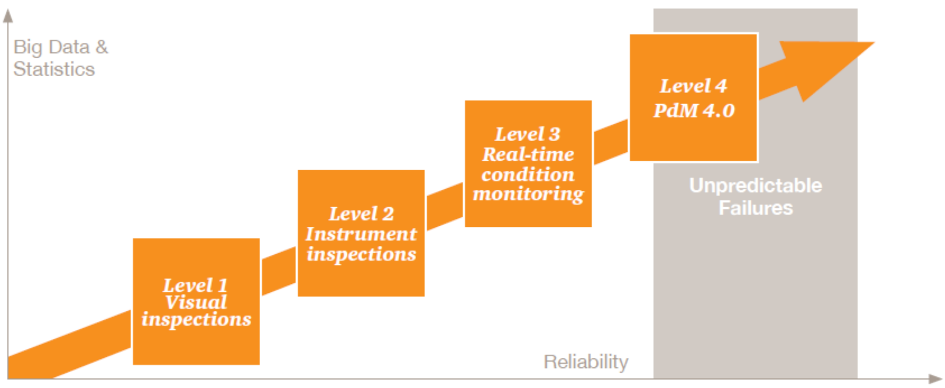


Figure 2.4: Predictive Maintenance Maturity Matrix

The first level of the maturity matrix is visual inspections where periodic physical inspections are made, and the conclusion is based solely on inspector's expertise.

The second level is Instrument inspections which is periodic; conclusions are based on a combination of inspector's expertise and instrument read-outs.

The third level is Real-time condition monitoring: continuous real-time monitoring of assets, with warnings given established on pre-determined rules or critical levels.

Finally, the fourth level is PdM 4.0 which involves continuous real-time monitoring of assets and external data (e.g. environmental data, usage, etc.) with alerts based on predictive techniques such as regression analysis, for at least one important asset.

2.2.5.1 Functioning of Predictive Maintenance

According to SEEBO[1], for predictive maintenance to be carried out on an industrial asset, the following base components are essential:

1. ***"Sensors:*** *data-collecting sensors positioned in the physical product or machine.*
2. ***Data communication:*** *the communication system that allows data to securely flow between the monitored asset and the central data store.*
3. ***Central data store:*** *the central data hub in which asset data (from OT systems), and business data (from IT systems) are stored, processed and analysed; either on premise or on-cloud.*
4. ***Predictive analytics algorithms:*** *employed to the aggregated data in order to identify patterns and generate insights in the form of dashboards and alerts.*
5. ***Root cause analysis:*** *data analysis tools used by maintenance and process engineers to investigate the insights and determine the corrective action to be performed."*

Production asset data is streamed from the sensors to a central repository using industrial transmission protocols and gateways. Business data from Enterprise Resource Planning (ERP) and Manufacturing Execution System (MES) systems, together with manufacturing process flows, are integrated into the central data repository to provide context to the production asset data. Then, predictive analytics algorithms are applied to provide insights for reducing downtime, which is investigated using root cause analysis software. Figure 2.5 shows a predictive maintenance architecture.

[1] Seebo (2020). Seebo's website *https://www.seebo.com/predictive-maintenance/, accessed on September 6th, 2020.*

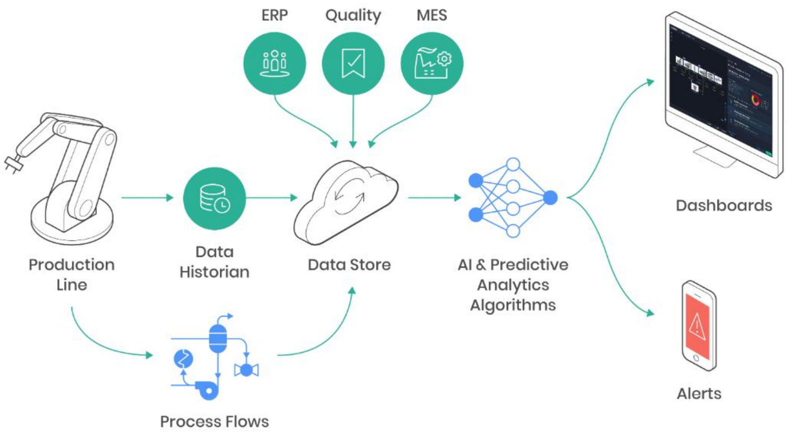


Figure 2.5: Predictive Maintenance Architecture

According to Coleman et al. [22], understanding how PdM works also requires an examination of the specific connected technologies that enable it: sensors and communication protocols, analytics and data-handling tools, and data visualization and collaborative tools.

2.2.5.2 Benefits of Predictive Maintenance

Manufacturers and their customers get a range of business advantages from predictive maintenance.

Here are presented the main reasons to do PdM:

- Improves availability and reliability.
- Increase of the life span of equipment.
- Saves maintenance costs by reducing repair costs.
- Increases safety [23].
- Increases revenue.
- Reduces downtime from equipment failures [23].
- Minimizes the number of failures of critical equipment.
- Decreases the number of maintenance operations causes decreasing of human error influence.
- Production quality is optimized by operating machinery without interruption due to failures [24].
- Profit of predictive maintenance increases with the underlying maintenance costs.
- Reduction of energy consumption.
- Detection of the root causes of the failures [25].

2.2.5.3 Predictive Maintenance Techniques

The main PdM techniques to monitor the performance and condition of equipment or systems in order to detect degradation are the following:

- **Vibration Monitoring:** Once most plants consist of electromechanical systems, vibration monitoring is very used to detect misalignment, imbalance, defective bearings, mechanical looseness, defective rotor blades or any other structural problem. It involves assessing the condition of the rotating components such as pumps, motors, turbines and compressors [19].
- **Thermography:** Procedure that can be used to monitor not just electrical equipment, but the condition of plant machinery, structures, and systems, not just electrical equipment. There are three types of instruments that are generally used as part of an efficient predictive maintenance program [26]: infrared thermometers which typically monitors bearing cap temperatures, motor winding temperatures, spot checks of process piping temperatures, and similar applications; line scanners that offer a one-dimensional scan or line of comparative; and infrared imaging which unlike other infrared techniques, provide the means to scan the infrared emissions of full machines, process, or equipment in a very short time. Most of the imaging systems operate much like a video camera and the user can see the thermal emission profile of a wide area by merely looking through the instrument's optics.
- **Tribology:** A general term that refers to design and operating dynamics of the bearing-lubrication-rotor assistance structure of machinery. Two primary techniques are being used for predictive maintenance [26]: lubricating oil analysis which establishes the condition of lubricating oils used in mechanical and electrical equipment but it is not a tool to determine the operating condition of machinery or detect potential failure modes; and wear particle analysis that provide direct information about the wearing condition of the machine-train. Particles in the lubricant of a machine can deliver significant information about the machine's condition.
- **Ultrasonics:** Ultrasonics, as vibration analysis, is a subset of noise analysis. The only distinction between the two techniques is the frequency band they monitor. In the case of vibration analysis, the monitored range is between 1 Hertz (Hz) and 30,000 Hz; Ultrasonics screens noise frequencies above 30,000 Hz. These higher frequencies are helpful to pick out applications, such as detecting leaks that generally create high-frequency noise triggered by the expansion or compression of air, gases, or liquids as they flow through the orifice, or a leak in either pressure or vacuum vessels. These higher frequencies are also effective in measuring the ambient noise levels in various areas of the plant [26].

2.3 Internet of Things

2.3.1 Internet of Things in Pulp and Paper Industry

Pulp and paper manufacture are highly complex and integrate many different process areas including wood preparation, pulping, chemical recovery, bleaching and papermaking to convert wood to the final product. Therefore, and in order to optimize the forest performance and consequent process control in such severe process conditions, stable and accurate solutions are needed [1] in order to minimize manufacturing setbacks, such as the stops and starts in pulp production, the consumption of resources and energy optimization, and/or the support of the monitor paper production monitorization in order to support continuous improvement.

Therefore, we can consider the Internet of Things (IoT) as the ultimate leader of transformation which drives down costs, increases throughput, and gains a competitive edge with costumers.

The Internet of Things (IoT) is a sort of network technology linking sensitive apparatuses to a range of wireless communication equipment, being able to smartly monitor and position thanks to gathered data. Therefore, it facilitates management and control, and due to these characteristics, it can keep evolving as it gathers data from increasingly smart networking equipment. It can be said the IoT distinguishes itself through its wide range of comprehensive sensor technology; identifiable RFID tags; and suitable and flexible embedded system technology [27].

When speaking of the pulp and paper industry, which is facing an industrial revolution (industry 4.0), it will very soon be able to link product customization with large production series, linking machines to machines and products to services. With Internet of Things (IoT), the whole process of papermaking will be revolutionized, and the complete eco-system will be driven by real-time communication. Trough sensors, the equipment will interact with its environment and it will communicate with other machines, this way triggering actions or reactions to the process of production. Therefore, it will help the company not only for easy monitoring but also to enlarge their production based on the received data. Efficiency and flexibility will also be increased.[2]

Considering the needs and the goals described above, this chapter aims to analyse all IoT services offered by the main automation vendors and suppliers, and briefly describe the tools offered in order to make the best use of the pulp and paper industry.

---

[2] *Pulp and Paper Technology. (2020). Pulp and Paper Tecnology's website https://www.pulpandpaper-technology.com/articles/role-of-iot-in-pulp-and-paper-industry?fbclid=IwAR3p3dCjm3hDi1x4yiVj60ayh3PcAzjfLWZ5k-F8chbSsETjNt7JHHQ_7Co, accessed on September 11th, 2020.*

2.3.1.1 Suppliers' Services of the Industry

Table 2.1: Synthesis of the Analysed Services of Suppliers

Services\Supplier	Valmet	Andritz	Voith
Distributed Control System	Valmet DNA automation system[3]	PrimeDCS[4]	-
Cyber security service	Valmet DNA automation system	-	OT/IT Managed Security Services[5]
Quality Control System	Valmet IQ - Quality management system[6]	Quality control systems[7]	OnEfficiency[8]
Drive system	Valmet DNA Drive Controls[9]	ANDRITZ Drive Technology[10]	-
Analytics service	Valmet DNA automation system	Metris OPP[11]	OnCumulus.Suite[12]
Process Control	APC Advanced Process Controls[13]	-	OnControl[14]
Cloud	-	-	OnCumulus.Platform

---

[3] *Valmet. (2020). Valmet's website https://www.valmet.com/automation/control-systems/, accessed on September 11th, 2020.*

[4] *Andritz. (2020). Andritz's website https://www.andritz.com/products-en/group/automation/distributed-control-system-paper-process, accessed on September 7th, 2020.*

[5] *Voith. (2020). Voith's website http://voith.com/corp-en/industry-solutions/internet-of-things/kudelski-and-voith-security-for-the-iiot.html, accessed on September 7th, 2020.*

[6] *Valmet (2020). Valmet's website https://www.valmet.com/board-and-paper/automation-for-board-and-paper/quality-management-solutions-for-board-and-paper/valmet-iq-product-portfolio/process-and-quality-vision/, accessed on September 11th, 2020.*

[7] *Andritz. (2020). Andritz's website https://www.andritz.com/products-en/group/automation/quality-control-system , accessed on September 7th, 2020.*

[8] *Voith (2020). Voith's website https://voith.com/corp-en/products-services/automation-digital-solutions/onefficiency.html, accessed on September 11th, 2020.*

[9] *Valmet (2020). Valmet's website https://www.valmet.com/automation/control-systems/valmet-dna/drive-controls/, accessed on September 11th, 2020.*

[10] *Andritz (2020). Andritz's website https://www.andritz.com/resource/blob/65756/027fa48582e3cdf0b74937aa513d4f49/aa-ammd-drive-technolog-web-data.pdf , accessed on September 11th 2020.*

[11] *Andritz (2020). Andritz's website https://www.andritz.com/products-en/group/automation/optimization-process-performance-opp, accessed on September 11th, 2020.*

[12] *Voith (2020). Voith's website http://voith.com/corp-en/digital-solutions/oncumulus.html, accessed on September 11th, 2020.*

[13] *Valmet (2020). Valmet's website https://www.valmet.com/pulp/automation-for-pulp/apc-advanced-process-controls/, accessed on September 11th, 2020.*

[14] *Voith. (2020). Voith's website http://voith.com/corp-en/papermaking/oncontrol.html , accessed on September 7th, 2020.*

After analysis of Table 2.1 (regarding the Analysed Services of Suppliers), we can observe that 3 Suppliers (Valmet, Andritz and Voith) offer the following range of services:

- **Distributed Control System:** This System combines various tools in a single Platform. These functions can be applied to control processes, machines, drives or even to evaluate the process' quality. This way, by having a unique Platform, costs and effort can be saved while optimizing future challenges.
- **Cyber Security System:** This System has great importance due to the need of protecting a facility's operation technology (OT), while using IT services for this purpose. Through a Security System, this tool – by accessing essential aspects, eventual hazards and fragility points of the sector – creates customed safeguards which quell security gaps identified in the client's operations, enabling fast and prudent response to threats through education and training for security awareness.
- **Quality Control System:** Through this product, operators can quickly detect specific quality problems that end up causing profitability loss. This way, through the software offered, performance will be accessed during the entire pulp and paper production process, helping to maximize production line efficiency, end product quality and business performance. The stabilization of the dry line can also be settled, and consequently the subsequent process will be optimized, which leads to the saving of energy.
- **Drive System:** This service aims to combine different drives (for instance, the control logic, operator interfaces or alarms) into one network. This way, with a uniform and effective interface it will be easier to operate.
- **Analytics Service:** This Service helps to enhance benefits in a short amount of time by analysing huge amounts of data collected from the production systems through smart sensors, big data and augmented reality. Consequently, this analysis is given to human expertise who will prioritize opportunities and make corrections – which will therefore increase operational stability and reduction of waste.
- **Process Control:** This tool aims to carry out a performance audit for the paper and pulp process, which will estimate target values and areas to optimize. Once the first production process optimization is made, this feature can continue to monitor its performance and maximize the production levels. This way, the process can be stabilized, and cost can be reduced.
- **Cloud:** It serves as an information hub to range information from a wide number of sources built on standardized technologies. Safe and efficient information access are enabled by local machines, providing systems while preserving privacy, security, and compliance industry standards.

Overall, we can conclude that Valmet and Voith offer the most complete products and services, being the recommended suppliers for the paper and pulp industry.

2.3.1.2 Automation Vendors' Services of the Industry

Table 2.2: Synthesis of the Analysed Services of Automation Vendors

Services\Vendor	ABB	Honeywell	Siemens	Rockwell
Distributed Control System	ABB 800xA Control System[15]	Experion PKS[16]	SIPAPER DCS APL	PlantPAx DCS[17]
Cyber security service	ABB Ability Cyber Security Services[18]	CyberVantage Managed Security Services[19]	-	Industrial Security Services[20]
Quality Control System	ABB Ability Performance Optimization for QCS[21]	Experion MX[22]	SIPAPER QCS APL	Industrial Automation and Control
Drive system	ABB Ability Performance Optimization for LV drives[23]	Experion PMD[24]	SIPAPER Drive Systems	Drive Systems

[15] ABB. (2020). ABB's website, https://new.abb.com/control-systems/system-800xa/800xa-dcs, accessed on September 7th, 2020.

[16] Honeywell. (2020). Honeywell's website, https://www.honeywellprocess.com/en-US/explore/products/control-monitoring-and-safety-systems/integrated-control-and-safety-systems/experion-pks/Pages/default.aspx, accessed on September 7th, 2020.

[17] Rockwell Automation. (2020). Rockwell Automation's website, https://www.rockwellautomation.com/en-us/capabilities/process-solutions/process-systems/plantpax-distributed-control-system.html, accessed on September 7th, 2020.

[18] ABB. (2020). ABB's website, https://new.abb.com/process-automation/process-automation-service/advanced-digital-services/abb-ability-cyber-security-services, accessed on September 7th, 2020.

[19] Honeywell. (2020). Honeywell's website, https://www.honeywellprocess.com/en-US/explore/services/industrial-it-solutions/Pages/cybervantage-managed-security-services.aspx , accessed on September 7th, 2020.

[20] Rockwell Automation. (2020). Rockwell Automation's website https://www.rockwellautomation.com/en_UK/capabilities/industrial-security/overview.page?pagetitle=Industrial-SecurityServices&docid=d6ac303e88918a5ca6e35bca41f6f3b6, accessed on September 7th, 2020.

[21] ABB. (2020). ABB's website, https://new.abb.com/process-automation/process-automation-service/advanced-digital-services/pulp-paper-services/qcs-performance-services/abb-ability-performance-optimization-for-qcs, accessed on September 7th, 2020.

[22] Honeywell. (2020). Honeywell's website, https://www.honeywellprocess.com/en-US/explore/products/control-monitoring-and-safety-systems/quality-control-systems/experion-mx/Pages/default.aspx, accessed on September 8th, 2020.

[23] ABB. (2020). ABB's website, https://new.abb.com/process-automation/process-automation-service/advanced-digital-services/lv-drives-services/abb-ability-performance-optimization-for-lv-drives, accessed on September 7th, 2020.

[24] Honeywell. (2020). Honeywell's website, https://www.honeywellprocess.com/en-US/explore/products/control-monitoring-and-safety-systems/integrated-control-and-safety-systems/experion-pks/Pages/experion-pmd.aspx, accessed on September 8th, 2020.

Analytics service	ABB Ability Analytics and Visualization Services[25]	Uniformance Process Studio[26]	SIPAPER PPA[27]	-
Manufacturing Execution System	OptiVision MES[28]	MES[29]	-	-
Process History Database	-	Uniformance PHD[30]	-	-

From analysis of Table 2.2 we can extract that four main Vendors provide Analysed Services of Automation (ABB, Honeywell, Siemens and Rockwell), which translates on the following products:

- Distributed Control System, Cyber Security Service, Quality Control System, Drive System and Analytics Service: These products have the same goals and descriptions as seen on subsubsection 2.3.1.1.
- **Manufacturing Execution System:** This System helps to reduce costs on logistics and lower production costs by using sophisticated algorithms and business logic. This way, it collects accurate data and helps with uphold costumer commitments, decision-planning, inventory and shipment management, billing and shop floor devices' connectivity.
- **Process History Database:** This Product aims to face unplanned production losses through converting process data into valuable information for detecting faults and improving processes. Therefore, and through a scalable, distributed architecture, a secure system configuration and an event history, data gathering time is reduced, maximizing its resources and consequently saving money.

Overall, we can conclude that ABB and Honeywell lead the vendors' product offering, being considered by Control Magazine the second and fourth best automation vendors worldwide [28].

[25] ABB. (2020). ABB's website, https://new.abb.com/pulp-paper/abb-in-pulp-and-paper/collaborative-operations/analytics-and-visualization, accessed on September 7th, 2020.

[26] Honeywell. (2020). Honeywell's website, https://www.honeywellprocess.com/en-US/explore/products/advanced-applications/uniformance/Pages/uniformance-process-studio.aspx, accessed on September 8th, 2020.

[27] Siemens (2020). Siemens website, https://assets.siemens-energy.com/siemens/assets/api/uuid:1ce134b1-5b59-40b5-9ef8-8d611297d09c/flyer-sipaper-ppa-en.pdf, accessed on September 8th, 2020.

[28] Honeywell (2020). Honeywell's website, https://www.honeywellprocess.com/en-US/explore/products/advanced-applications/optivision/Pages/default.aspx , *accessed on September 11th, 2020.*

[29] Honeywell. (2020). Honeywell's website, https://www.honeywellprocess.com/en-US/explore/solutions/industry-solutions/refining/Pages/manufacturing-execution-systems.aspx, accessed on September 7th, 2020.

[30] Honeywell. (2020). Honeywell's website, https://www.honeywellprocess.com/en-US/explore/products/advanced-applications/uniformance/Pages/uniformance-phd.aspx, *accessed on September 11th, 2020.*

2.3.2 Industrial Internet Reference Architecture (IIRA)

The IIRA[31] is a standard-based open architecture for IIoT systems. It optimizes its value by having a vast industry applicability to drive interoperability, map applicable technologies, and guide technology and custom development. The architecture description and representation are generic and at a high level of abstraction to support the broad industry applicability.

2.3.2.1 Industrial Internet Architecture Framework (IIAF)

Many stakeholders are involved when thinking of complex systems as those expected from IIoT systems. These stakeholders have many related concerns pertinent to the system of interest. Their concerns cover the full lifecycle of the system, and their complexity calls for a framework to identify and classify the concerns into appropriate categories in order to enable systematic evaluation and resolution to architect and build such systems.

To address this need, the Industrial Internet Consortium used `ISO/IEC/IEEE 42010:2011'[32] as its Industrial Internet Architecture Framework (IIAF) definition. The IIAF points out conventions, principles and practices for consistent description of IIoT architectures. This standard-based architecture framework facilitates not only an easier evaluation, but also a systematic and effective resolution of stakeholder concerns.

2.3.2.2 Industrial Internet Viewpoints

The various concerns of an Industrial Internet system (IIS) are classified as four viewpoints, as described in Figure 2.6 [15, 29]:

- **Business Viewpoint:** Attends to the concerns of the identification of stakeholders and their business vision, values and objectives when establishing an IIS in its business and regulatory context. It further identifies how IIS achieves the stated objectives through its mapping to vital system capabilities. These concerns are business-oriented and are of great importance to business decision-makers, product managers and system engineers.
- **Usage Viewpoint:** Focus on the concerns of expected system usage. Normally depicted as a string of events concerning logical user´s which deliver its intended functionality in ultimately

[31] *IIConsortium (2020. IIConsortium's website http://www.iiconsortium.org/, retrieved in August 2017*
[32] ISO/IEC/IEEE 42010:2011 Systems and software engineering - architecture description, https://www.iso.org/standard/50508.html , accessed on September 11th, 2020.

achieving its fundamental system capabilities. The stakeholders of these concerns typically include system engineers and product managers.

- **Functional Viewpoint:** Focuses on the functional components in an IIS, their correlation and structure, the interfaces and interactions between them, and the system's connections and activities with other entities within the environment, in order to assist the usages and activities of the overall system. These concerns are of particular interest to system and component architects, developers and integrators.
- **Implementation Viewpoint:** Deals with the technologies needed to implement functional components, their communication schemes and their lifecycle procedures. These components are linked by activities (Usage viewpoint) and supportive of the system capabilities (Business viewpoint). These concerns are of greater interest to system and component architects, developers and integrators, and system operators.

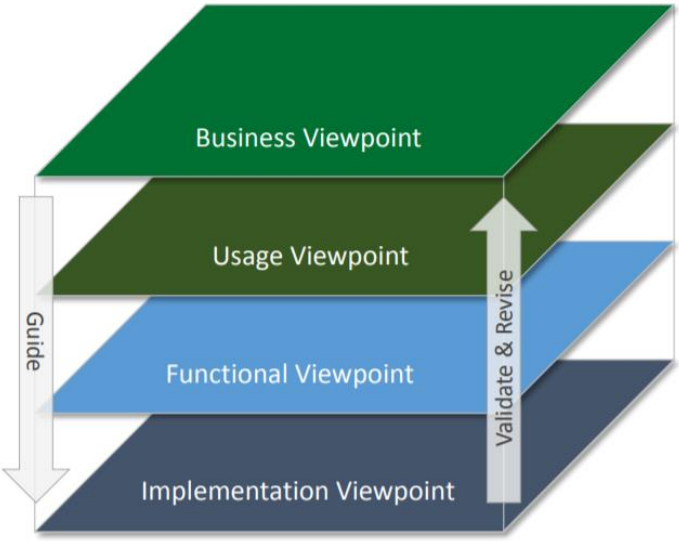


Figure 2.6: Industrial Internet Architecture Viewpoints

2.4 Automation Pyramid

Industrial automation systems are very complex due to a vast number of devices with confluence of technologies working in synchronization. In order to know the system performance, we need to understand the various parts of the system [30]. This integration of technologies is represented by using an Automation Pyramid model which includes the five technological levels which can be considered in an industrial environment. The technologies interdepend both within each level and between the different levels by using industrial communications.

The Automation Pyramid is organized hierarchically as illustrated in Figure 2.7 [31] [33]:

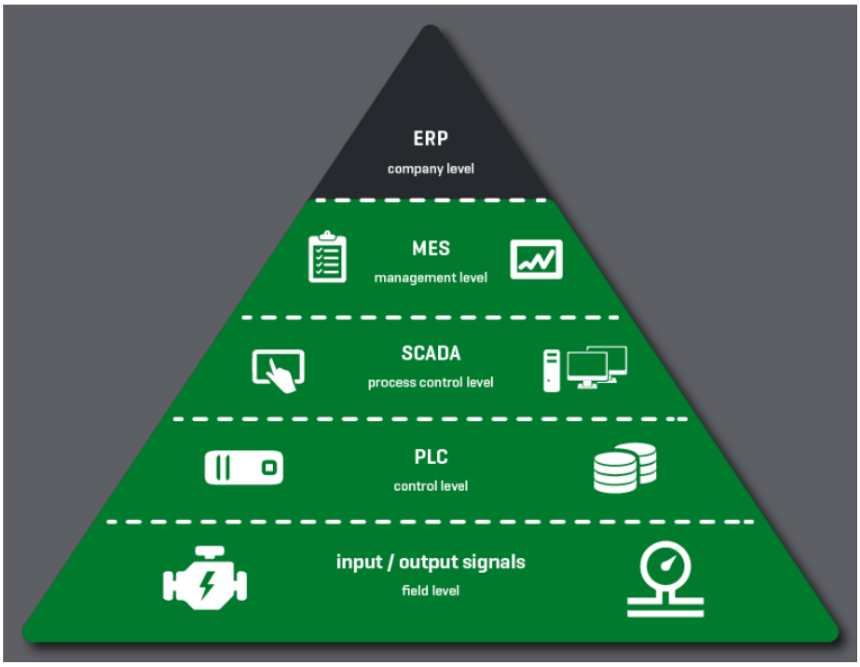


Figure 2.7: Automation Pyramid by invilution

1. **Field Level:** The first layer essentially consists of product and manufacturing assets and components which become information carriers as they can be addressed, located and identified through sensors and then connected. These are the devices, actuators, and sensors which can be seen in the field or on the production floor.
2. **Control Level:** The second level uses devices like Programmable Logic Controller (PLC) and Proportional Integral Derivative (PID) to control and run the devices in the field level that do the physical work. They take in information from all the sensors, switches, and other input devices in order to make decisions on what outputs should be turned on to complete the programmed task.
3. **Process Control Level:** This level is where equipment is monitored through a Human Machine Interface (HMI) or a Supervisory Control and Data Acquisition (SCADA) system. SCADA is essentially the combination of the previous levels used to access data and control multiple systems from a single location. Furthermore, it usually adds a graphical user interface, or an HMI, to control functions remotely.
4. **Management Level:** The fourth level allows management to see exactly what is happening and allows them to make decisions based on that information. They can adjust raw material orders or shipment plans based on real data received from the systems we talked about earlier. This level uses a computer management system known as MES or manufacturing execution system.

[33] *Automation pyramid by involution (2020). Invilutions's website: http://www.invilution.com/comprehensivesolution accessed on September 11th, 2020.*

MES controls the entire manufacturing process in a plant or factory from the raw materials to the finished product.

5. **Company Level:** The top level is focused on business planning and logistics and is often managed in an Enterprise Resource Planning (ERP) system. This is where a company's top management can observe and control their operations. ERP is usually a set of different computer applications that can see everything going on inside a company. It uses all of the previous levels technology plus some more software to accomplish this level of integration. This allows the enterprise to be able to monitor all levels of the business from manufacturing, to sales, purchasing, finance and payroll, plus many others. The integration of the ERP encourages the company by keeping everyone in the same page through efficiency and transparency.

3 Problem Context and Analysis

Taking into account that The Navigator Company's main goal is to be able to perform predictive maintenance which, as mentioned in subsection 2.2.5, avoids asset failure by analysing production data to predict problems before they occur, and considering that APM is a system that will integrate the Company's existing plant systems to collect data but didn't have a solution not only for determining what assets are being monitor and what data is being collected but also how the data is being collected and in what system is stored, a research of the whole production of papermaking within the Company is shown is section 3.1. Furthermore, as cited in subsubsection 2.2.5.3, there are various predictive maintenance techniques that aim to control the performance and state of an equipment and identify degradation, thus a list of types of maintenance techniques that are performed in Figueira da Foz mill was created in section 3.2.

3.1 Pulp and Paper Industry at The Navigator Company

With an annual production capacity of 12 million plants, the *Aliança* nurseries ensure the needs of the group's afforestation activities (more than 130 ornamental and shrub species). Their main crop is *Eucalyptos Globulos*.

The Navigator Company manages about 120,000 hectares of forest, following a sustainable management policy. Its planted forest has a 12-year life cycle. The Group manages in Portugal a vast forest area certified by the FSC[34] and PEFC TM[35].

All wood from a forest planted and managed with responsibility by the Group is cleaned and cut on the ground in logs of fixed length and then transported to the pulp mill.

The wood is collected, transported by lorries, and received at the industrial complexes of The Navigator Company. Here, the logs are peeled and transformed into small pieces with controlled dimensions, which are called shavings.

---

[34] Forest Stewardship Council, https://www.fsc.org/, *accessed on September 10th, 2020.*

[35] Programme for the Endorsement of Forest Certification, https://www.pefc.org/, *accessed on September 10th, 2020.*

In order to produce the pulp, we start by cooking the wood in the digester. For this, we separate the cellulose fibres from the lignin, by dissolving the lignin by the action of chemicals (Sodium Sulphate), temperature and pressure, in order to obtain the raw brown paste.

The energy produced in the recovery boiler in thermoelectric power plants exclusively produces electricity and this energy produced in these plants is distinguished by the end given to it, since it is exclusively injected into the national electricity grid. Then, raw, brown-coloured pastes are subsequently bleached with oxidizing agents to produce printing and writing papers. The bleaching process of the pulp aims to eliminate the residual lignin and the components that accompany the cellulose fibres in successive steps, obtaining, after each step, increasingly bleached pulps.

Through its final destination - market sales or its use in other Group factories - the pulp is subjected to a drying process in order to be transported, obtaining pulp sheets. If the pulp is used in the same industrial unit where it was produced, as in integrated factories which simultaneously produce pulp and paper, the bleached pulp in aqueous suspension is sent directly by pumping, through pipelines, to the paper production zone.

After being conveniently prepared, the pulp enters the Paper Machine where it passes through three main sections before the paper is rolled up in the form of a large roller:

1. **Bleached Pulp Treatment:** The bleached pulp, in an aqueous format, is refined to increase the inter fibre bond. Subsequently, mineral fillers and other additives are added to the aqueous pulp in order to improve the strength and optical properties of the paper. At this stage, the pulp is prepared to produce paper, and placed at the beginning of the paper machine, called the arrival box.
2. **Transformation of wet pulp into continuous sheet:** In the wet part, the suitably treated and diluted pulp is raised the so-called "infeed box" which distributes at a constant and proper speed but also on a regular basis over an endless "web". After we have the fibrous suspension in the web, its transformation into a web starts by eliminating the water through the combined action of gravity with suction and vacuum. At the end of this zone, the sheet exhibits humidity percentages of 80 to 85 percent.
3. **Pre-drying:** In the Pre-Drying, which is the second zone of the Paper machine, the water extraction continues, by means of a compression often combined with a vacuum action. After the pre-drying, the possibility to extract more water to the sheet has ceased, by mechanical means, and ends up containing 58 to 60% of humidity at this stage.

After passing through the pre-drying, the paper is subjected to an intermediate process that consists of passing on the rubber coated rolls, where a starch solution is applied to the surface of the paper to improve the interaction of the paper surface with the print inks. After this application the paper becomes wet and has to be dried again in a specific machine mode that we call post-drying. Post-drying is the evaporation of the humidity by the action of heat. In this process the evaporation of the moisture by the action of the heat is obtained by the contact of the paper sheet with drying cylinders, completing thus the last phase of the water extraction.

The sheet of paper is collected on the winder in the form of a reel with big dimensions and the machine width, called the Jumbo Roll. The jumbo reels are then processed into smaller reels, the size of which allows them to be sent to customers or to the robotized warehouse, later being used for processing into several formats. The paper spools thus obtained are then fed to a packaging machine - the "Packer" - in order to be suitably protected against moisture variations and to allow it to be moved and transported. These reels can be transformed into sheets of different formats or shipped to customers who will transform them, for example, into stationery or receipts.

When processed, the paper is cut into large format sheets (offset paper) for the printing industry, or in reduced size sheets (A4 and A3) to use at home and office environment. Ream pallets are formed, each one containing 500 sheets. Then the Group’s products may be shipped by sea and rail to 123 countries spread across 5 continents [32].

3.2 Maintenance at The Navigator Company

The Navigator Company wants to increase equipment's reliability and reduce maintenance costs, so they must act on maintenance management to optimize processes and equipment reliability to increase availability. Preventive Maintenance (PM) consists of frequently scheduled inspection, corrections, cleaning, lubrication, parts replacement, calibration, and restoration of components and equipment. PM schedules periodic inspection and maintenance at pre-defined intervals (time, operating hours, or cycles) in an attempt to reduce equipment failure. It is performed regardless of equipment condition. The main maintenance model of the company is PM and PdM to eliminate corrective maintenance, non-planned or emergency.

The Navigator Company uses the following PM techniques [33]:

- **Autonomous Maintenance:** Planned actions are essentially from a surveillance type and register detected anomalies.
- **Lubrication:** Consists in lubrication routines, lubricant changes and sample collect to external analysis; it includes surveillance tasks, filter cleaning and substitution and failure detection in these circuits.
- **Sensory:** It consists in first level maintenance routines, providing the identification of potential problems through the agent senses maintenance. Supervising the detected anomalies, the person in charge emits intervention requests to the cases that require the equipment to stop.
- **Systematic (Programmed Shutdowns):** Maintenance actions periodically accomplished, requiring that equipment must stop running. Most of these plans are accomplished on programmed plant shutdowns.

Moreover, the PdM techniques used are the following [33]:

- **Vibration control and analysis of rotative machines:** Values registered by the off-line and on-line systems and kept in Historical Record for posterior processing (by specialized technicians).
- **Temperature control and registration (thermography):** Allows to identify the reduction of thermal isolation areas and defective or improper electrical isolations and electrical unfastening. Periodic routine inspections are executed every six months in Paper Mill and every three months in Pulp Mill.
- **Thickness control of static equipment:** Allows condition analysis of equipment, being able, through obtained values, to identify failure risks. The equipment is essentially made of pipe sets (ex: pipes of auxiliary and recovery Boilers, water and steam pipes, etc).
- **Spectrographic and ferrographic control of lubricant oils:** Very small concentrations of metallic wear products suspended in lubricating oil can be identified and therefore allows to detect failure evidences. It is possible to set corrective action through contamination elimination source, filter improvement, or the use of another type of lubricating oil.

3.3 Data Catalog

Having identified the types of maintenance practiced in Figueira da Foz mill, a data catalog ordered by equipment was created to identify the existent data sources, as listed in Table A.

The data catalog is divided into six columns:

1. **Equipment:** Asset that is being monitor in the mill.
2. **Data System:** The system by which data is being collected.
3. **Data:** The data of the data system.
4. **Periodicity:** Frequency which data is being retrieved from the system.
5. **Data Structure:** If the data collected is structured or unstructured.
6. **Data Storage:** Where the data is stored and can be found.

Although the catalog identifies the equipment being monitor, the identification of the data system and the data storage, regarding the data itself it is a initial version because it does not entirely answer to what relevant data is being collected or how.

3.4 Visual Modelling Profile

In order to understand what useful data is being collected and how, a structure of all the data systems is required, therefore an architecture of the data collecting system of Figueira da Foz mill was modelled.

Considering the numerous physical devices and machines that all systems of the Company are made of, the best solution to modelling the problem would be Systems Modeling Language (SysML) which is specialized in these systems. However, considering that The Navigator Company was not aware of this modelling language and was already familiar with the SAP PowerDesigner tool, although it does not have SysML, it included Unified Modelling Language (UML) as displayed in Figure 3.1.

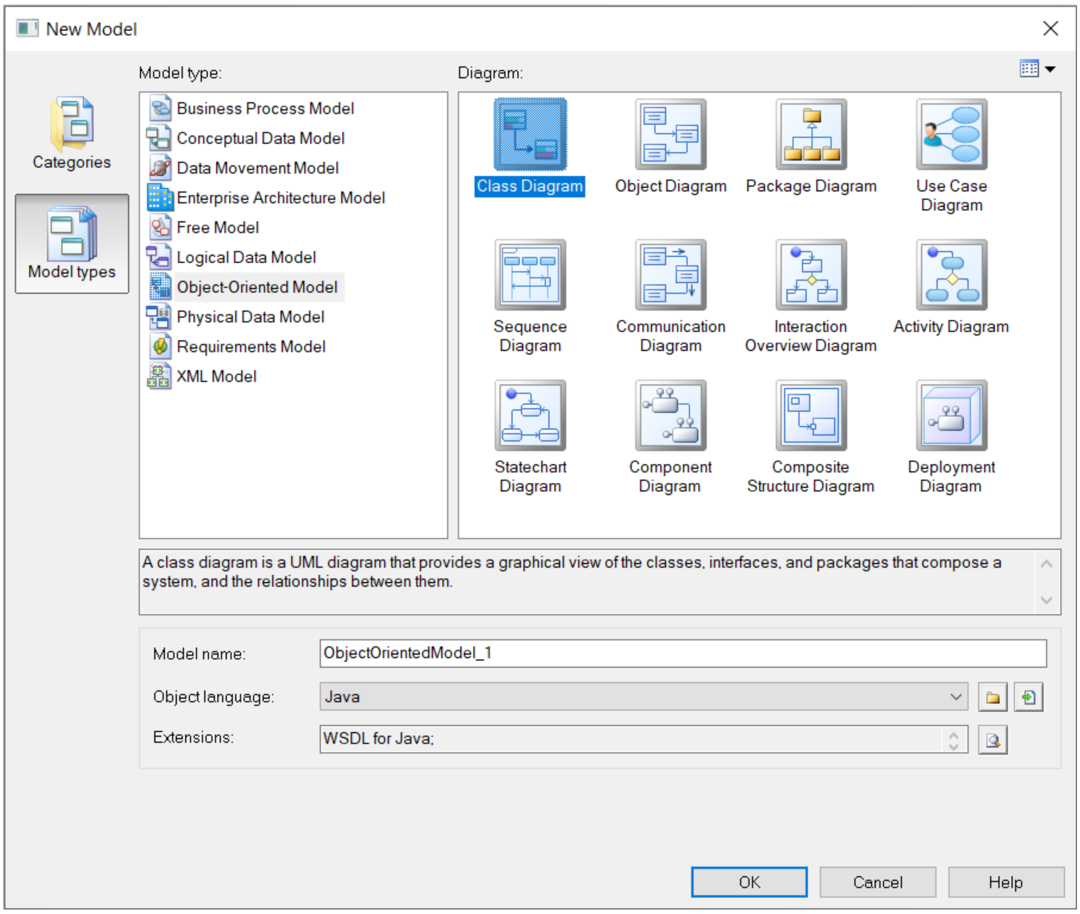
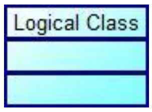
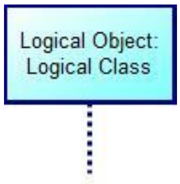
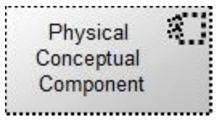
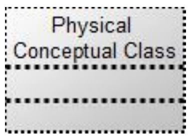


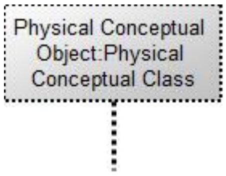
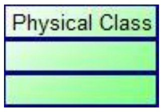
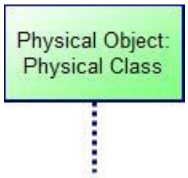
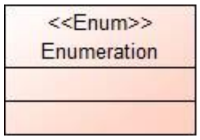
Figure 3.1: SAP PowerDesigner Overview

Since UML focuses more on modelling logical systems and being rather software and information specific, an UML visual modelling profile was created to model the data architecture of the Figueira da Foz Mill using SAP PowerDesigner tool.

Table 3.1 shows the visual modelling profile in use in this document. It is ordered by the name of the element, its definition, and the notation. The profile also identifies the logical, physical, and physical conceptual components, classes, or objects that are used.

Table 3.1: Visual Modelling Profile

Element	**Definition**	**Notation**
Logical Component	Represents a logical modular part and gives structure to a system. It communicates with other components through the use of interfaces.	
Logical Class	Describes logical objects that share the same attributes and relationships to give structure to a system. The first compartment is relative to the class's name and the second to its attributes name and type.	
Lifeline of a Logical Class and Object	Exposes an interacting logical object in the first partition and a logical class in the second. Time is illustrated along the vertical axis.	
Physical Conceptual Component	Represents a physical conceptual modular part and gives structure to a system. It communicates with other components over the use of interfaces.	
Physical Conceptual Class	Describes physical conceptual objects that share the same attributes and relationships to give structure to a system. The first compartment is relative to the class's name and the second to its attributes name and type.	

Lifeline of a Physical Conceptual Class and Object	Exposes an interacting physical conceptual object in the first partition and a physical conceptual class in the second. Time is illustrated along the vertical axis.	
Physical Component	Represents a physical modular part and gives structure to a system. It communicates with other components through the use of interfaces.	
Physical Class	Describes physical objects that share the same attributes and relationships to give structure to a system. The first compartment is relative to the class's name and the second to its attributes name and type.	
Lifeline of a Physical Class and Object	Exposes an interacting physical object in the first partition and a physical class in the second. Time is illustrated along the vertical axis.	
Enumeration Class	An element that represents a data type which contains fixed values, also known as literals. The first partition includes the classifier «Enum» and the enumeration's name while the second contains literals.	
Actor	An individual or entity that performs behaviour in the system.	
Interface	A point of access of a component to other components.	
Report	A report included in a component to represent data generated by another component.	

3.5 System Overview

The architecture of the data collecting system of Figueira da Foz mill includes six different data collecting subsystems from different sectors of the factory, those being: a Process Data System (PDS), a Quality Data System (QDS), a Maintenance Data System (MDS), a Vibration Data System (VDS), an Inspection Data System (IDS) and lastly, a Lubrication Data System (LDS).

To model the architecture of the data collecting system of Figueira da Foz mill, a global architecture with the integration of all subsystems is needed to provide a view of how the system (as a whole) is structured.

From Figure 3.2 the system in question can be seen and it starts with process data being collected by sensors. These measurements are transferred via a Profibus-DP communication protocol to a process controller that processes the data and sends its results to the DCS by the same protocol which will then be collected by a data historian through OPC UA.

In addition to process data, quality data is also retrieved from sensors over a 10Base2 communication to a QCS to analyse the received data and sends it to a quality controller via OPC DA. QCS not only sends data to the DCS, which therefore will send to the respective controllers to improve the process, but also quality and production reports to the historian data through OPC UA. This, consequently, will transfer the reports to both MES and ERP over OPC UA as well.

Regarding sensor data, vibration is the last measurement being collected and it can be so in two ways: through a portable data collector, which with a coiled cable removes the measurements and sends it via TCP/IP to the CMS; or over an online data collector that has a cable connected to the sensors and sends the data via RS-485 to the CMS.

In Figure 3.2 a CMMS that is part of an ERP can be identified and that contains a thermography and an oil reports which are presented in detail in section 5.3.

Lastly, there is a lubrication system which is described in section 5.4 that includes lubrication reports but does not have any connection with the other subsystems.

There were two more system overview models created: an informal model which The Navigator Company is used to seeing and is represented in Figure B, displaying the field device, control device, and the enterprise level of the hierarchy levels of RAMI4.0 (listed in subsubsection 2.2.4.1), and also the all levels of the automation pyramid in section 2.4; and a simplified SysML that should have been used in this work shown in Figure C.

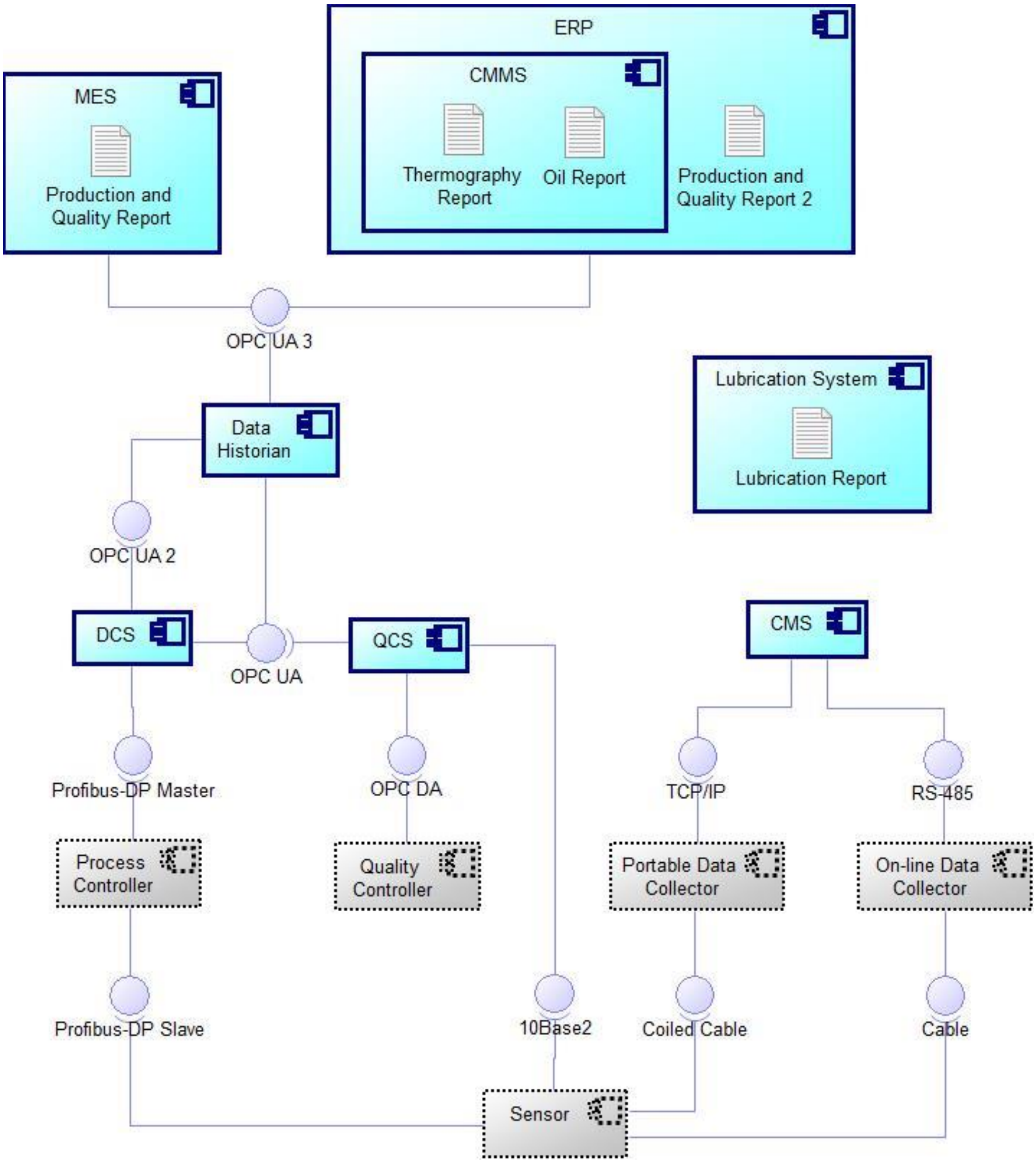


Figure 3.2: System Overview

4 Process and Quality Data Subsystems

This chapter presents the PDS and QDS architectures.

4.1 Process Data Subsystem

A PDS is end-to-end, meaning it starts from the beginning to the end of the whole process of making paper. It focuses on the control of industrial procedures in order to guarantee the efficiency and quality of the automated production line and to be able to optimize it.

The control of these processes is carried out by controllers which receive values of several measured variables through sensors, processing the given values and determining the correction signal to be carry out by actuators.

To begin the representation of this subsystem, a structure of its components and their interfaces are needed. Consequently, a component model was designed as shown in Figure 4.1.

In the diagram there are instruments - pieces of technical equipment - that measure or control measurements, also known as field devices which can be sensors, controllers, or actuators.

Regarding sensors that measure variables, two main types can be established: an analog sensor, which measures various variables with values between 0% and 100%, and a digital sensor which develops a binary signal, identifying two possible status: ON or OFF.

Controllers analyse measurements and can be divided into three categories: a Proportional Integral Derivative (PID) which constantly computes an error value (the variance between a desired setpoint (SP) and a calculated process variable (PV)), and then applies a correction built on proportional, integral, and derivative terms; a cascade controller that implicates the use of two controllers with the output of the first controller offering the setpoint for the second controller; and a motor controller which is part of a Motor Control Centre (MCC): an assembly to control several electrical motors in a central place. The motor controller is an instrument that regulates a motor and consists of three main components: a relay, an overload relay and a contactor which together enable it to start or stop the motor, therefore protecting against electrical fails and overloads.

Actuators are accountable for moving and controlling a mechanism, and consist of two types: an ON/OFF valve which receives a digital signal from a controller and either opens or closes the valve in order to allow or inhibit the flow to circulate; and a control valve that receives values from 0 to 100%, indicating the desired opening for the valve. This valve contains a position sensor, which is used to accurately control the desired position.

In this model there is also a DCS a and a Data Historian which records and retrieves process data in a time series database.

Concerning the interfaces between each component, Figure 4.1 shows a Process Field Bus-Decentralized Peripherals (Profibus-DP) - which is a bidirectional network based on a master and at least one slave device. This connection is made by the controller with the digital sensor and the ON/OF valve, and by the DCS with the controller which in this case will be considered the slave.

A 4-20 mA is a current loop with the two values of 4 and 20 mA being 0 and 100% of the scale of measurement or control. This interface is used between analog sensors and controllers and also between control valves and controllers.

The last connections of this model are the relation between a motor controller and a motor that is a serial cable, and between the DCS and the Data Historian which is Open Platform Communications Unified Architecture (OPC UA) that is mainly a client-server with focus in the communication of equipment and industrial systems.

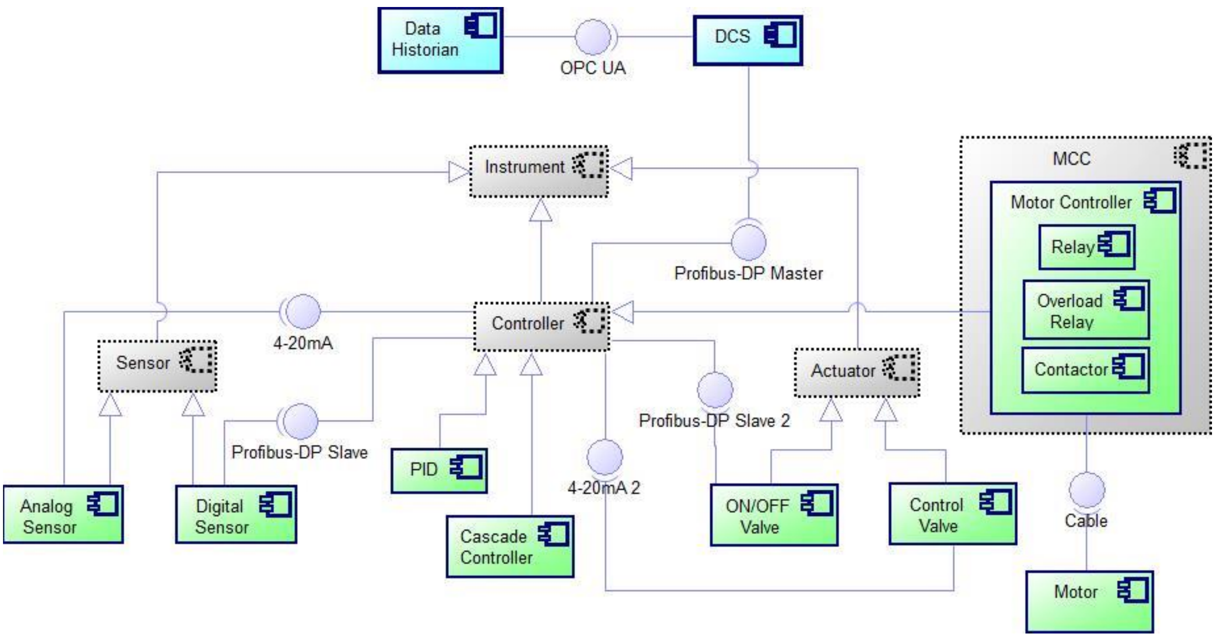


Figure 4.1: Process Data Component Model

There is a need to display all types and codes that are used in this subsystem and for that, a domain model with only enumeration stereotypes was established.

From Figure 4.2 it can be seen that there are types and codes of locations, measured variables, function modifiers, output functions, readout functions, modifier variables and parameters. Moreover, there is also types of sensors and trends enumerated.

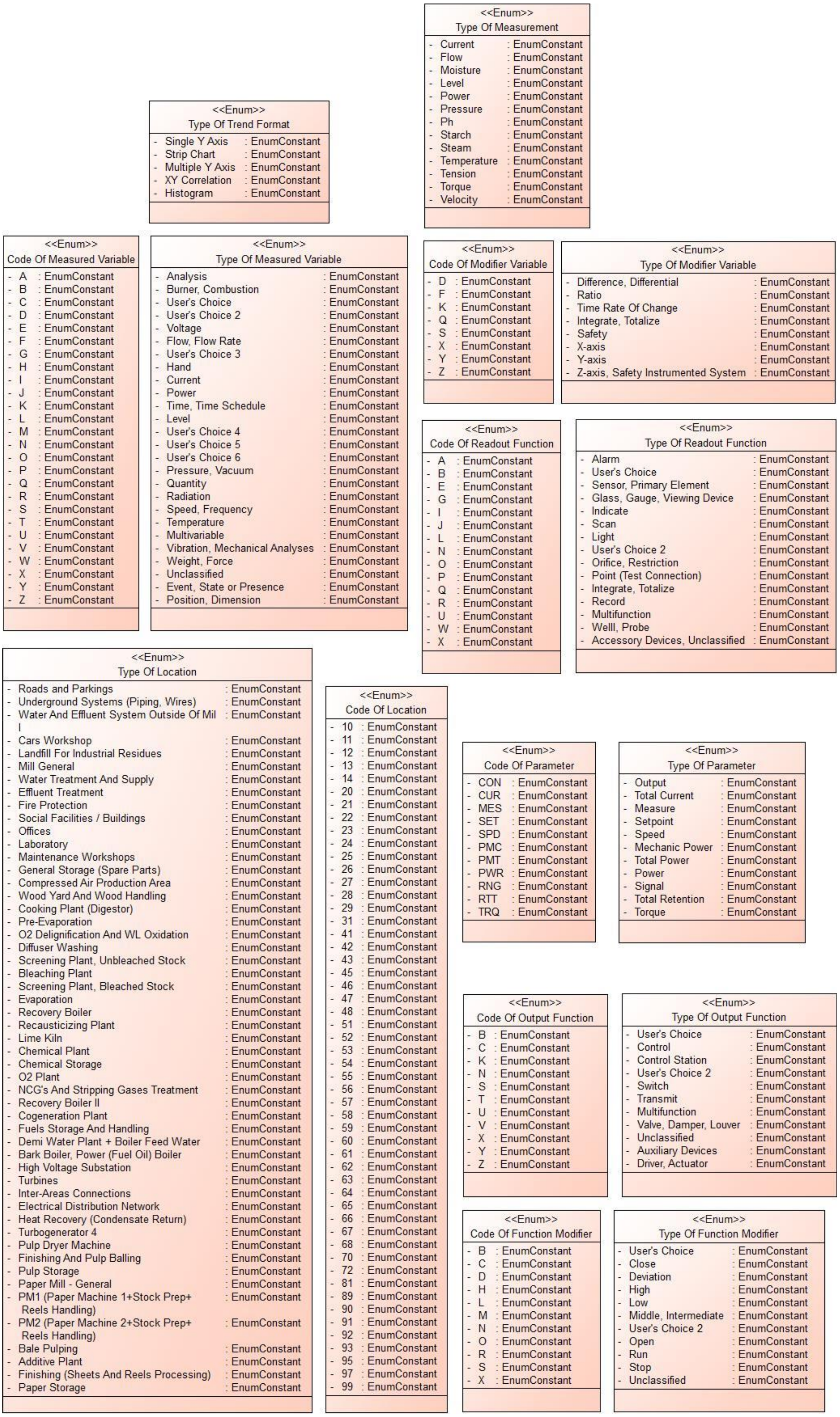


Figure 4.2: Process Data Enumeration Domain Model

4.1.1 Equipment

Starting from the field level as described by the Automation Pyramid in section 2.4 (the sensors and actuators that are a type of equipment), a domain model identifies all the equipment that are part of the subsystem and how they are identified within the organization modelled.

There are various equipment included in this subsystem, as illustrated in Figure 4.3: motors, pumps, rolls, gear boxes, instruments, valves, transformers, power and energy cells, and MMC's. There are also fans that include ventilation and exhaust fans and lastly, autonomous equipment such as compressors, dryers and chillers.

Regarding the instruments which were mentioned in Figure 4.1, each one contains a tag with a location code as listed in Figure 4.2, a functional identification, a sequence number and a possible suffix number in case of being part of a group of equipment.

The functional identification of the tag is based on the identification letters' table shown in Table D in Appendix D. It is a combination of 2 to 5 letters which involves a measured variable, an optional modifier variable, and at least a function: a readout function, an output function, and a possible functional modifier. All these variables and functions can be identified in Figure 4.2.

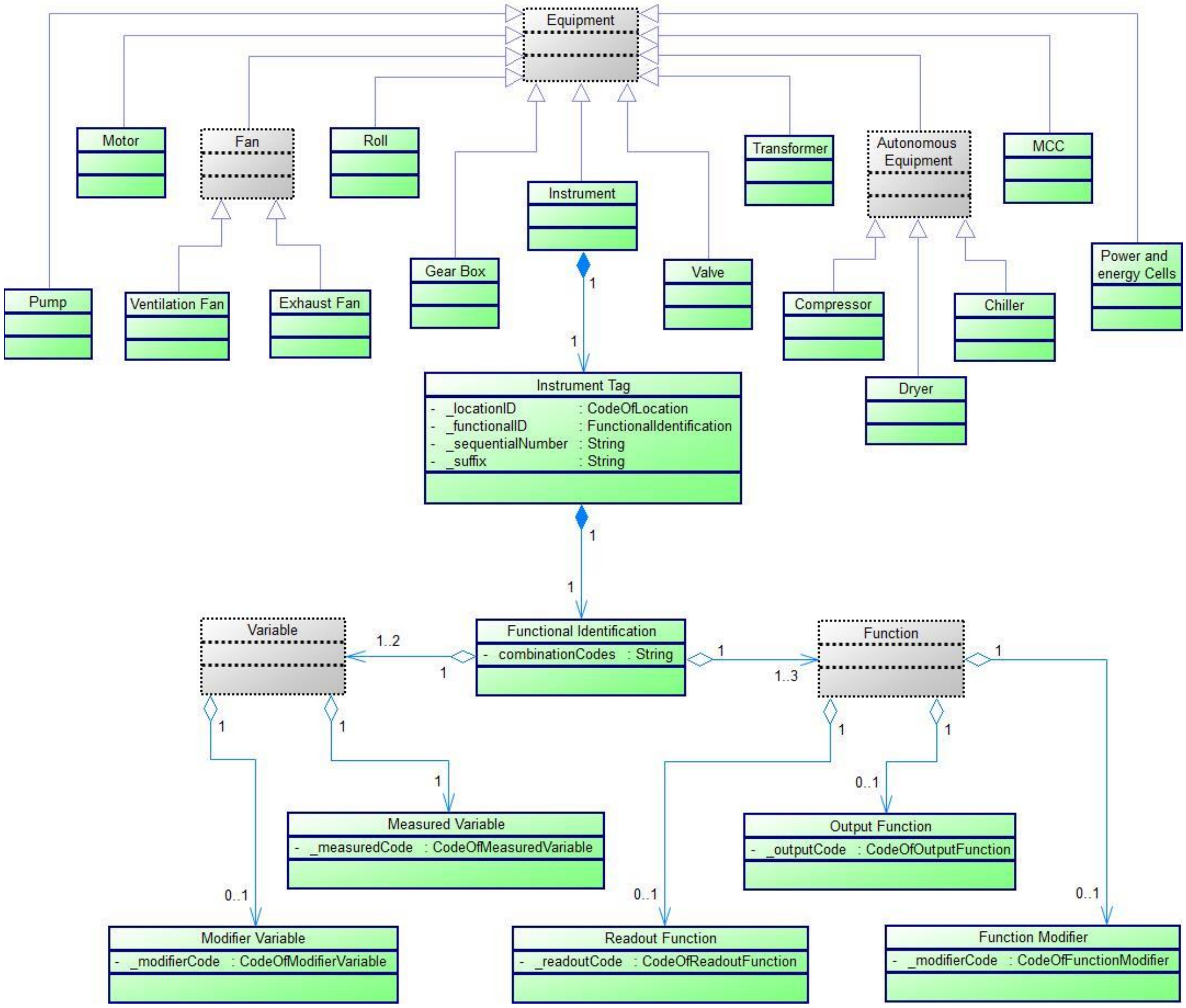


Figure 4.3: Equipment Identification Domain Model

To represent the structure and the data that each instrument includes, another domain model was originated.

From Figure 4.4 it can be seen not only the field level but also the control level as defined in section 2.4 by the appearance of the controllers.

Sensors, controllers, and actuators are instruments as previously mentioned in section 0. Digital sensors transmit a signal and analog sensors, like controllers and actuators, have a configured range because of the 4-20 mA current loop connection and send a processed value of the measurement to the controller. The type of measurements collected by the sensor is listed in Figure 4.2

Every controller has a setpoint to calculate the error value and the cascade controller has a connection to the PID because its output value will be received and processed by it as mentioned in section 4.1. Consequently, the actuators (ON/OFF valve and control valve) will receive the values and actuate accordingly.

Regarding the motor control, it is part of the MCC and contains 3 main components to manage a motor: a relay which receives signals and includes a switch; a contactor which controls the electrical power; and an overload relay to provide thermal protection for the motor. When there is an overload of the current, the relay cuts the supply circuit to the motor. All these components are constituted by contacts, an armature, a spring, and a coil.

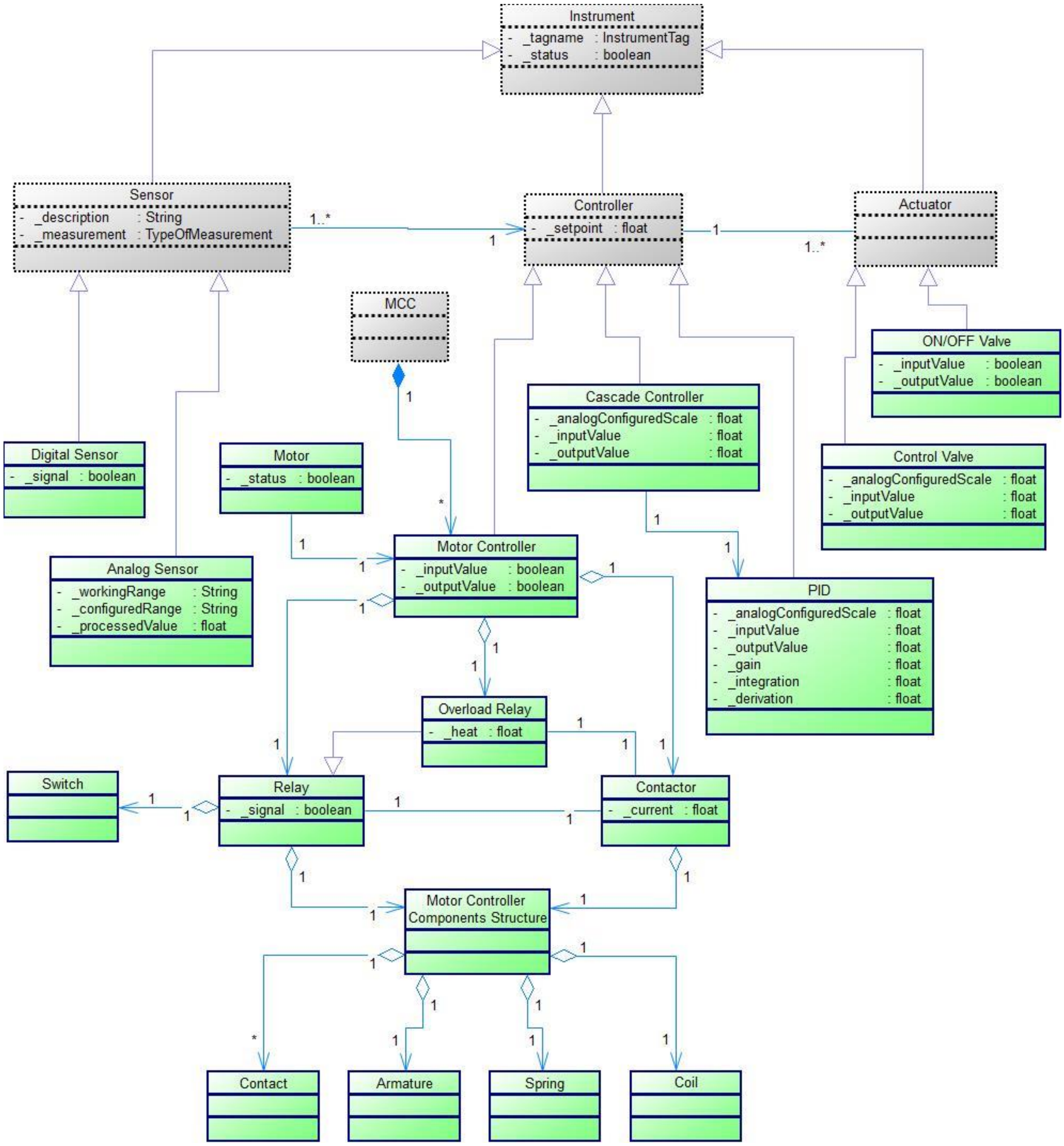


Figure 4.4: Instrument Domain Model

4.1.2 Distributed Control System

This section is based on Honeywell's DCS, named Experion Process Knowledge System (PKS) which helps process manufacturers increase profitability and productivity.

In the case of Figueira da Foz mill, the DCS is considered to be in the process control level as illustrated in section 2.4.

In this subsystem it is required to know the DCS composition and what data it contains. Therefore, a domain model was created as shown in Figure 4.5.

The DCS receives and sends values to the controllers. Specifically with the motor controller (mentioned in sections 4.1 and 4.1.1), a digital signal that will trigger the relay will be generated. Consequently, this relay will close the contactor of the motor supply circuit and the contactor, when closed, acts as an auxiliary contact that will give a digital signal to the DCS, meaning that the motor is running. When the DCS starts the engine and does not receive the engine running signal, it can generate an alarm signal.

Concerning its structure, the DCS is constituted by 4 main sections: a list of alarms, events and trends identified by the instrument tag name as described in Figure 4.3 and in the case of a trend also a code of the parameter which is defined in Figure 4.2 and the most commonly used are MES (measure), SET (setpoint), CON (controller output) and a HMI.

The DCS's HMI contains several displays within a display list where it is possible to select the display chosen. There are 7 main displays, each with an instrument tag name and its available trend: an ON/OFF valve that shows if the valve is opened or closed; a control valve with the input and output values; digital and analog sensors displaying signals and processed values correspondingly; a motor exhibiting if it is running or stopped; a controller with the setpoint and its processed and output value; and an extension display with general information (for instance a tag name of the instrument and the measurement, and an associated display with will present the display list).

Although valves do not have any extension display, it is contained by sensors, motors, and controllers' display. There are several additional extensions displays: sensors include an advanced section with signal information; motors and controllers have access to specific loop parameters where it is possible to see valves data, to consult the interlock causes when an engine or controller is unable to function, to see the control parameters specifics and in the case of controllers also the alarm limit details.

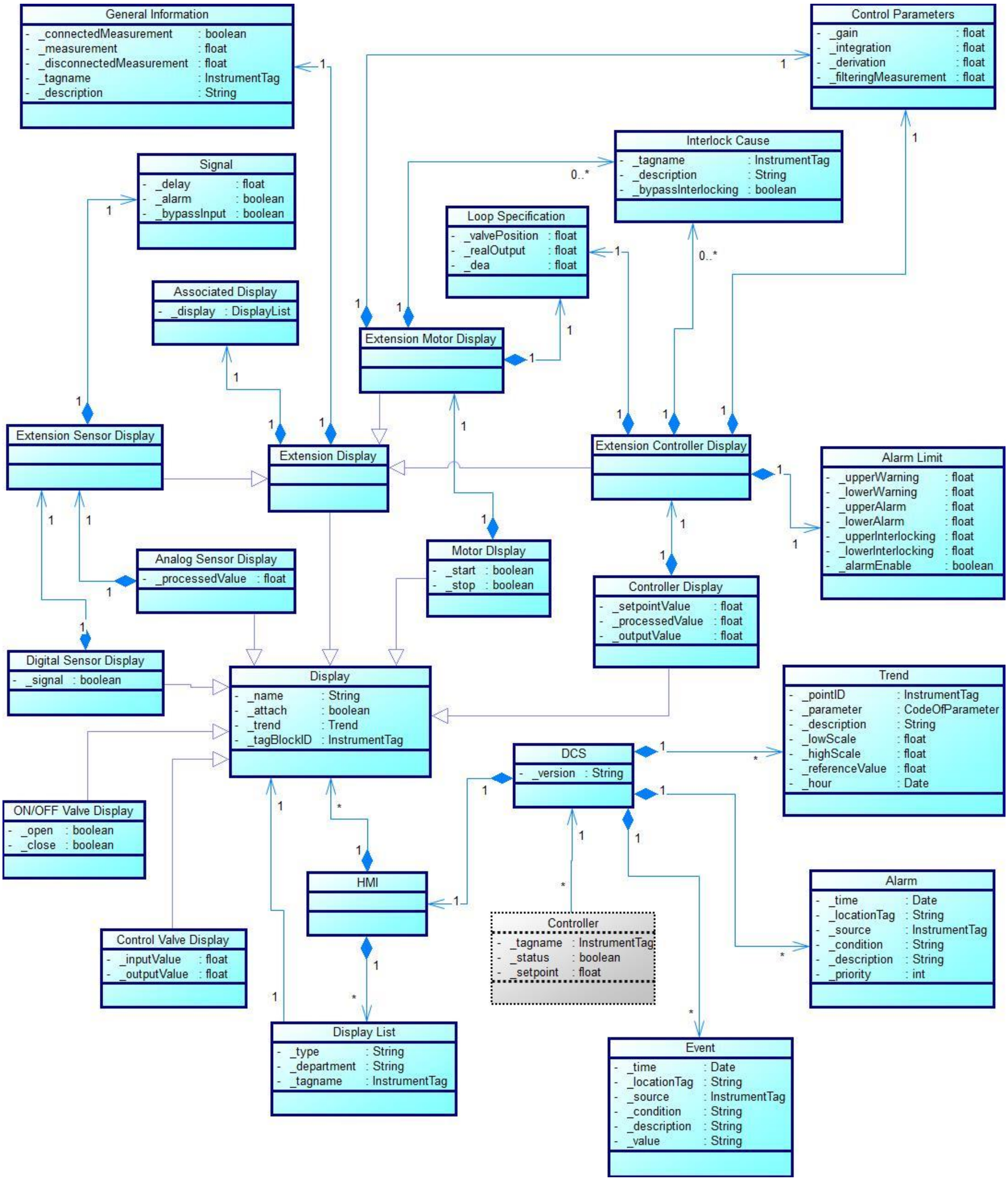


Figure 4.5: Distributed Control System Domain Model

4.1.3 Data Historian

A Data Historian is based on Uniformance Process History Database (PHD) of Honeywell which levels on top of the DCS, offering a historian not only for engineering but also for business analytics.[36] It retrieves, stores, and records historical process data.in a time series database.

Considering the need to understand in what data historian is composed and what data does it collect and store, a domain model was created.

From Figure 4.6 it can be seen that the data historian has several servers which collect data from the DCS, therefore containing an enormous database with various tables and indexes defined. Each table has several variables: a data historian tag name which is composed by the number of the paper machine, the instrument tag name as modelled in Figure 4.3 and the code of parameter as detailed in Figure 4.2; a description of the data historian tag name, the unit and type of the variable and the periodicity of the collection.

The data historian also includes a process regarding the historical analysis which is based on Uniformance Process Studio, mentioned in subsubsection 2.3.1.2: a tool to help analyse process performance through the visualization of trends. This tool contains three main windows: a content window which the user is able to exhibit numerous displays by selecting the ones of interest to analyse; a workspace window that can have various folders and subfolders with displays inside whenever they are added to the content window and which is possible to save the work made; and a browser window where the user can pick the desired data source and the data historian tag name to be added to the user's display choice for analysis.

Regarding the displays, there are four main types in which each one has a time control where is possible to select the period that the user wishes to inspect: a graphic display with access to DCS's HMI - being able to explore and record specific process controls; a table display that shows a table ordered by the data source and the data historian tag name; a trend display with five types of format available to choose as listed in Figure 4.2; and a multi-trend display which contains at least two trends to present.

The trend display includes a menu with its properties where it is possible to change the trend's font of the title, axis, and subtitle texts. Furthermore, the menu of the trend properties also includes a setup where the user can customise the trend's title, the zoom and the displaying of certain properties of the horizontal and vertical axis, the grid, the hairline cursor and the trace area. It is also possible to change the colour of the horizonal and vertical axis, the grid and the hairline cursor while the trace area can change the background colour.

---

[36] *Honeywell. (2020). Honeywell's website,* https://www.honeywellprocess.com/en-US/explore/products/advanced-applications/uniformance/Pages/uniformance-phd.aspx, *accessed on September 5th, 2020.*

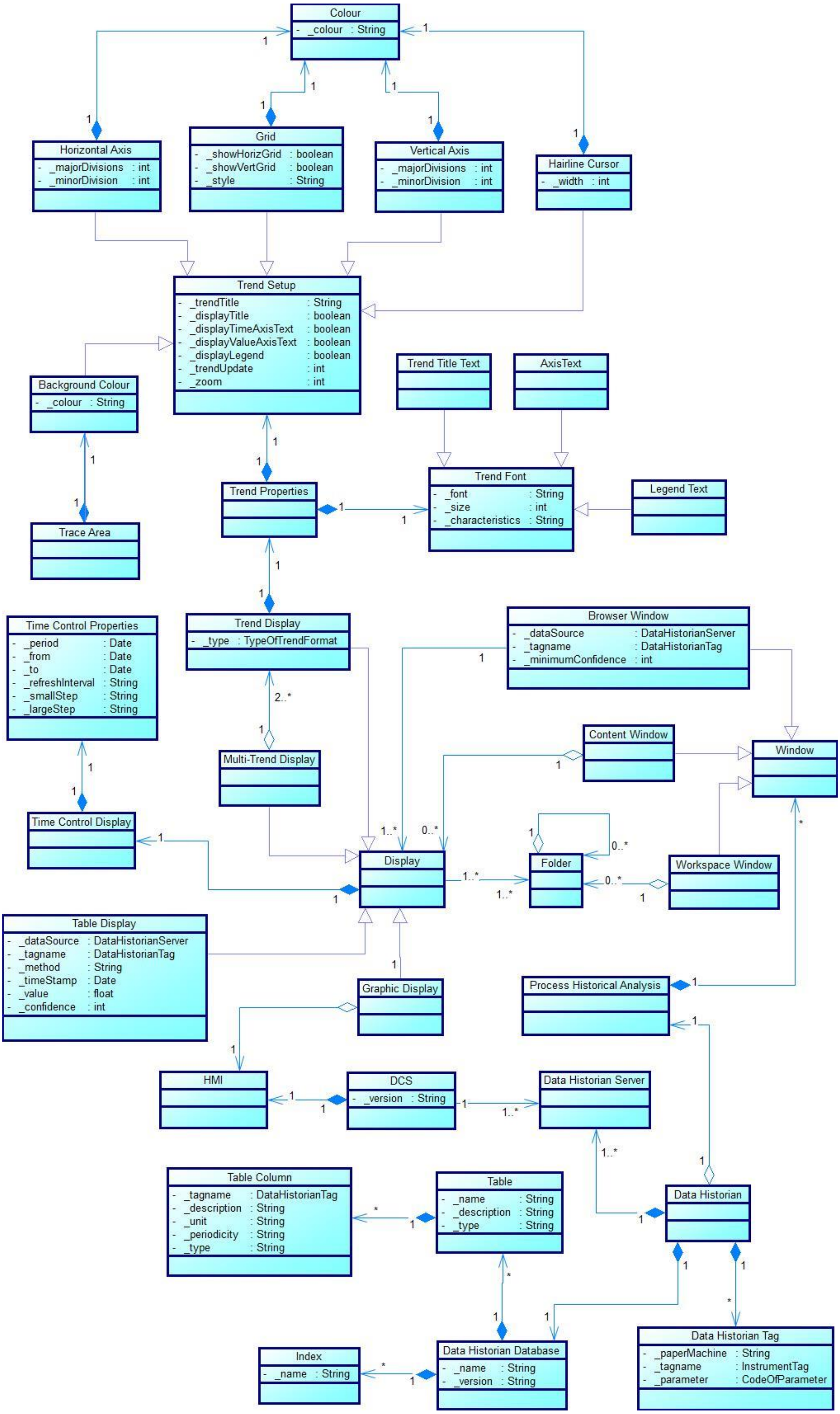


Figure 4.6: Data Historian Domain Model

To conclude the PDS, a sequence model was designed to represent how process data is developed, the interactions between the classes and their order as shown in Figure 4.7.

The diagram begins with a technician defining a setpoint value in Experion PKS, which will edit the respective controller value. Then, the technician will define the margin values in Experion PKS where each measure should be in that will also update the controller.

The controller is continuously requesting sensor measurements that will read and send its value. Then, the controller will compare the processed value with the setpoint and transmit the output value to the actuator that will reduce the margin previously defined and send its output value for controller confirmation of the correct action. Furthermore, the controller conveys its values to the Experion PKS which will analyse and send the relevant data to the Uniformance PHD.

In case of the processed value not being within the specified margin, the controller will send an alarm to the Experion PKS which will transfer the alarm record to Uniformance PHD and alert maintenance.

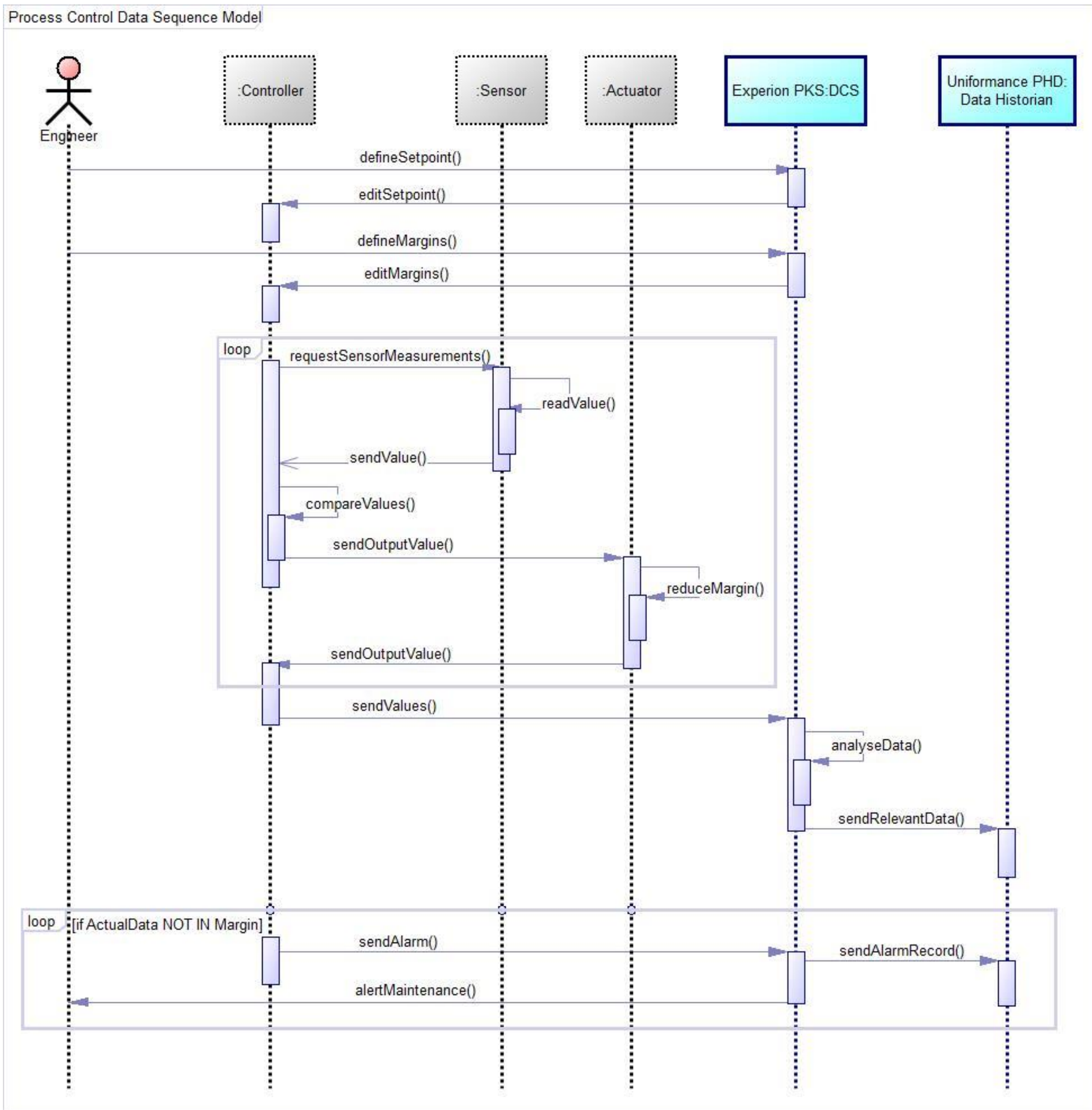


Figure 4.7: Process Control Data Sequence Model

4.2 Quality Data Subsystem

A QDS is based on a Quality Control System (QCS) which is installed at the final part of the paper machine, allowing to control the final product online. It measures and controls the quality characteristics of the paper, for instance weight, humidity, thickness or colour, and provides uniform quality during the production process, thus complementing the PDS.

The QCS consists of sensors installed inside scanners at the end of the machine, a system capable of executing complex control chains, and actuators capable of optimizing paper profiles.

The subsystem requires to represent not only the QCS, but also all other components, how they are connected to it, and where the quality data is stored at the end. Therefore, a component model was built and is displayed in Figure 4.8.

In the diagram is possible to see that there are scanners which have sensors heads in it and the QCS collects the sensor's measures through 10Base2, also known as *thinwire* or *cheapernet*, which is a derived of Ethernet using a thin coaxial cable. Then, the QCS communicates with its controllers through an Open Platform Communications Data Access (OPC DA), which is part of the OPC Classic that consists of a group of client-server standards that presents requirements for communicating real-time data.

Regarding the controllers there are Machine Direction (MD), they are in charge of minimizing the future predicted deviation of all controlled variables in the papermaking process, and Cross Direction (CD) controllers which will align the profile measured by the scanner, and connect to the actuators over Modbus Remote Terminal Unit (RTU) - a data communication protocol between a master (controller) and its slaves (actuators) – that will ensure a correspondence between the movements with the desired position on the sheet.

The QCS communicates not only with the DCS via OPC UA, but also to the data historian which will transmit production and quality reports to the MES and ERP as described in section 2.4, are considered to be in the management and company level, respectively.

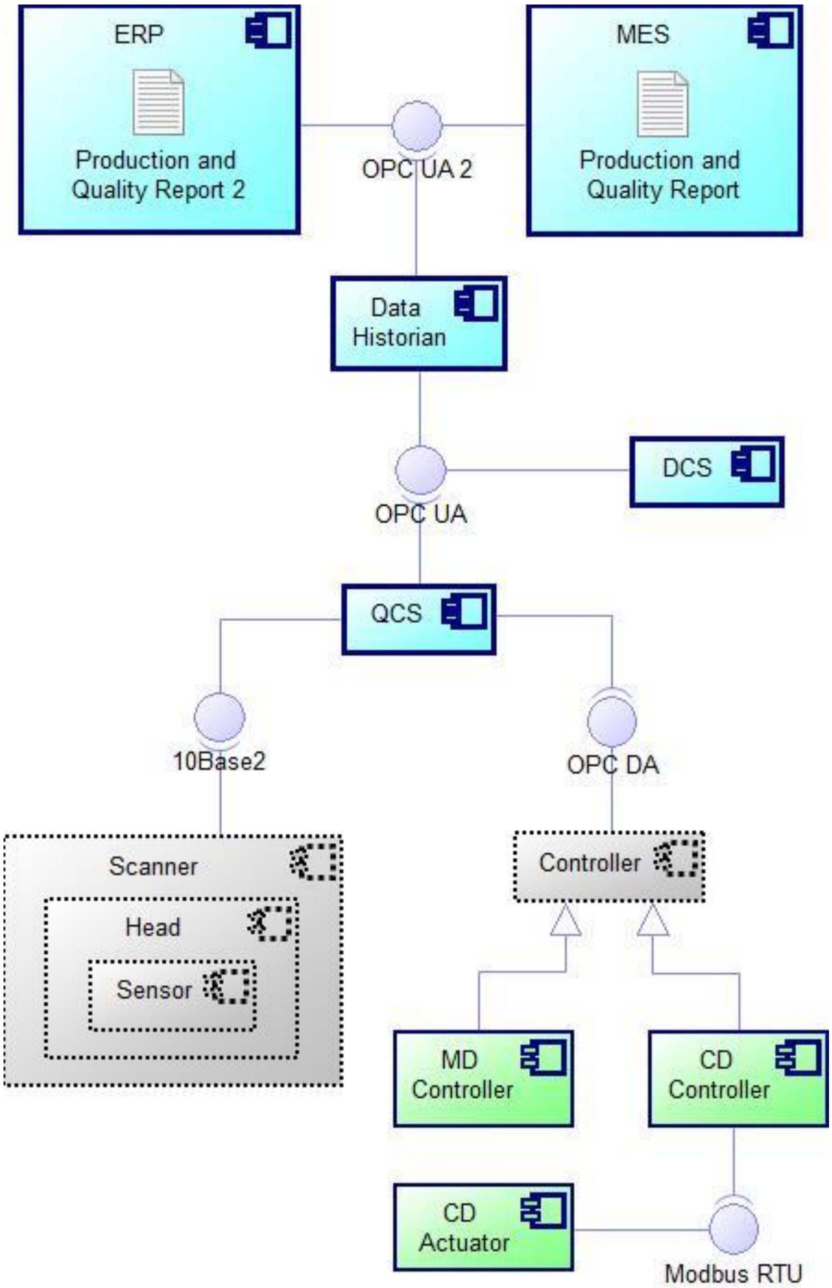


Figure 4.8: Quality Control System Component Model

After representing how the subsystem works and its communicates, a domain model was performed with the goal of showing what measurements are collected, how they are analysed and controlled in the QCS and what does the production and quality report contains.

The diagram is illustrated in Figure 4.9 that starts by showing that there are six types of sensors with measurements being retrieved: a colour sensor which measures properties such as brightness, illuminant, whiteness, fluorescence and colour scale characteristics; a caliper sensor responsible for measuring thickness; a formation sensor that detects flocs, also known as smaller particles; a basis weight sensor that measures basis weight; an ash sensor to detect ash; and a moisture sensor measuring moisture. Each one of these sensors are integrated in sensor heads that are always moving from side to side within a scanner, providing values of the paper in the machine direction and cross direction whenever paper is being produced. Consequently, there are 2 scanners: one located in the size press which only measures moisture, and another situated in the final reel that contains all 6 sensors and both transmit their measurements to the QCS.

At the end of each scan, various types of CD profiles are calculated in the QCS by measurement: an instant profile, obtained with each scan of the scanner, with 864 processed zones; a low resolution instant profile where each zone is calculated by averaging 9 sections of the instant profile; a high resolution filtered profile, acquired from the instant profile with 864 processed zones and that applies an exponential filter; a low resolution filtered profile that is collected from the previous one by averaging 9 sections; and an average reel profile which is of low resolution with 96 zones, which is retrieved by averaging all scans of the reel and also by applying a filter. The QCS will send the calculated averages of each profile to the MD and CD controllers. There are two types of CD controllers: a basis weight and a caliper CD controller which will align the profile measured by the scanner through the use of CD actuators that will ensure that the movements correspond with the desired position of the paper.

The QCS is composed by seven sections: the profile that was previously mentioned; a production data which is based not only on a table with the description of the measurement, its value, and its units, but it also contains profiles; a quality data showing scanner status information, measurements and quality information; a trend display exposing up to 4 trends at a time, including their properties; a list of all alarms with their details; a colour map which shows a 2-dimensional plot using colours to reveal the amplitude of the data displaying; and several reports with production and quality results that can be generated.

Regarding the reports available in the system, there are four types which can be produced: a reel, a grade, a shift, and a day report. They all have the same structure: a summary section with general data about the report; a production section with its descriptions and values; a lost time production section; and a quality section with quality information. However, they don’t have the same displayed data and, as detailed in Figure 4.9, reel and grade reports are joint because they share exactly the same input data, as well as the shift and day report.

To conclude the model, the QCS will update the DCS with output values of the controllers and also sends the production and quality reports to the Data Historian which will transmit it to MES and ERP.

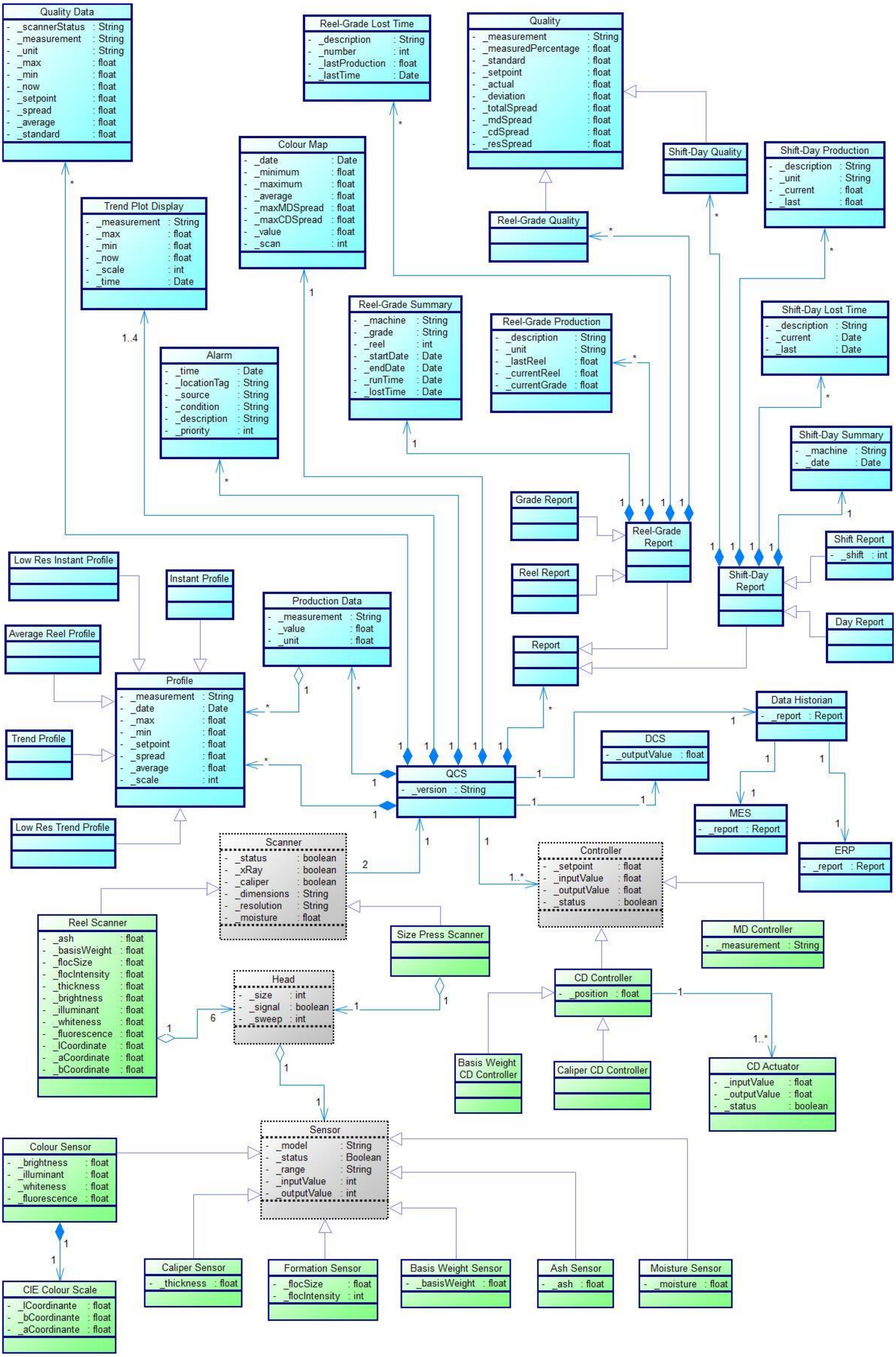


Figure 4.9: Quality Control System Domain Model

Considering it is necessary to represent not only the structure, but also the actors involved, and how and the order which quality data is transmitted in this subsystem, a sequence model was modelled.

From Figure 4.10 it can be seen that it begins with a technician defining a setpoint value in QCS DaVinci, a product from Honeywell, which will update the respective controller. Afterwards, the scanner is going to be collecting quality measurements through its sensors and transmitting it to the QCS which will calculate the profiles and send its averages values to each controller. Consequently, the controller will compare the data and send the output value to the actuator which is going to optimize the paper profile. The actuator will also send its output value to the controller which will transmit it to the QCS that will update the Experion PKS.

The QCS will generate a reel or any other available production and quality report type and send it to the Uniformance PHD which will transfer it to the Mill Information System (MIS), also known as MES, and to SAP ERP accordingly.

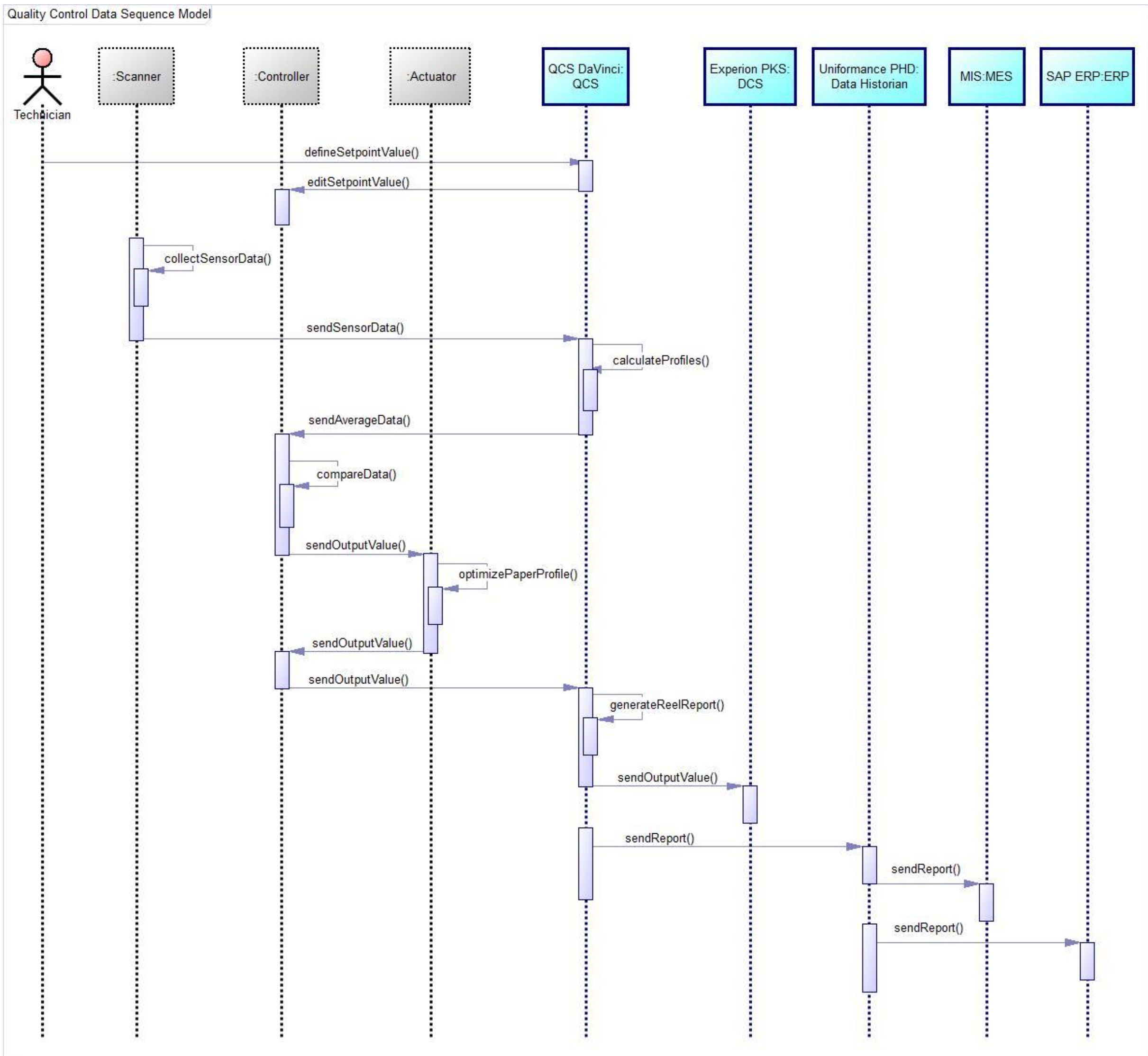


Figure 4.10: Quality Control Data Sequence Model

5 Specialized Subsystems

This chapter presents specialized subsystems which collect relevant data for advanced analysis: the MDS, VDS, IDS and LDS.

5.1 Maintenance Data Subsystem

The MDS is based on SAP Plant Maintenance (SAP PM) which is a software product that manages all maintenance activities in an organization. SAP PM module consists of key activities to include inspection, notifications, corrective and preventive maintenance, repairs, and other measurements to maintain an ideal technical system.

In this subsystem there are notifications and work orders used for equipment repairments when a breakdown occurs or for preventive maintenance, maintaining a current condition by discovering weak spots in all equipment and providing regular inspection with minor repairs.

To initiate the modelling, it is necessary to show what types and codes are defined and used in maintenance management. Therefore, a domain model with only enumeration stereotypes was created.

In Figure 5.1 are represented several enumerations of different types and codes of locations, notifications, orders, equipment and activities that are used in the Computerized Maintenance Management Software (CMMS) which is SAP PM.

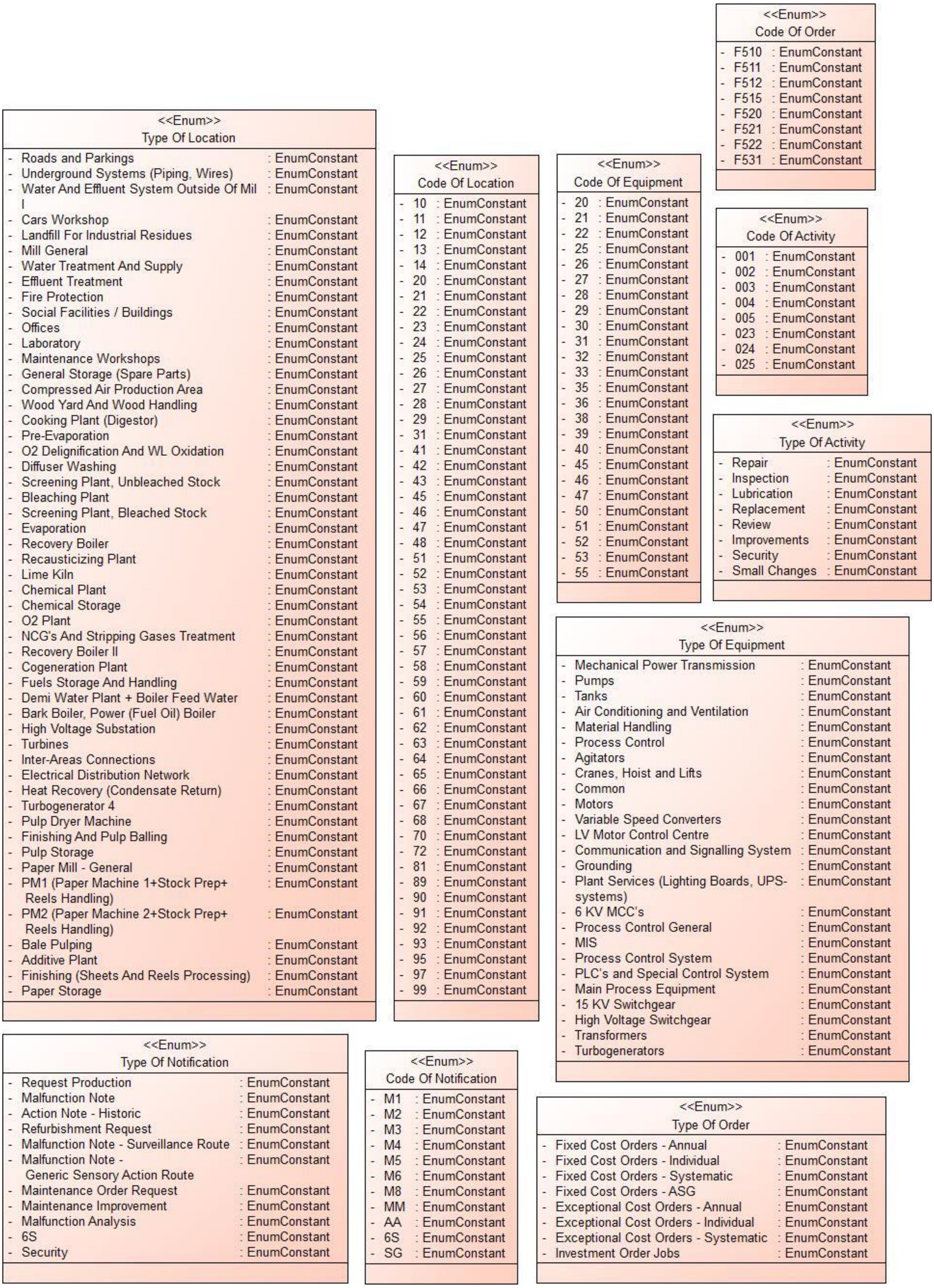


Figure 5.1: Maintenance Management Enumeration Domain Model

Considering this subsystem is based on CMMS, a domain model was designed to show the structure of the software and all its properties.

A CMMS is composed by six main classes: notifications, orders, maintenance plans, equipment, installation locations and a structure list as indicated in Figure 5.2.

An equipment is constituted by general data - a structure where the actual and superior installation location of the equipment is - and an action log that shows a list of all changes made to the equipment. Furthermore, it also has a type and code of the equipment as listed in Figure 5.1, where it is possible to access the structured list.

An installation location not only includes various equipment but also general data and a structure with the superior installation location and the type and code of equipment. The type and code of location are also included, as well as a connection to the structured list.

A maintenance plan contains a counter type to be measured, several maintenance plan cycles (which define the time interval between the generated orders), and various items with the installation location, the equipment, the type of order, and the type and code of activity of the order. Moreover, an item can have a task list which generates operations and that can include sub-operations to be executed.

A structure list is composed by a representation of a structure of the installation locations which have equipment in the form of a hierarchical list.

A notification includes a type and code of the notification as detailed in Figure 5.1, an order associated, general data with the installation location and the equipment, and an action log that shows a list of all changes made to the notification.

To conclude, an order contains the type and code of the order and six relevant sections: general data with access to the notification, the installation location and the equipment, and subsequently the type and code of the installation location, the equipment and the activity; an action log that shows a list of all changes made to the order; all costs associated to the order; a warehouse component with the list of stock material that can be integrated in the order; several objects which are a list of materials for which maintenance tasks should be performed with access to the installation location, the equipment or the warehouse component; and a scanning validation which tracks the work order through the usage of a barcode scanning.

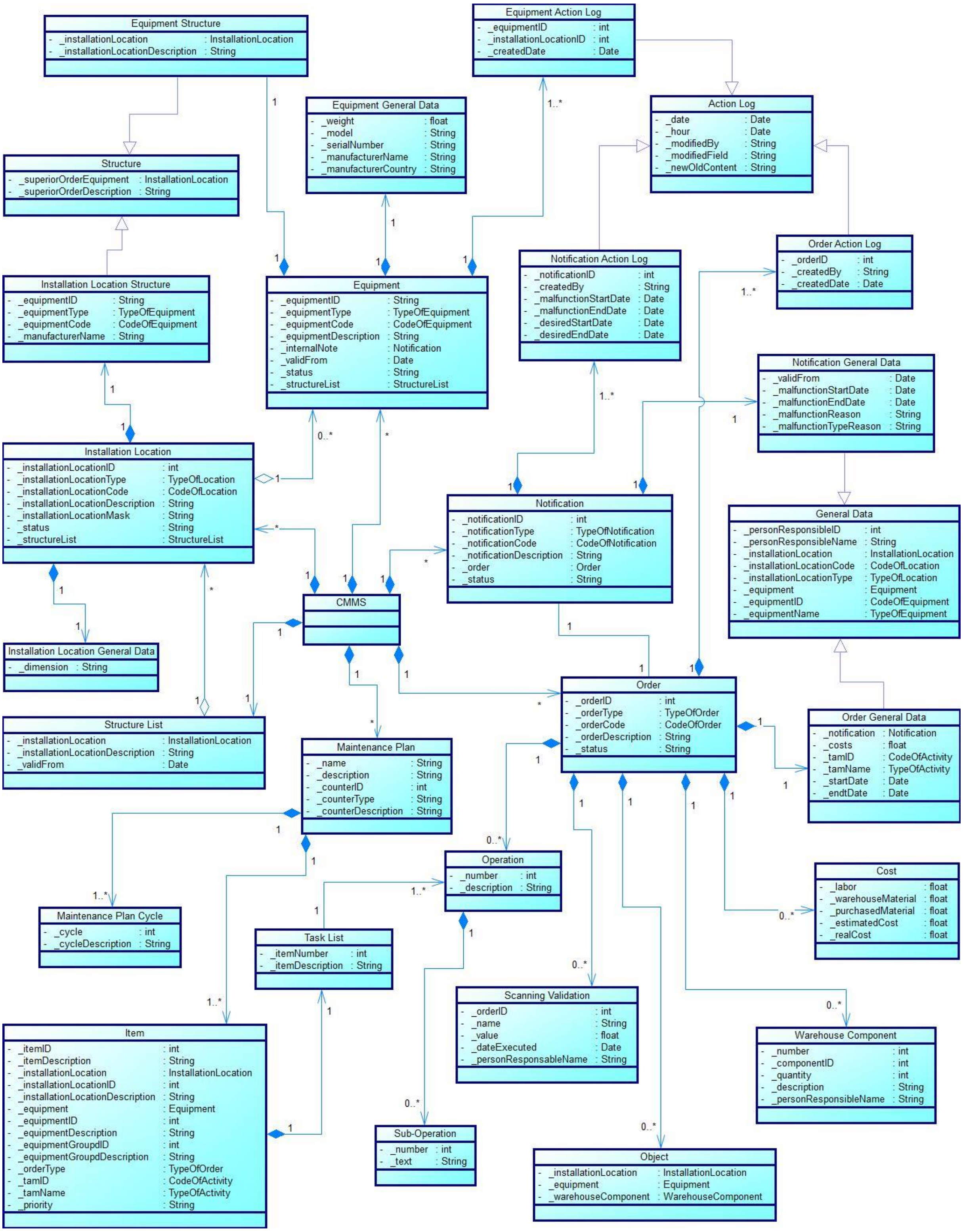


Figure 5.2: Computerized Maintenance Management Software Domain Model

In MDS there is also a need to represent not only what are the equipment that are part of CMMS and subject to maintenance but also how they can be identified. With that objective in mind, another domain model was originated and is displayed in Figure 5.3.

In this model there are several equipment involved: motors, pumps, rolls, gear boxes, instruments, valves, transformers, power and energy cells, and MMC's. There are also fans which include ventilation and exhaust fans and lastly, autonomous equipment such as dryers, compressors and chillers.

Each equipment has an equipment tag associated with the code of location and equipment as shown in Figure 5.1, a sequential number and an optional suffix number in case of being part of a group of equipment.

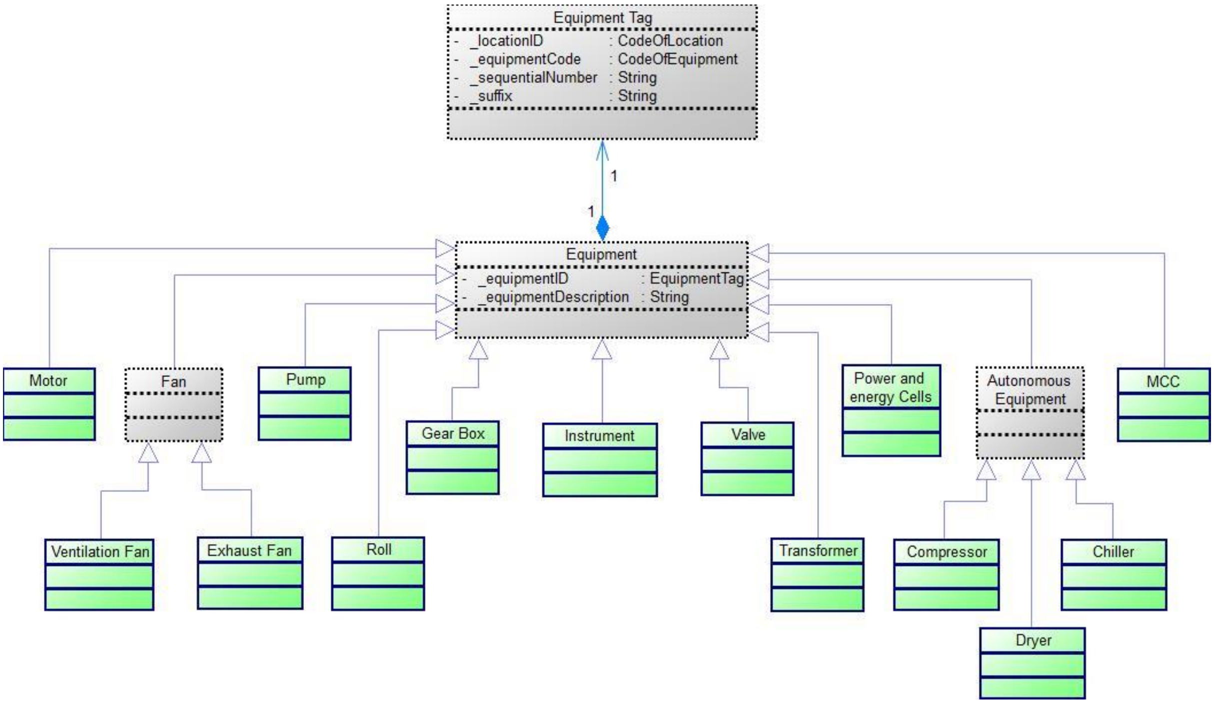


Figure 5.3: Maintenance Management Equipment Domain Model

To conclude de modelling of MDS, a sequence model was designed to demonstrate how maintenance is executed and who are the actors that have a role in it.

From Figure 5.4 it can be seen that an engineer begins by designing a preventive maintenance plan, creating and saving it in SAP PM.

In Figueira da Foz mill the maintenance plan can be corrective or preventive. If it is corrective, the supervisor technician starts by creating a malfunction notification and saves it in SAP PM. Then, he initiates an order associated to the previously notification created, saves it in SAP PM and prints both the order and notification. Afterwards, the technician supervisor appoints and delivers the order to a technician who will repair the problem and once the repairment is concluded, the supervisor technician closes the order and the notification, and saves all modifications in SAP PM.

In the case of the maintenance plan being preventive, the order is created automatically in SAP PM by the preventive maintenance plan previously defined. Furthermore, the supervisor technician prints the order produced, appoints and delivers the order to a technician who will repair the problem and once the repairment is finished, the supervisor technician closes the order and saves all modifications in SAP PM.

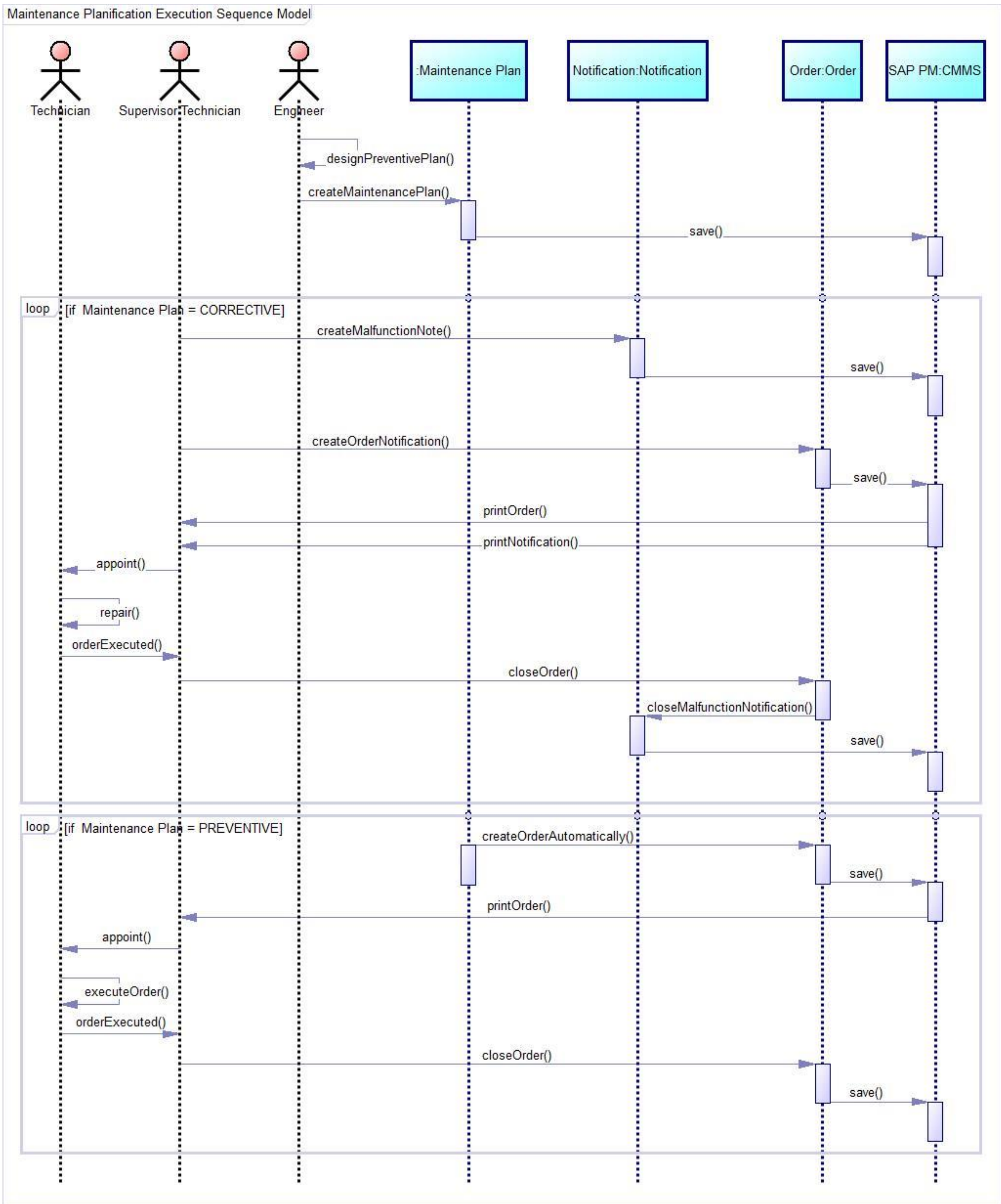


Figure 5.4: Maintenance Planification Execution Sequence Model

5.2 Vibration Data Subsystem

The VDS is based on SKF @ptitude Analyst which provides storage, analysis, and retrieval of asset information, making it accessible throughout the organization. It is a software that manages asset condition data from portable and on-line devices.

SKF @ptitude Analyst not only integrates SKF Microlog for portable data and SKF Multilog for on-line data, but also SKF Microlog Inspector for the use in Operator Driven Reliability (ODR) which is a framework for establishing an operator's activities that allows their own operation members to make their rounds, collect machine condition, and make inspections more easily.

To begin the representation of this subsystem, it is not only required to see what Condition Monitoring Software (CMS), which is SKF @ptitude Analyst, consists of but also other components that make up this subsystem and how they are connected. Therefore, a component model was built and is visible in Figure 5.5.

The model shows that an equipment has vibration sensors that send data through a cable to an online data collector which transfers data through a RS-485 standard, a certain balanced line with transmission distances of up to 1.2 kilometres (km), to the CMS. Furthermore, this software mainly contains an ODR module, an HMI, and a portable data module.

A portable data collector retrieves vibration sensor measures over a coiled cable and transfers via Transmission Control Protocol/Internet Protocol (TCP/IP), which is a standard Internet communication protocol that allow digital machines to communicate with each other, to the portable data module.

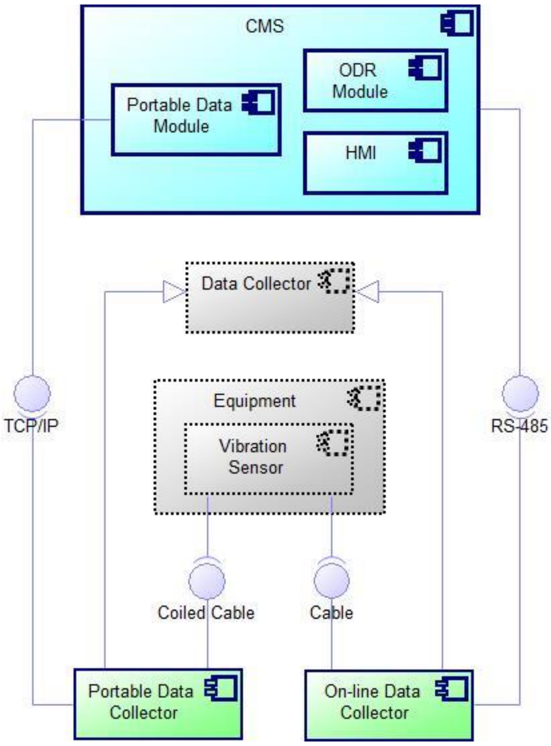


Figure 5.5: Vibration Condition Monitoring Component Model

Considering the need to show what equipment are part of the subsystem, how measurements are collected and the internal structure of CMS, two domain models were created: one to represent this and another that complements this model by exhibiting enumerations with the types of reports, alarms, graph displays and analysis which are used in CMS as displayed in Figure 5.6.

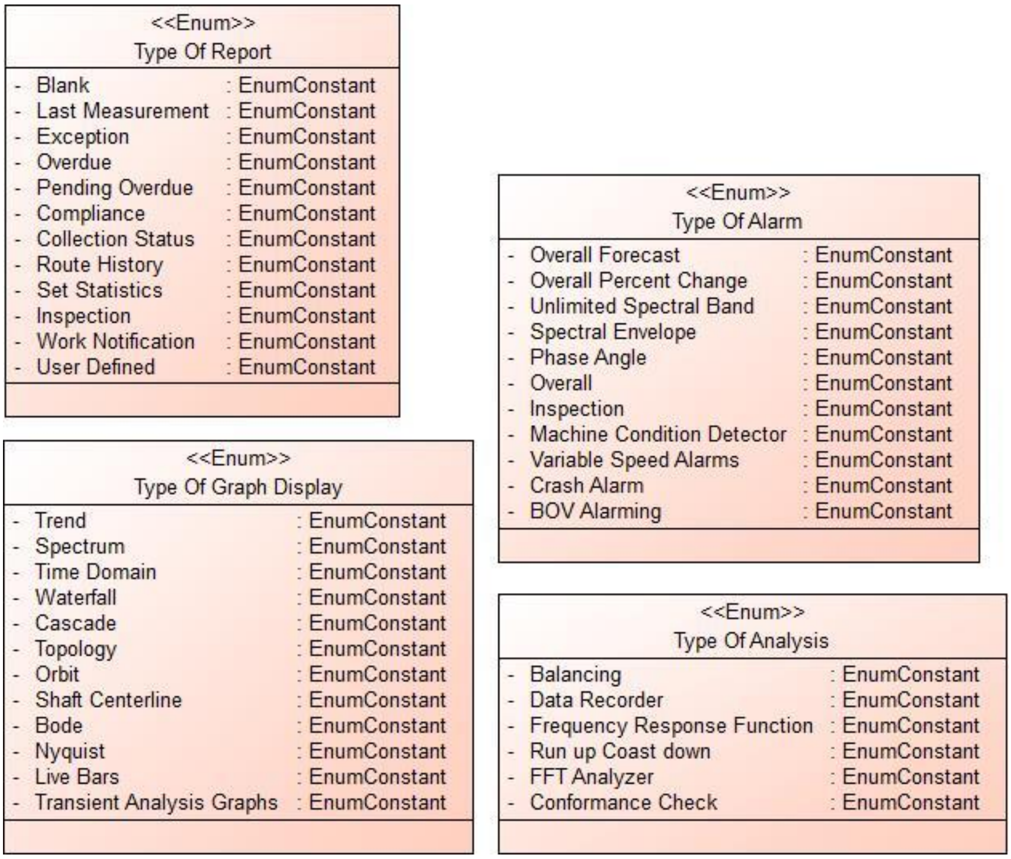


Figure 5.6: Condition Monitoring Software Enumeration Domain Model

From Figure 5.7 it can be seen that a motor, a roll, a gear box, a pump and a fan which includes ventilation fans and exhaust fans, are different types of equipment that contain several vibration sensors which are composed by displacement, velocity and acceleration sensors.

The various vibrations sensors of the rolls send their measurements to an on-line data collector which functions with a battery and a power supply, each with their own property details, and consequently transfer the data to the CMS.

A data collector can be not only an on-line data collector but also a portable data collector which includes a battery and it is used by a technician to retrieve measurements from vibration sensors of fans, motors, pumps and gear boxes. Furthermore, each portable device sends its data to the portable data module that is part of the CMS.

Regarding the portable data module, it not only contains customized alarms with different types associated, but also several types of interactive graph plots to be displayed, distinct types of advanced analysis to be performed and various types of template reports that can be generated as listed in Figure 5.6.

Lastly, CMS also includes an HMI showing an interface to the user and a ODR module where operators share a list of equipment that are marked as under surveillance.

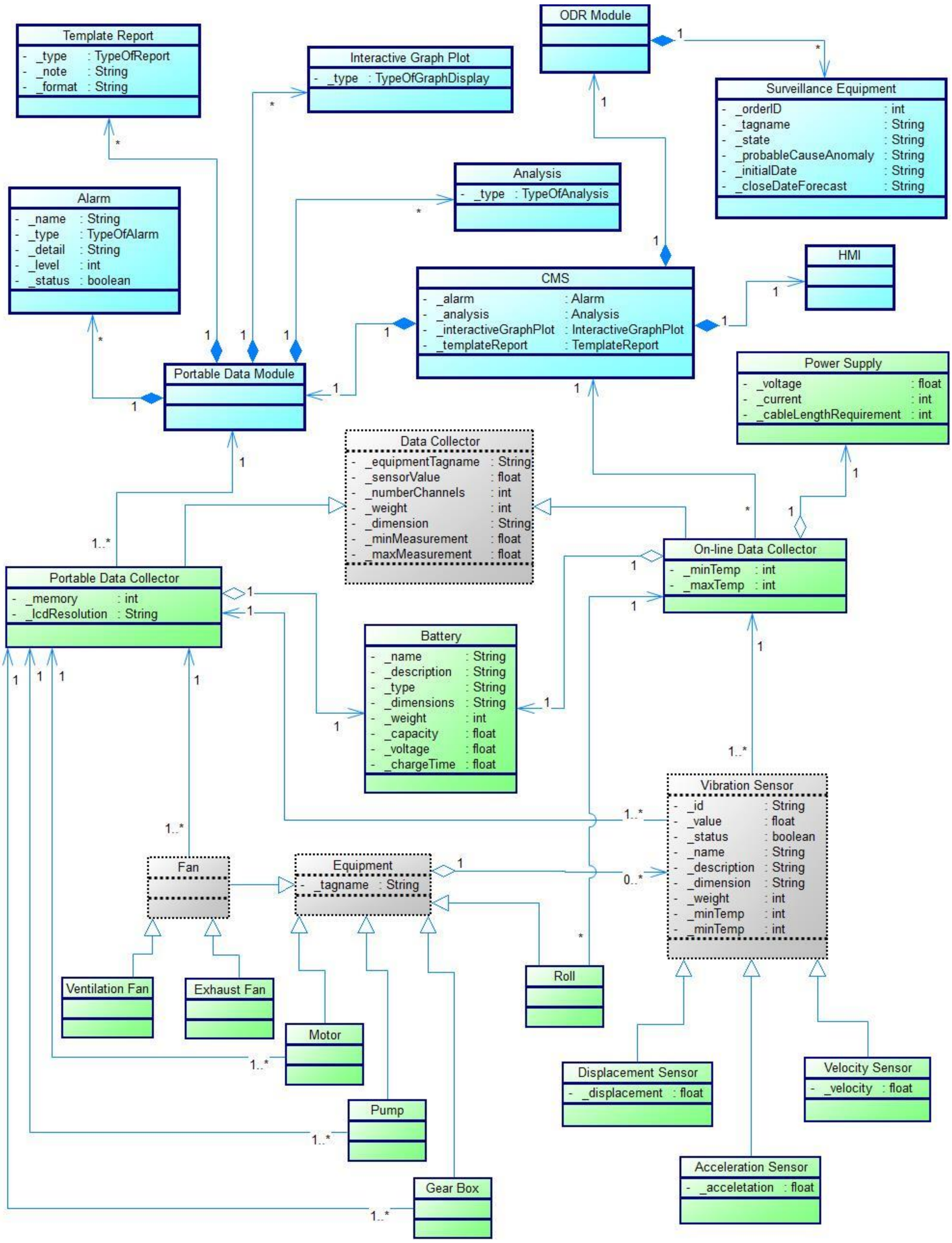


Figure 5.7: Vibration Condition Monitoring Domain Model

To conclude the representation of this subsystem, it also required to know which actors are part of it, for what they are responsible, their communication and if there is more useful data besides the one on CMS. Thus, a sequence model was produced as show in Figure 5.8.

The diagram begins with a SKF technician defining the margins values in SKF @ptitude analyst where each measure should be in. Afterwards, a vibration sensor reads measures and SKF multilog on-line, also known as on-line data collector, retrieves it and sends it to SKF @ptitude Analyst where the data will be analysed. Happening in parallel, the SKF technician uses a SKF microlog analyzer, known as portable data collector, to read and collect data from the equipment. Then, the measurements will be upload directly into the Analysis and Reporting Manager (ARM) - the portable data module - where data will be analysed.

In Figure 5.8 it is also possible to observe if any of the measures exceeds the margins previously defined. If it does, an alarm will be generated in SKF @ptitude analyst and a SKF technician working in the mill will notify the maintenance engineering department which will create a work order in SAP Plant Maintenance (SAP PM). The Engineer will then print the order and appoint a maintenance technician to repair the problem which, when it is finished, the engineer will be notified and closes the order in SAP PM.

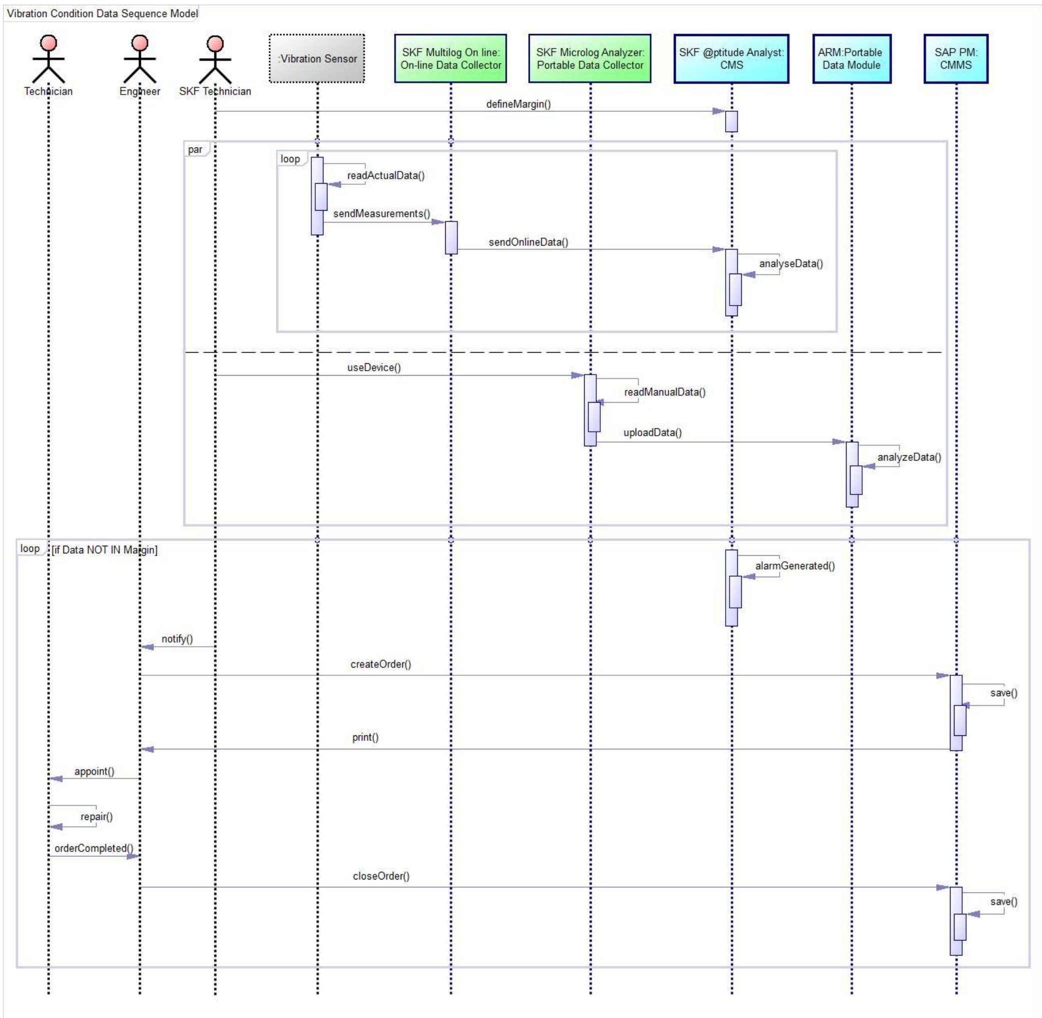


Figure 5.8: Vibration Condition Data Sequence Model

5.3 Inspection Data Subsystem

The IDS collects oil and thermography measurements and analysis through requested services which are provided by external companies.

5.3.1 Thermography Inspection

The thermography inspection service is performed by the *Instituto de Soldadura e Qualidade* (ISQ), that with the *Laboratório de Ensaios de Termodinâmica e Aeroespaciais* (LABET), one of the ISQ laboratories, carries out numerous types of tests and elaborates a very detailed thermography technical reports in accordance with criteria and international standardization.

To represent the thermography inspection that occurs in Figueira de Foz mill, it is necessary to apprehend what and how equipment are inspected, and the results of that analysis. To model this, a domain model was created as illustrated by Figure 5.9.

Firstly, the equipment used are motors and transformers which have an associated tag name. A thermographic camera retrieves images from these equipment through infrared radiation and it not only contains a battery and a power supply to work but also an image analyser responsible for processing and displaying the image through the temperature of the equipment and an image storage that stores all images in a memory card.

Secondly, the thermography entity laboratory has several thermographic cameras and elaborates a thermography report which will be integrated in the thermography customer application. A thermography history with the past reports will be part of the customer's application which is also contained by the same thermography entity as the thermography entity laboratory.

Regarding the thermography report, it contains three different sections: a list with the defective equipment details that were considered unsafe by the produced results; a list with the equipment without anomaly specifications; and several equipment analysis with the generated thermogram, the original image and comments and recommendations about the analysis of the equipment. The equipment analysis also includes the identification with all the data about the equipment and its installation location, and the point analysis with temperature measures of the equipment in question.

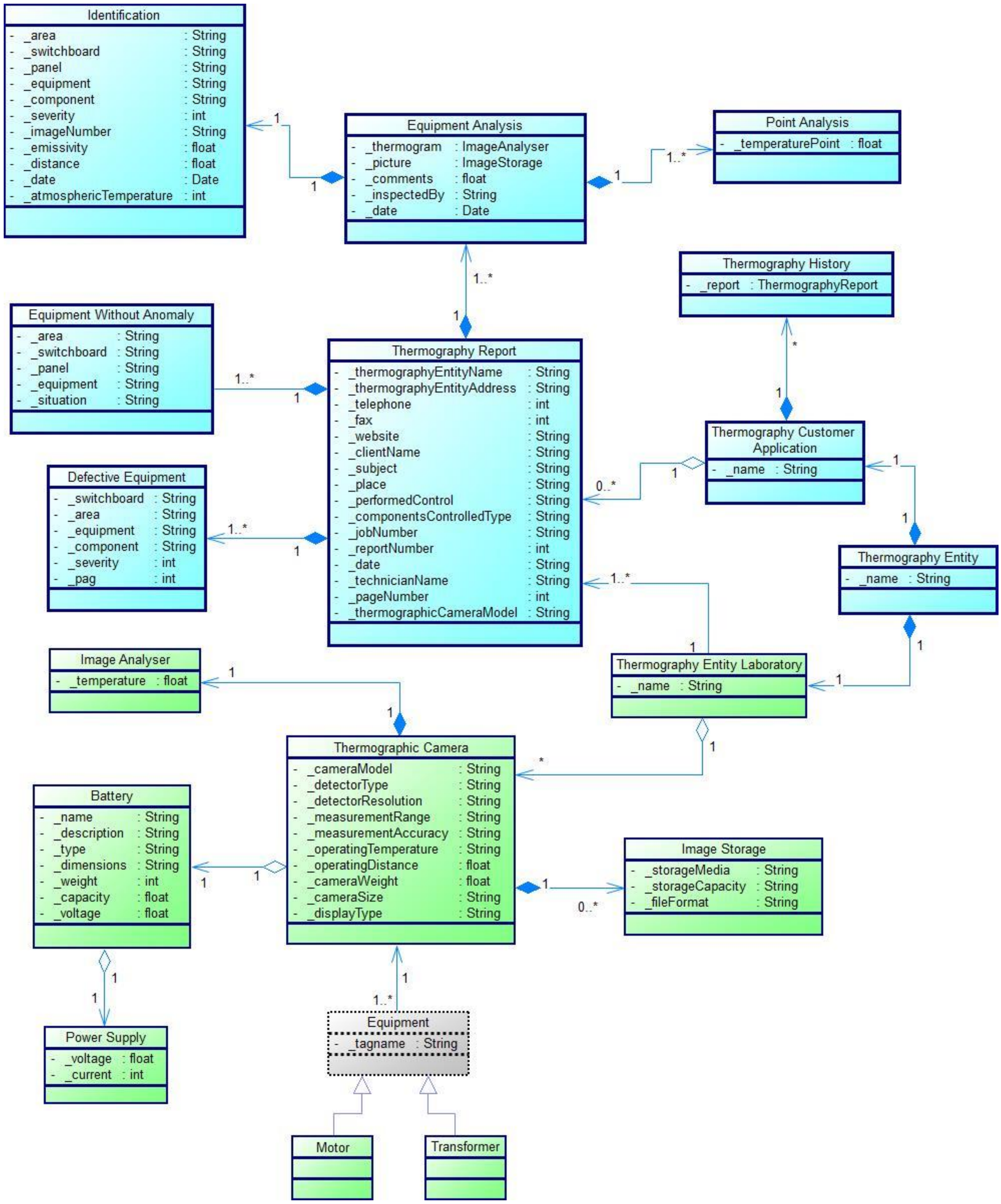


Figure 5.9: Thermography Inspection Domain Model

Considering that it is necessary to know which actors participate in this inspection and for which they are responsible, their interactions and where the thermography report is kept, a sequence model was designed.

The sequence model is presented in Figure 5.10 and can be observed that a maintenance engineer creates an order for inspection in SAP PM and the order is printed. Consequently, the engineer requests a thermography service in his ISQ website account and once confirmed, an ISQ technician will go to Figueira da Foz mill with one or more thermographic camera if required.

The ISQ technician uses the thermographic camera to scan the equipment, retrieve the images and sends it to ISQ LABET which will analyse the data. Furthermore, after analysing the data, the ISQ LABET will write one or more thermography reports that will be transmitted to the ISQ website which sends a notification to the engineer responsible for requesting the service.

In conclusion, the maintenance engineer will access his ISQ LABET account, extract the thermography report, attaches it to the order in SAP PM and then close the order that was previously created.

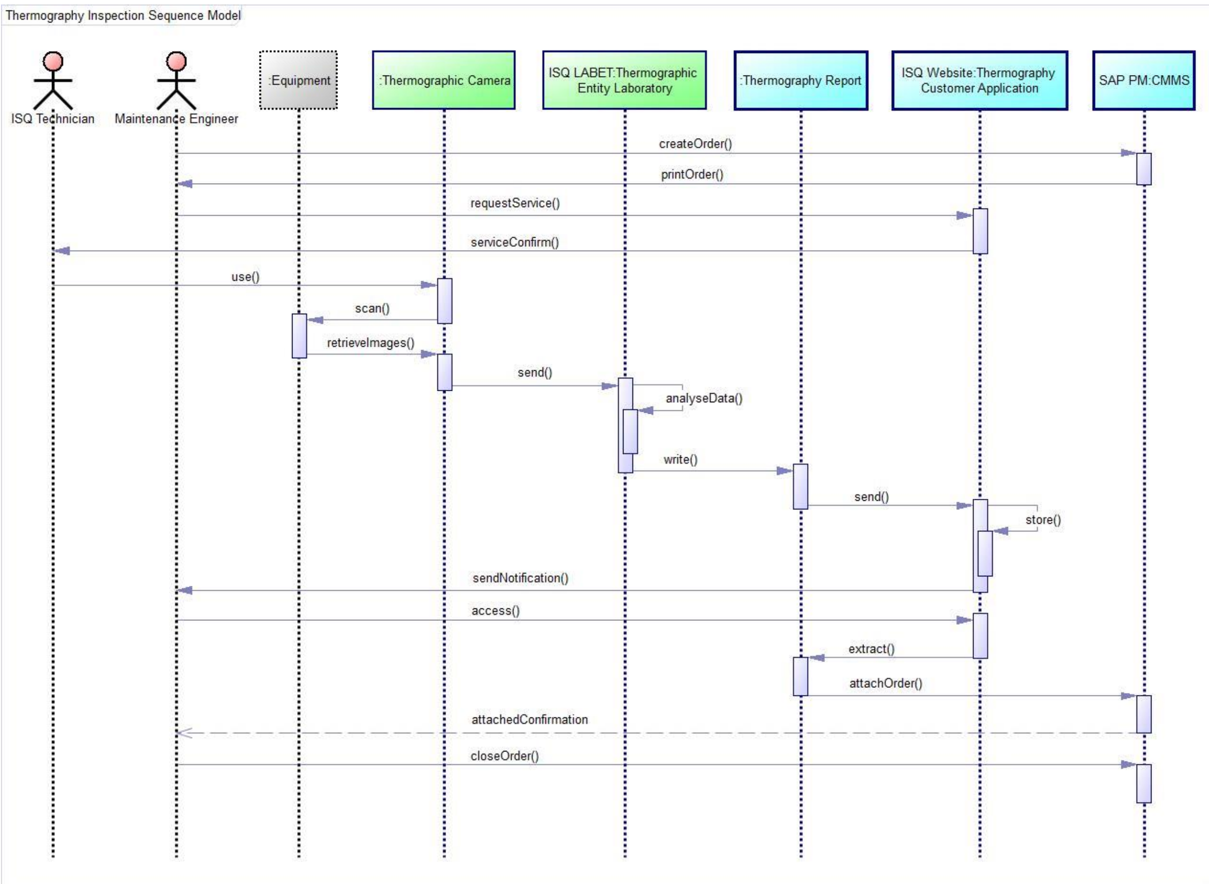


Figure 5.10: Thermography Inspection Sequence Model

5.3.2 Oil Inspection

The oil inspection service is executed by BP (British Petroleum) which is the oil supplier of Figueira da Foz mill, that receives an oil sample and elaborates a result and analysis report is also made by their laboratory.

This inspection, allied with the thermography inspection, also requires a domain model that represents which and how the equipment is subject to inspection, and what analysis and its details are produced.

From Figure 5.11 it can be seen that a motor, a transformer and a gear box are equipment with an associated tag name and that they transfer oil through custom tap samplings which are adapters that reduce the pressure to take samples from the equipment to several oil samplings bottles which include each a type of oil.

The oil entity laboratory has the oil sampling bottles collected and all tests and visual inspections to be performed on the oil. Moreover, it originates one or more oil reports which will be integrated in the oil customer application own by the common oil entity.

The oil customer application not only includes the oil report produced but also the past reports and graph generations which include the data to create graphics with the selected measures.

Regarding the oil report, it is composed by several details about the client and equipment data, a graphic section with the generated graphs, the result analysis, and column inputs with the actual and past result analysis regarding the same oil and equipment.

Lastly, the result analysis has three sections: a state section with the visual inspection and testing results, a wear and contamination metal section with the different types of tested metals and a particle section with the iron measurements present in the oil sample.

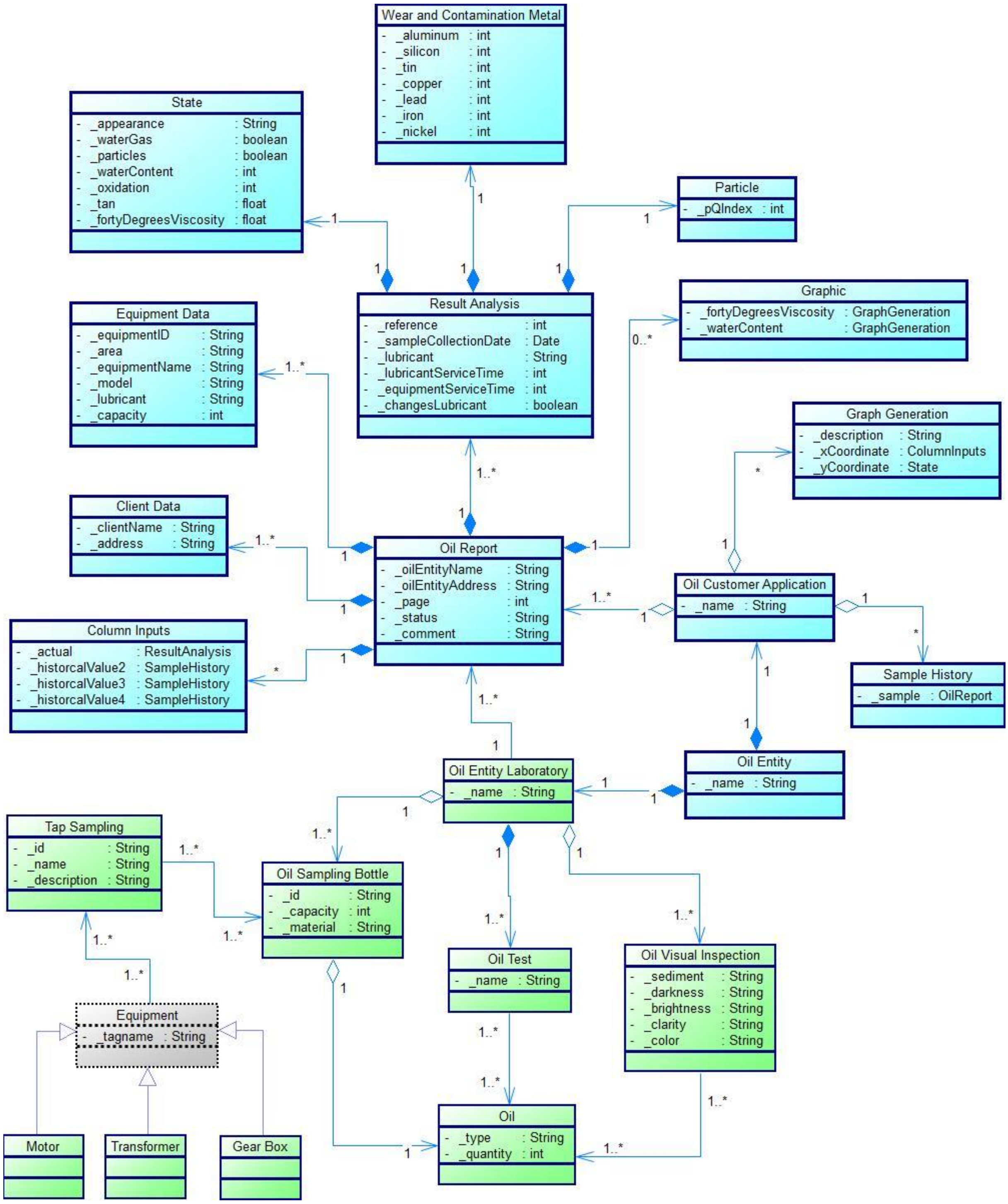


Figure 5.11: Oil Inspection Domain Model

Since it is essential to know which actors participate in the oil inspection and for which they are responsible, their interactions and where the oil report is stored, a sequence model was modelled.

The diagram detailed in Figure 5.12 demonstrates that an engineer creates an order for inspection in SAP PM and the order is printed. Thus, he will appoint a technician that will retrieve oil sampling bottles and deliver them to the responsible engineer.

The engineer will fill a form and send it to the BP laboratory which will perform several tests to the samples and write one or more oil reports. Furthermore, the reports will be sent to BP detecta online that will store it and notify the responsible engineer for filling the form.

To conclude, the engineer will access his BP detecta online account, extracts the oil report, attaches it to the order in SAP PM and then closes the order that was previously created.

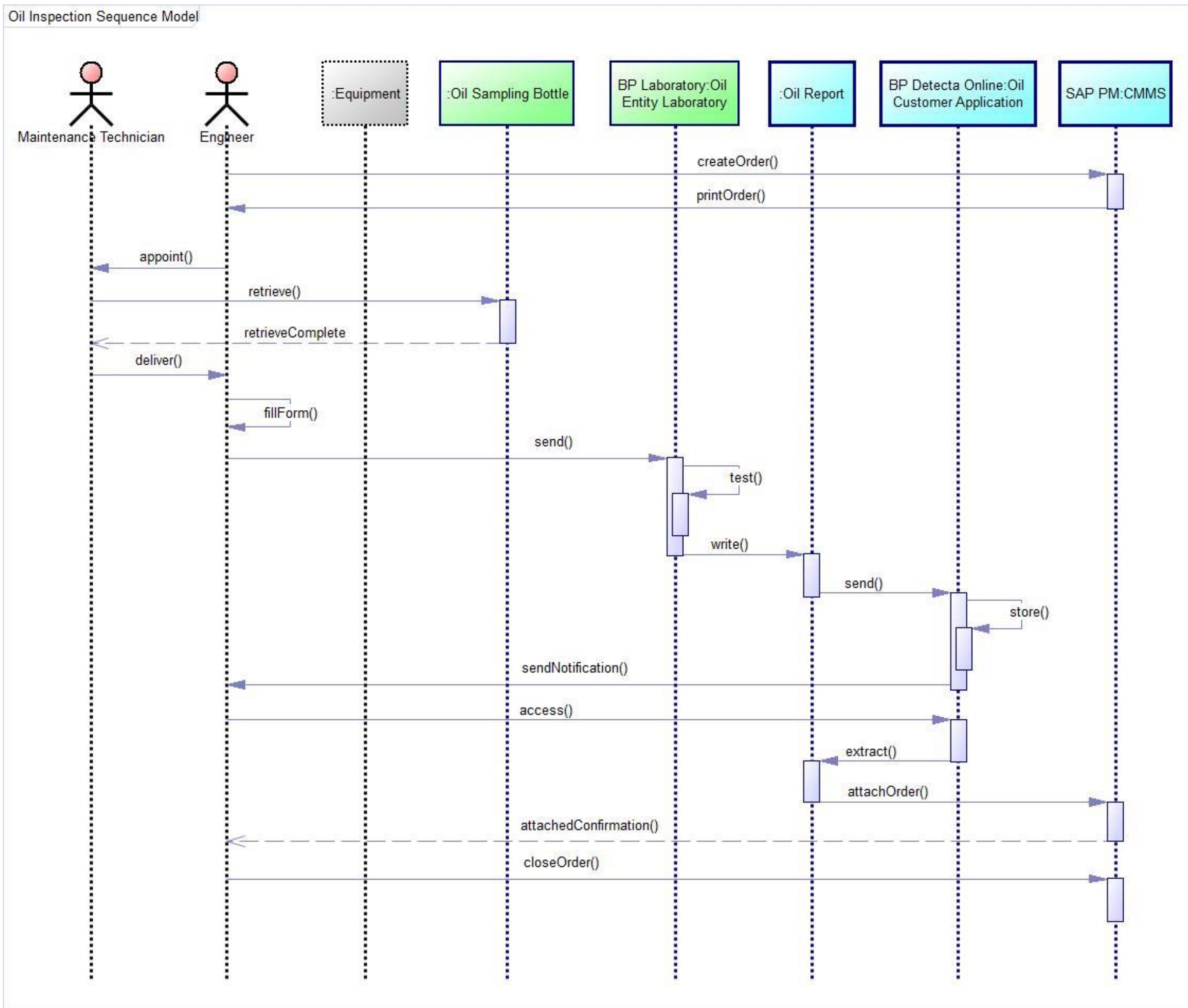


Figure 5.12: Oil Inspection Sequence Model

5.4 Lubrication Data Subsystem

The LDS is based on a Lubrication System provided by BP, Lubgest, that integrates all standard equipment planification of several types of equipment, with its lubrication points and lubricant to use. Afterwards, Lubgest will create regular reports with the tasks to be performed in each equipment.

To start modelling LDS, a structure of the lubrication system is needed to demonstrate how the system is composed and its responsibilities, consequently a domain model of it was created.

As detailed in Figure 5.13, a standard equipment plan contains various equipment with an associated tag name and different types of lubricants which will be applied in the lubrication points that an equipment possesses.

The lubrication system includes numerous standard equipment plans and produces several lubrication reports based on the data integrated in the system.

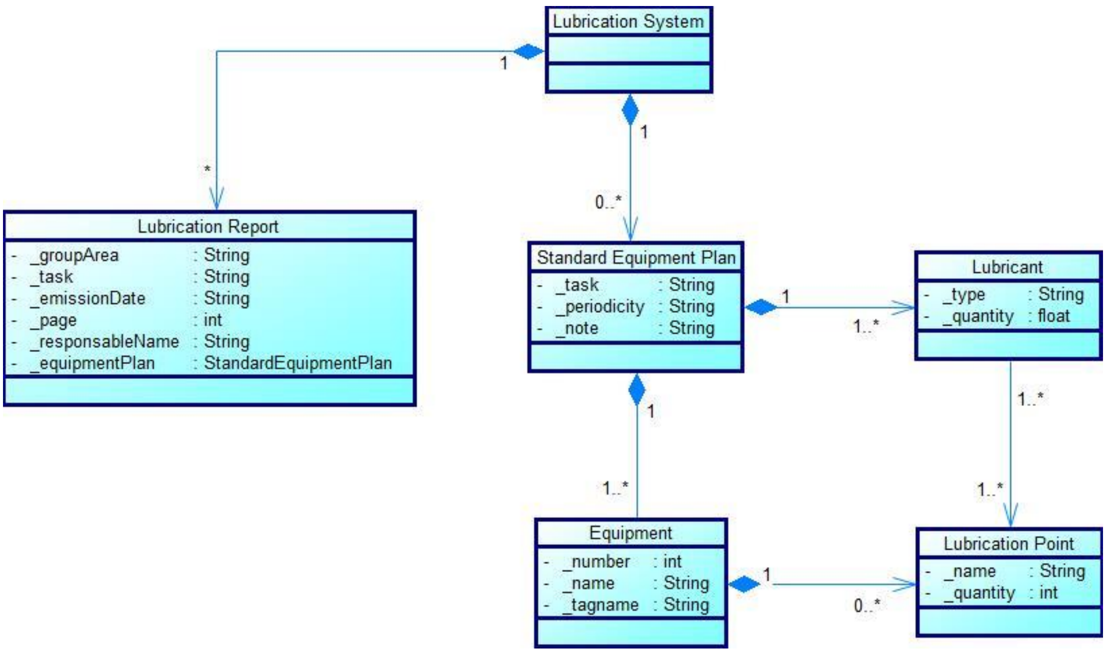


Figure 5.13: Lubrication System Domain Model

With the objective to represent what are the equipment in LDS where lubrication technicians will be able to execute the tasks of the lubrication reports originated by the lubrication system, another domain model was originated.

A motor, a roll, a gear box and a pump are equipment with an associated tag name, and which has several lubrication points, as shown in Figure 5.14. Various lubricants will then be applied in these lubrication points of an equipment.

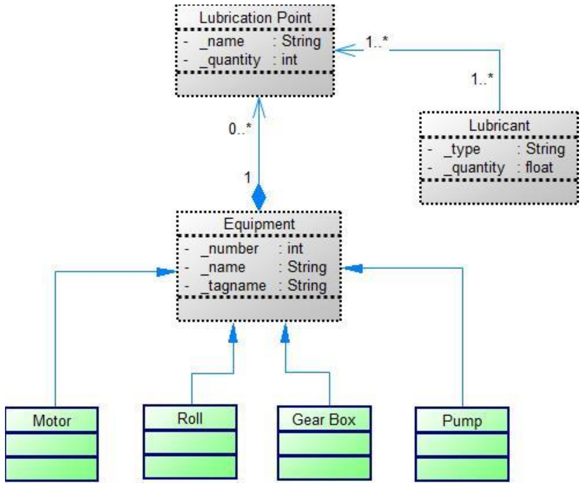


Figure 5.14: Equipment Lubrication Domain Model

To conclude LDS, a sequence model was designed to show how a lubrication task are generated, executed and what actors have a role in it.

From Figure 5.15 it can be seen that an engineer integrates a standard equipment plan which can, if needed, be modified, and saved in Lubgest. Consequently, the engineer can verify the Lubgest system and generate a lubrication task report that will be printed by the engineer and delivered to an appointed lubrication technician.

The lubrication technician selects a lubricant and lubricates the corresponding equipment. This action will be done until all the tasks pointed out in the lubrication report by equipment are finished. Once the lubrication report is finished, it will be archived for two years.

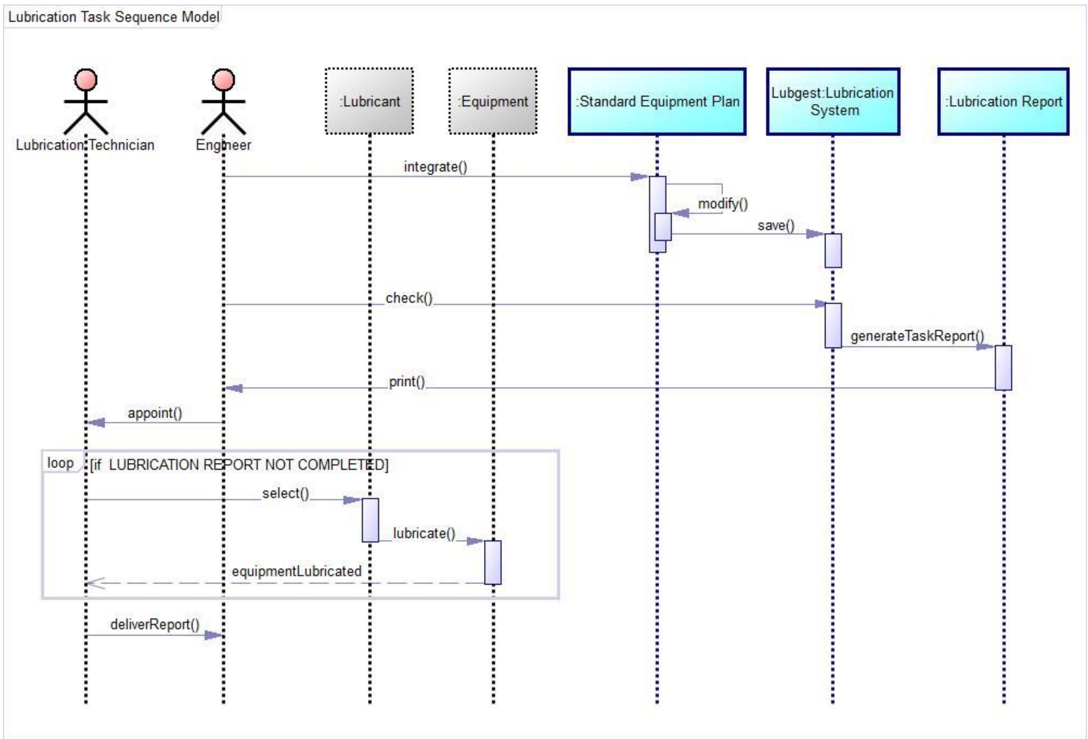


Figure 5.15: Lubrication Task Sequence Model

6 Conclusions and Future Work

This chapter describes de conclusions made by the work done and also its limitations and future work to be done.

6.1 Conclusion

Throughout this Dissertation, an architecture of the data collecting system of Figueira da Foz mill was conceived.

Considering the architecture - through the identification of the subsystems and its interfaces - it was identified how data is being collected. Furthermore, it was also described in each subsystem every asset that is subject to monitorization.

Regarding the collected data being collected and where t is stored, it can be concluded that in the data historian there are process trends analysis, production and quality reports generated by the QCS, and through the data historian tag name, a history of most of the measurements that are being collected and generated alarms from the DCS and QCS.

The CMMS reveals relevant equipment data and their locations, maintenance plans integrated, and notifications and work orders which present work history and failure dates and its causes. Beside the data being retrieved by the MDS, CMMS also stores thermography and oil reports history which include the detailed analysis made by the laboratories described in IDS.

Concerning the CMS, it includes lists of surveillance equipment, causes of anomalies, vibration alarms, reports, and analysis and graph display that can be generated.

In the lubrication system, there are equipment plans with information about the assets, their lubrication points and lubricants to apply, and also lubrication task reports executed in the lubrication system.

Considering the whole system of the mill, and with the purpose of centralizing data managing, The Navigator Company would benefit by integrating the lubrication reports in CMMS. This way the APM will only collect data through the data historian, the CMMS and the CDS.

6.2 Limitations and Future Work

This work has two main limitations: the identification of the tag name of the equipment in the CMS; and the modelling of the whole system with actual objects instead of classes due to lack of information.

Regarding future work, there are three interesting routes that can be explored: taking into account the Company's goal of decreasing pollution and energy consumption, it would be interesting to model the responsible systems for energy management and electricity production of the mill, which connect to the electrical distribution systems, allowing the sectioning of each energy generation and distribution zone; after the implementation of APM in the Figueira da Foz mill, the architectures of Setubal and Aveiro mills of the Navigator Company could also be created for more uniform, effective production systems; and lastly, a proposal for the future architecture of the work done.

Bibliography

[1] Bajpai, P., Green chemistry and sustainability in pulp and paper industry: Springer International Publishing, 2015.

[2] M. Suhr, G. Klein, I. Kourti, M.R. Gonzalo, G.G. Santonja, S. Roudier, L.D. Sancho, Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board, Publications Office of the European Union, 2015

[3] U. S. E. P. Agency, "The Pulp and Paper Industry - The Pulping Process and Pollutant Releases to the Environment" Office of Water, pp. EPA-821-F-97-011, November 1997

[4] Pereira, S. F., Modeling of a wastewater treatment plant using GPS-X, Master Thesis in Chemical and Biochemical Engineering, Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, September 2014.

[5] Fleiter T., Fehrenbach D., Worrell E., Eichhammer W., Energy efficiency in the German pulp and paper industry: A model-based assessment of saving potentials, Energy, 2012.

[6] Rojko, A., Industry 4.0 Concept: Background and Overview, International Journal of Interactive Mobile Technologies (IJIM) 11 (5): 77–90, 2017

[7] Li Da Xu, Eric L. Xu and Ling Li, Industry 4.0: State of the Art and Future Trends, International Journal of Production Research, vol. 56, no. 8, pp. 2941-2962, 2018

[8] Li, L, China's Manufacturing Locus in 2025: With a Comparison "Made-in-China 2025" and "Industry 4.0", Technological Forecasting and Social Change, vol. 135, pp.66-74, 2018

[9] Gilchrist, A., Industry 4.0: The Industrial Internet of Things, Springer, New York, 2016

[10] M. Hermann, T. Pentek, and B. Otto, Design Principles for Industrie 4.0 Scenarios., 49th Hawaii International Conference on System Sciences (HICSS), 2016

[11] M. Rüβmann, M. Lorenz, P. Gerbert, M. Waldner, J. Justus, P. Engel, and M. Harnisch, Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries, Boston Consulting Group, 2015

[12] A. Benešová, M. Hirman, F. Steiner, and J. Tupa, Analysis of Education Requirements for Electronics Manufacturing within Concept Industry 4.0, 41st International Spring Seminar on Electronics Technology (ISSE), pp. 1-5, 2018

[13] Stephan Weyer, Torben Meyer, Moritz Ohmer, Future Modeling and Simulation of CPS-based Factories: An Example from the Automotive Industry, IFAC-PapersOnLine, 49 (31), pp. 97–102, 2016

[14] H. Ahuett-Garza, T. Kurfess, A brief discussion on the trends of habilitating technologies for Industry 4.0 and Smart Manufacturing, Manufacturing Letters, 15, 60-63, 2018

[15] Breivold, Hongyu P., A Survey and Analysis of Reference Architectures for the Internet-of-Things. ICSEA 2017, 143, 2017

[16] DIN SPEC 91345, Reference Architecture Model Industrie 4.0 (RAMI4.0), DIN Std, April 2016

[17] Sino-German Industrie 4.0/Intelligent Manufacturing Standardisation Sub-Working Group, Alignment Report for Reference Architectural Model for Industrie 4.0/Intelligent Manufacturing System Architecture, Berlin, 2018

[18] Paiva, M., The Enterprise Architecture of Industry 4.0: Modelling RAMI4.0 in ArchiMate, Instituto Superior Técnico, Universidade de Lisboa, 2019

[19] Levitt, J., The Complete Guide to Preventive and Predictive Maintenance, Industrial Press, Second Edition, New York, 2011

[20] Han, T., Yang, B.-S., Development of an e-maintenance system integrating advanced techniques, Computers in Industry, 57(6), 569-580, 2006

[21] M. Haarman, P. de Klerk, P. Decaigny, M. Mulders, C. Vassiliadis, H. Sijtsema, I. Gallo, Predictive Maintenance 4.0 - Beyond the hype: PdM 4.0 delivers results. PwC and Mainnovation, 2018

[22] C. Coleman, S. Damodaran, M. Chandramouli, E. Deuel, Making Maintenance Smarter: Predictive Maintenance and the Digital Supply Network, Deloitte Insights, 2017

[23] J. Lee, H. A. Kao, and S. Yang, Service innovation and smart analytics for industry 4.0 and big data environment, Procedia CIRP, vol. 16, pp. 3-8, 2014

[24] M. Lupinucci, J. Pérez, G. Davila, L. Tiseyra, Improving sheet metal quality and product throughput with Bentley's machinery management system, Orbit (Bently Nevada), 21(3), 37-41, 2000

[25] R. Keith Mobley, An Introduction to Predictive Maintenance, Second Edition, Boston, USA, Butterworth-Heinemann, 2002

[26] David J. Edwards, Gary D. Holt, F. C. Harris, Predictive Maintenance Techniques and their Relevance to Construction Plant, Journal of Quality in Maintenance Engineering 4:1, 25-37, 1998

[27] Fenglian Qi, Guancheng Liu, The Summary of Internet of Things Applications in the Field of Pump Monitoring, Proceedings of the 2nd International Forum on Management, Education and Information Technology Application (IFMEITA 2017), Advances in Social Science, Education and Humanities Research (ASSEHR), vol. 130, 2018

[28] W. Boyes, L. O'Brien, The 50 Largest Automation Companies Around The World Keep On Keepin' On Despite The Recession, Control/ARC, 6, December 2009

[29] Shi-Wan Lin, B. Miller, J. Durand, G. Bleakley, A. Chigani, R. Martin, B. Murphy, M. Crawford, The Industrial Internet of Things Volume G1: Reference Architecture, Industrial Internet Consortium, 2017

[30] NPTEL, Architecture of Industrial Automation Systems, Version 2 EE IIT, Kharagpur, 2009

[31] Akerman, M., Implementing Shop Floor IT for Industry 4.0, Doctoral thesis in Philosophy, Chalmers University of Technology, Gothenburg, 2018

[32] The Navigator Company, Relatório de Sustentabilidade, 2015

[33] The Navigator Company, The Navigator Company: PLANO MANUTENÇÃO 2016-2020, 2018

[34] American National Standards Institute/International Society of Automation (ANSI/ISA), ANSI/ISA-5.1-2009: Instrumentation symbols and identification, Research Triangle Park (NC), 2009

Appendix A – Data Catalog

Table A: Data Catalog

Equipment	Data System	Data	Periodicity	Data Structure	Data Storage
Motor	Process	Power	1/10 seconds	Structured	Uniformance PHD
		Velocity	1/10 seconds	Structured	Uniformance PHD
		Current	1/10 seconds	Structured	Uniformance PHD
		State Signal	1/10 seconds	Structured	Uniformance PHD
		Torque	1/10 seconds	Structured	Uniformance PHD
		Temperature	1/10 seconds	Structured	Uniformance PHD
	Vibration (Portable)	Velocity	Monthly	Structured	SKF @ptitude
		Acceleration	Monthly	Structured	SKF @ptitude
		Alarm	Monthly	Structured	SKF @ptitude
		Alarm Level	Monthly	Structured	SKF @ptitude
	Lubrication	Planning	Defined accordingly	Unstructured	Lubgest
		Time Interval	Defined accordingly	Unstructured	Lubgest
	Inspection	Oil	Quarterly	Unstructured	SAP PM
		Thermography	Semiannual	Unstructured	SAP PM
	Maintenance	Order	Daily	Unstructured	SAP PM

		Notification	Daily	Unstructured	SAP PM
		Installation Location	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Unstructured	SAP PM
Pump	Process	Power	1/10 seconds	Structured	Uniformance PHD
		Velocity	1/10 seconds	Structured	Uniformance PHD
		Current	1/10 seconds	Structured	Uniformance PHD
		State Signal	1/10 seconds	Structured	Uniformance PHD
	Vibration (Portable)	Velocity	Monthly	Structured	SKF @ptitude
		Acceleration	Monthly	Structured	SKF @ptitude
		Alarm	Monthly	Structured	SKF @ptitude
		Alarm Level	Monthly	Structured	SKF @ptitude
	Lubrication	Planning	Defined accordingly	Unstructured	Lubgest
		Time Interval	Defined accordingly	Unstructured	Lubgest
	Maintenance	Order	Daily	Unstructured	SAP PM
		Notification	Daily	Unstructured	SAP PM
		Installation Location	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Structured	SAP PM

		Equipment Characteristic	Not Applicable	Unstructured	SAP PM
Roll	Process	Velocity	1/10 seconds	Structured	Uniformance PHD
	Vibration (On-line)	Velocity	10 seconds	Structured	SKF @ptitude
		Acceleration	10 seconds	Structured	SKF @ptitude
		Alarm	10 seconds	Structured	SKF @ptitude
		Alarm Level	10 seconds	Structured	SKF @ptitude
	Lubrication	Planning	Defined accordingly	Unstructured	Lubgest
		Time Interval	Defined accordingly	Unstructured	Largest
	Maintenance	Order	Daily	Unstructured	SAP PM
		Notification	Daily	Unstructured	SAP PM
		Installation Location	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Unstructured	SAP PM
Gear Box	Process	Power	1/10 seconds	Structured	Uniformance PHD
		Velocity	1/10 seconds	Structured	Uniformance PHD
		Current	1/10 seconds	Structured	Uniformance PHD
		State Signal	1/10 seconds	Structured	Uniformance PHD
	Vibration (Portable)	Velocity	Monthly	Structured	SKF @ptitude
		Acceleration	Monthly	Structured	SKF @ptitude
		Alarm	Monthly	Structured	SKF @ptitude

		Alarm Level	Monthly	Structured	SKF @ptitude
	Inspection	Oil	Quarterly	Unstructured	SAP PM
	Lubrication	Planning	Defined accordingly	Unstructured	Lubgest
		Time Interval	Defined accordingly	Unstructured	Lubgest
	Maintenance	Order	Daily	Unstructured	SAP PM
		Notification	Daily	Unstructured	SAP PM
		Installation Location	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Unstructured	SAP PM
Valve	Process	Power	1/10 seconds	Structured	Uniformance PHD
		Velocity	1/10 seconds	Structured	Uniformance PHD
		Current	1/10 seconds	Structured	Uniformance PHD
		State Signal	1/10 seconds	Structured	Uniformance PHD
	Maintenance	Order	Daily	Unstructured	SAP PM
		Notification	Daily	Unstructured	SAP PM
		Installation Location	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Unstructured	SAP PM

Instrument	Process	Power	1/10 seconds	Structured	Uniformance PHD
		Velocity	1/10 seconds	Structured	Uniformance PHD
		Current	1/10 seconds	Structured	Uniformance PHD
		State Signal	1/10 seconds	Structured	Uniformance PHD
	Maintenance	Order	Daily	Unstructured	SAP PM
		Notification	Daily	Unstructured	SAP PM
		Installation Location	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Unstructured	SAP PM
Fan (Ventilation and Exhaust Fan)	Process	Power	1/10 seconds	Structured	Uniformance PHD
		Velocity	1/10 seconds	Structured	Uniformance PHD
		Current	1/10 seconds	Structured	Uniformance PHD
	Vibration (Portable)	Velocity	Monthly	Structured	SKF @ptitude
		Acceleration	Monthly	Structured	SKF @ptitude
		Alarm	Monthly	Structured	SKF @ptitude
		Alarm Level	Monthly	Structured	SKF @ptitude
	Maintenance	Order	Daily	Unstructured	SAP PM
		Notification	Daily	Unstructured	SAP PM
		Installation Location	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Structured	SAP PM

		Equipment Characteristic	Not Applicable	Unstructured	SAP PM
Autonomous Equipment (Compressor, Dryer and Chiller)	Process	State Signal	1/10 seconds	Structured	Uniformance PHD
	Maintenance	Order	Daily	Unstructured	SAP PM
		Notification	Daily	Unstructured	SAP PM
		Installation Location	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Unstructured	SAP PM
Transformer	Process	Power	1/10 seconds	Structured	Uniformance PHD
		Current	1/10 seconds	Structured	Uniformance PHD
	Inspection	Oil	Quarterly	Unstructured	SAP PM
		Termography	Semiannual	Unstructured	SAP PM
	Maintenance	Order	Daily	Unstructured	SAP PM
		Notification	Daily	Unstructured	SAP PM
		Installation Location	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Unstructured	SAP PM
Power and Energy Cells	Process	Power	1/10 seconds	Structured	Uniformance PHD
		Velocity	1/10 seconds	Structured	Uniformance PHD
		Current	1/10 seconds	Structured	Uniformance PHD

	Maintenance	Order	Daily	Unstructured	SAP PM
		Notification	Daily	Unstructured	SAP PM
		Installation Location	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Unstructured	SAP PM
MCC	Process	Power	1/10 seconds	Structured	Uniformance PHD
		Velocity	1/10 seconds	Structured	Uniformance PHD
		Current	1/10 seconds	Structured	Uniformance PHD
	Maintenance	Order	Daily	Unstructured	SAP PM
		Notification	Daily	Unstructured	SAP PM
		Installation Location	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Structured	SAP PM
		Equipment Characteristic	Not Applicable	Unstructured	SAP PM

Appendix B – System Overview Informal Model

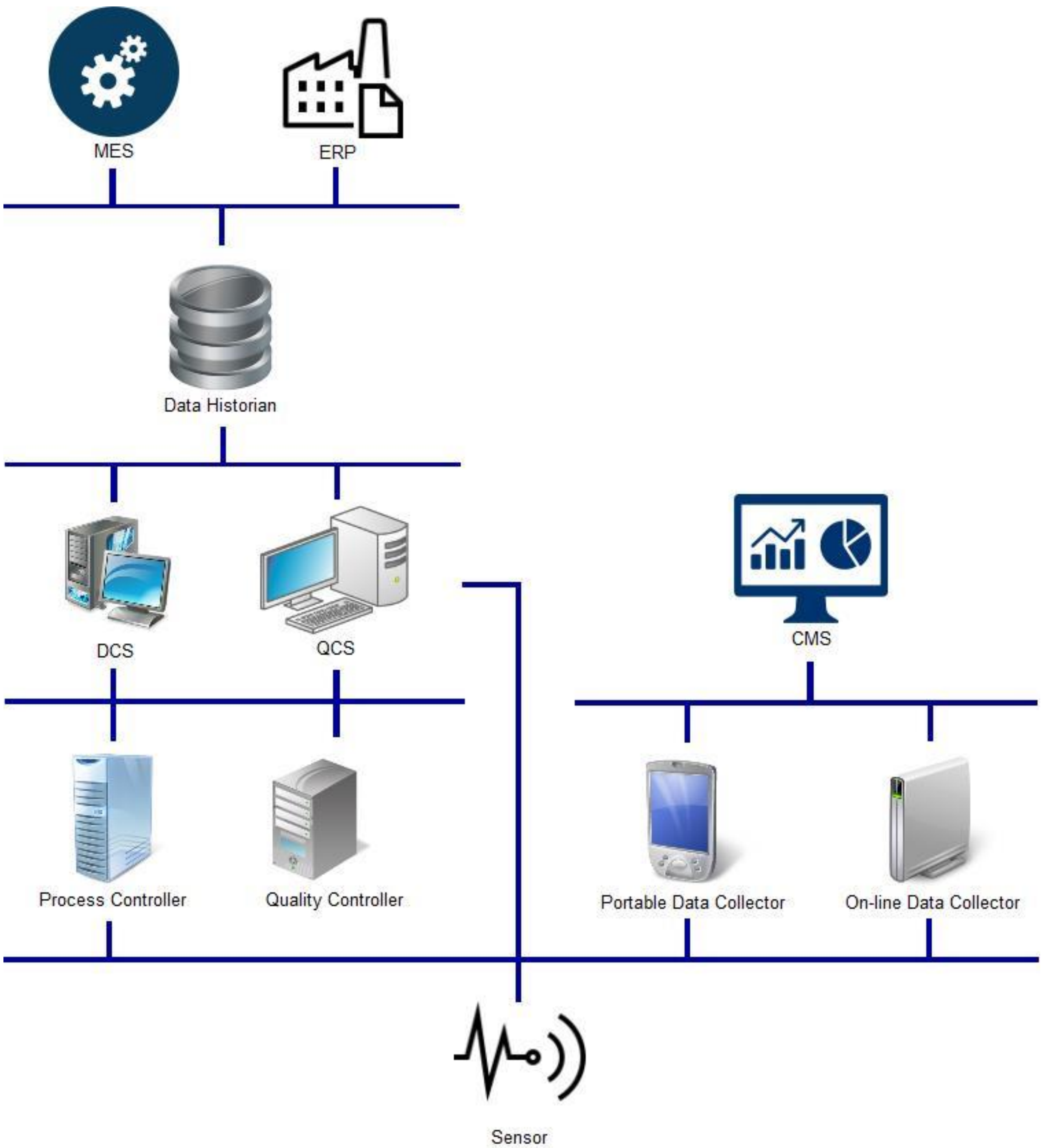


Figure B: System Overview Informal Model

Appendix C – System Overview SysML Model

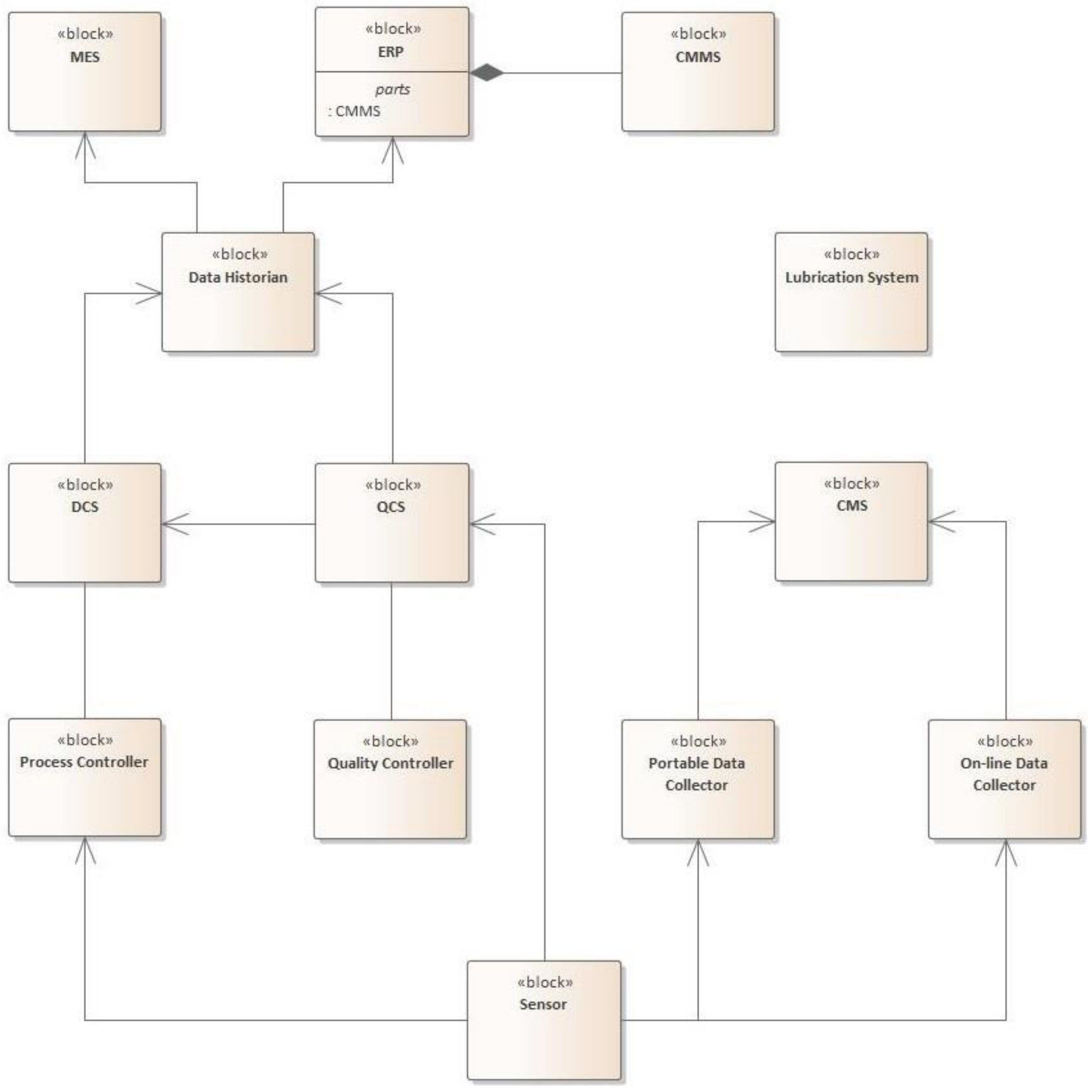


Figure C: System Overview SysML Model

Appendix D – Identification Letters

Table D: Identification Letters [34]

	First Letters		Succeeding Letters		
	Measured/Initiating Variable	**Variable Modifier**	**Readout/Passive Function**	**Output/Active Function**	**Function Modifier**
A	Analysis		Alarm		
B	Burner, Combustion		User's Choice	User's Choice	User's Choice
C	User´s Choice			Control	Close
D	User´s Choice	Difference, Differential			Deviation
E	Voltage		Sensor, Primary Element		
F	Flow, Flow Rate	Ratio			
G	User's Choice		Glass, Gauge, Viewing Device		
H	Hand				High
I	Current		Indicate		
J	Power		Scan		
K	Time, Schedule	Time Rate of Change		Control Station	
L	Level		Light		Low
M	User's Choice				Middle, Intermediate

N	User's Choice		User's Choice	User's Choice	User's Choice
O	User's Choice		Orifice, Restriction		Open
P	Pressure		Point (Test Connection)		
Q	Quantity	Integrate, Totalize	Integrate, Totalize		
R	Radiation		Record		Run
S	Speed, Frequency	Safety		Switch	Stop
T	Temperature			Transmit	
U	Multivariable		Multifunction	Multifunction	
V	Vibration, Mechanical Analysis			Valve, Damper, Louver	
W	Weight, Force		Well, Probe		
X	Unclassified	X-axis	Accessory Devices, Unclassified	Unclassified	Unclassified
Y	Event, State, Presence	Y-axis		Auxiliary Devices	
Z	Position, Dimension	Z-axis, Safety Instrumented System		Driver, Actuator, Unclassified final control element	