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Shop floor data in Industry 4.0: study and design of a Manufacturing Execution System

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Abstract

Industry 4.0 brings with it numerous challenges. However, it is being seen by companies as essential in their ability to adapt to the market and to the demands of consumers. Thus, intending to achieve more flexible and more decentralized production, the acquisition of technologies emerging from this fourth industrial revolution is crucial. This is where information systems will make a difference, as they will enable the cohesion of processes within the company, such as a more streamlined flow of information.

This article has as main objective to study and design an Information System with characteristics of a Manufacturing Execution System (MES), following an approach capable to respond to a whole set of key processes on the shop floor, such as addressing the problem of so-called information islands stored in fragmented information sources. This study was conducted in a company belonging to the chemical industry located in the center of Portugal.

Keywords: Industry 4.0; Smart Factory; Manufacturing Execution System; Unified Modelling Language (UML), System Design

1. INTRODUCTION

The labelling of a new Industrial Revolution establishes substantial changes within the industry sector at the technical, economic, and social levels. The “Industry 4.0” terminology showed up in Germany at the Hanover Fair event in 2011, demonstrating the start of the Fourth Industrial Revolution (Bibby & Dehe, 2018).

The Manufacturing industry is moving from mass production to mass individualization (Ding, Lei, Zhang, Wang, & Wang, 2020; Park, Lee, Kim, & Noh, 2020), flexibility, autonomy, and faster market reply (Ding et al., 2020). Digitalization is one course to face these enlarged market challenges (Joppen, Lipsmeier, Tewes, Kühn, & Dumitrescu, 2019). Although, it is important to emphasize that digital transformation is not just about using new technologies, but highlights the necessity of developing a strategy that places employees at the core to accomplish a successful implementation (Temel & Ayaz, 2019).

As mentioned in Yao et al (2019) the “Manufacturing is the backbone of our modern society”, so the advances in Information and Communication Technologies (ICTs) and the introduction of the

Internet of Things (IoT), brought, a new whole scenario in the industry, called Smart Factory, where manufacturing practices use networked data and ICTs to rule operations (Ding et al., 2020; Mittal, Khan, Romero, & Wuest, 2019).

Since interoperability and traceability are pillars in the I4.0's context, it is essential to understand how to achieve this state of smart manufacturing, being the information systems critical tools to this accomplishment (Soujanya Mantravadi & Møller, 2019; Rojko, 2017).

Enterprise Resource Planning (ERP) and Manufacturing Execution System (MES) are the two most important information systems which can provide, as long as they are properly integrated, a good overview of the shop floor, as well as a good readjustment to the long-term planning enabled by ERP.

ERP is acknowledged as the evolution of Manufacturing Resource Planning (MRP) and it can be seen as a tool that conducts the information in production systems and other departments in a company (Ferro, Ordóñez, & Anholon, 2017). It is largely used to control the production's planning and logistics functions (Subramanian, Patil, & Kokate, 2019).

MES is considered to be a decision support system (Arica & Powell, 2018) that simulates and administers intradepartmental material flows (Makarov, Frolov, Parshina, & Ushakova, 2019). It is responsible for simplifying the buffer management, as well as Work in Progress monitoring on the production control level (Reddy & Telukdarie, 2018).

Since MES is the software closest to the shop floor and with which it interacts, companies are interested in acquiring a distributed information system capable of establishing a continuous information flow without the existence of information islands being a problem. The integration of this system also provides the ability to construct a database structure which may further allow a more flexible data analysis, facilitating the data visualization, having consequences in the decision-making process.

It is known that, today, the major deficiencies that exist in companies that move them away from the reality of I4.0 are the lack of data capture in real-time and also the programs of the manufacturing systems to which suppliers do not allow access, or if they make it possible, they intend to grant this access only through a large amount of money (Yao et al., 2019). This concern causes the existence of information islands. In addition to this and, presented as two major barriers to the industry 4.0 paradigm, are the lack of process standardization and the lack of architecture and systems integration skills (Raj, Dwivedi, Sharma, Beatriz, & Sousa, 2020).

The main objective of this paper is to create a software specification and the corresponding conceptual model (using the Unified Modelling Language - UML) capable of filling the key processes of a factory floor, eliminating isolated information cores. This approach was carried out

using a case study in a company belonging to the chemical industry and the specification in question aims to address concerns such as interoperability, knowledge management, and data visualization. These three characteristics are imperative in the context of Industry 4.0.

The present article is structured as follows: in the second section, there is a literature review, where concepts such as Industry 4.0, Smart Factory, Information Systems, and Manufacturing Execution System (MES) are specified. Then in the third section, the case study is shown, where the context of the problem, goals, methodology used, results and discussion of them are presented. Finally, the conclusion intends to summarize the connection between the notions explained by the academy's analysis and the results taken in practice, to assume the approach demonstrated in this paper as being valid and capable of replication for other business contexts.

2. BACKGROUND

2.1 Industry 4.0 and Smart Factory

Industry 4.0's concept brings an approach that engenders a conversion from machine major manufacturing to digital manufacturing (Oztemel & Gursev, 2020). In this context, machines are allowed to process data and interconnect with other machines or humans, through a network, called Internet of Things (Jerman, Bertoneclj, Dominici, Pejić Bach, & Trnavčević, 2020; T. Kim, 2019). This paradigm has been transforming all the supply chain, because of the use of real-time sensing and transfer of data (Jerman et al., 2020). The Industry 4.0's context brings advantages which are already known by academia, such as a more production flexibility (Büchi, Cugno, & Castagnoli, 2020; Rojko, 2017) and a friendlier work environment (Rojko, 2017), an improvement of productivity (bigger output capacity) (Büchi et al., 2020; Soujanya Mantravadi & Møller, 2019), a faster real-time response both for the decentralized production control (Büchi et al., 2020) as well for customer responsiveness (Rojko, 2017) and developed product quality (Büchi et al., 2020), enabling at the same time customized mass production without increasing overall costs (Rojko, 2017).

In I4.0, likewise their physical representation, production elements have moreover a virtual identity (Rojko, 2017), which has the name of digital twin. Cyber-physical systems (CPSs) – which plays a crucial position in connection and sensor network (T. Kim, 2019) – and the Digital Twin (DT) technologies are capable of build, both on the physical shop floor and the corresponding cybershop floor, interconnectivity and interoperability (Cimini, Pirola, Pinto, & Cavalieri, 2020; Cupek, Drewniak, Ziebinski, & Fojcik, 2019). Sensors and actuators (from the physical world), integration, data and analytics (from the cyber world) are the digital twin enablers' components (T. Kim, 2019). Therefore, I4.0 opens doors to capabilities like tracking, communicating, and monitoring smart units, such as jobs, machines, tools, workers and other resources along the value chain (Ramadan, Salah,

Othman, & Ayubali, 2020). This accompaniment provides, at the same time, the production process performance improvement (Park et al., 2020).

A smart factory represents an imminent state of an entirely connected manufacturing system, where data will be generated, transferred, received and processed in order to perform all required tasks, with almost without human force (Osterrieder, Budde, & Friedli, 2020; Rub & Bahemia, 2019). The human force just needs to intervene in problem-solving phases (Oztemel & Gursev, 2020). All these interconnected and heterogeneous objects generate a huge amount of structured, semi-structured, and unstructured data, called big data (Alcácer & Cruz-Machado, 2019). Smart manufacturing is capable of using information continuously, contributing to improve and preserve performance (Mittal et al., 2019).

There are two types of systems integration in I4.0, the horizontal and the vertical one. In the first, there is a foundation for a near and high degree of cooperation between several companies (inter-company integration). In the second, the integration among the different levels of the enterprises' hierarchy (intracompany integration) (Alcácer & Cruz-Machado, 2019).

Although some of the advantages of implementing the I4.0 paradigm have already been unravelled by the academy, there is still some concern about its implementation. Barriers such as the high initial investment (Raj et al., 2020), risk of investing in technology that can quickly become obsolete (Moeuf et al., 2020), lack of digital skills (Moeuf et al., 2020; Raj et al., 2020) and lack of a strategy that aligns all the resources necessary for the achievement of this paradigm (Moeuf et al., 2020; Raj et al., 2020), hinder the entry of I4.0 in manufacturing companies. It is also known that the low levels of standardization of processes, regulations and forms of certification, as well as the low level of understanding of software architecture (Raj et al., 2020), become imperative obstacles and which must be strongly analysed to determining the success of an industry 4.0 project.

The lack of real-time data and information islands are two of the main deficiencies that manufacturing information systems have (Yao et al., 2019). Traditional manufacturing systems are poor in real-time data acquisition and processing and sometimes they do not capture data that would be valuable to the process. The other problem is related to all devices that need to be integrated vertically and horizontally in enterprises' shop-floors (Yao et al., 2019).

2.2 Information Systems: Automation Pyramid

As already mentioned before, the vertical integration represents the link among IT systems in different company's levels, ranging from the field level, via the control and process control to the operational and company management level (Joppen et al., 2019). To achieve success in the complete integration, IT systems must map and endorse entire business processes (Sauer, 2014).

In the I4.0's context, broad software support based on decentralized and customized styles of Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP) is essential for a smooth integration of manufacturing and business processes (Rojko, 2017).

In most companies, almost all the data is recorded by hand and this contributes to a time lag problem. Because of that, it is difficult to keep track of the work-in-progress (WIP) in real-time, as well as to estimate material consumption for production (T. H. Kim, Jeong, & Kim, 2019).

From a top-down automation perspective, Enterprise Resource Planning (ERP) systems are the top of the pyramid, where they are responsible for long-term planning (Hoffmann, Büscher, Meisen, & Jeschke, 2016). ERP can be seen as a global system for organizing the distribution of human and material resources (Rix, Kujat, Meisen, & Jeschke, 2016). Right after ERP, Manufacturing Execution Systems (MES) occupies the second place, and they are in charge of mid-term production planning and execution (Hoffmann et al., 2016). MES systems depend on the combination between machines and plants in production and assembly. Because of the machinery's heterogeneity, the connection between machines is always different and involves manual outlay for configuration and integration on the part of the MES providers, system integrators, and project operators (Sauer, 2014). Below the MES, it is possible to find the Supervisory Control and Data Acquisition (SCADA) which can be assumed as a control system of the conditions and states during operation, to prevent significant problems or serious failures (Hoffmann et al., 2016). The SCADA is constituted by sensors and actuators which are programmable by logic controls (PLC) (Rix et al., 2016).

This paper focuses its study on the MES layer, and for this reason, this type of information system will be detailed in the next chapter.

2.3 Manufacturing Execution System (MES)

Manufacturing Execution Systems are created to operate in aggregation with “workstations, manufacturing lines, conveyor belts and automated processes throughout a manufacturing facility” (Lynch et al., 2019). This type of system is used to track, inspect, and notify in real-time all that happens on the shop floor, ranging from raw materials to final products (Coito et al., 2019). Production reporting, planning, shipping, product tracing, maintenance procedures, performance analysis, workforce tracking, resource allocation, are all functions of the MES, which permits covering all that is shop floor management, as well as all communication between different systems (Rojko, 2017).

A good MES should provide a group of characteristics to be capable of delivering good service, they are:

Interoperability – the MES needs to be gifted with the capability of being integrated with other systems (Coito et al., 2019; Mittal et al., 2019). Nowadays, it is a reality that software solutions

accessible on the market are centralized and not dispersed to the shop floor elements (Rojko, 2017). This can create challenges when incorporating new equipment, since the interfacing of the two software packages (MES and the new equipment) can be a difficult process. The resolution settles in the development of Interoperability solutions that are capable of enabling communication between the two (Lynch et al., 2019).

Flexibility – The production environment, including the shop floor configuration, should be able to adapt in a way that answers customers ‘order flow, as well as product specifications and quality requirements (Govender, Telukdarie, & Sishi, 2019; Rojko, 2017). This can include the integration of new modules (creating the modularity’s capacity) (Coito et al., 2019; Mittal et al., 2019).

Virtualization – it is centred in the establishment of digital twins (Coito et al., 2019), letting and facilitating to manufacturing operations be planned, performed, and monitored easily (S. Mantravadi, Moller, & Christensen, 2018).

Real-time and data collection – data should be collected and then analysed, providing, almost immediately, insights (Arica & Powell, 2018; Coito et al., 2019; Naedele et al., 2015). Relational databases or even data historians store large volumes of data (Jaskó, Skrop, Holczinger, Chován, & Abonyi, 2020). The efficiency in data collection is about to obtain the desired data of the manufacturing’s traced entities and transmit it efficiently and precisely through the MES system (Arica & Powell, 2018).

Visualization/User Interface – Graphical user interfaces (GUI) are essential for backup complex industrial systems (like MES) (Jaskó et al., 2020). These interfaces (that should be user-friendly) can be embedded in web browsers, tablets or smartphones and they are particularly important for assuring collaboration among people and for concluding horizontal and vertical integrations (Arica & Powell, 2018; Coito et al., 2019; Jaskó et al., 2020).

Traceability/Monitoring – the system provides the ability to track and monitor the resources’ entire life-cycle in real-time (Govender et al., 2019). It is capable of record ample histories of lots, orders and equipment (Jaskó et al., 2020).

Analytics – the MES should provide visibility to the data which is collected by IoT’s (internet of things) mechanisms as well as cyber-physical devices. This data must be used for strategies that should be defined to improve enterprise’s operational efficiency (Govender et al., 2019). All the data needs to be stored to provide an analysis of historical data. This would be necessary, for example, to maintenance management (Naedele et al., 2015). In this way, it can be concluded that MES provides Business Intelligence from production procedures and can be used to measure, as well monitor Key Performance Indicators (KPIs), such as Overall Equipment Effectiveness (OEE) (Coito et al., 2019; Makarov et al., 2019) and Manufacturing Cycle Effectiveness (MCE) (Makarov et al., 2019). The integration of data into the production flow is required by control and performance

management. The efficiency can be further increased by using artificial intelligence and machine learning techniques (Jaskó et al., 2020).

Level of access – Data access policies must persist in MES and, to diminish risks, the needed data must be moved to the data warehouse to preserve their integrity (Coito et al., 2019).

Decentralization – MES should have incorporated decision support systems, which make decisions on their own (using the existing data) (Arica & Powell, 2018). In this line of thought, MES can be seen as an intermediate translator layer, which turns raw data stream into valuable information, essential to the decision making (Makarov et al., 2019).

Prognostics – It is supposed that MES enables the planning of future processes as well as allows prompt warning of process or quality nonconformities (Naedele et al., 2015).

Knowledge Management – the MES must allow the information flow through the organization (Coito et al., 2019), as well document control, where relevant information is distributed at the right time to the people working on tasks and the documents resulting from production are collected (Naedele et al., 2015).

To achieve a completely integrated and successful MES, important attention needs to be given to the modelling phase, this means: software architecture together with a specification of features. The complexity's growth of information systems and the concern about the optimization of software applications design encouraged scientists to establish some modelling methods (Sekkat, Kouiss, Saadi, Deshayes, & Deshayes, 2013). The object-oriented methods are the most appropriate tactics of development (Sekkat et al., 2013). The Unified Modelling Language (UML) is an OMG (Object Management Group) standard and is constituted by a group of diagrams. It is used for taking a specification of a software system (highlighting all requirements), detailing the structure, disintegrating into objects, and construing relationships between them. With UML software development teams can communicate among themselves (Cao, Jing, & Wang, 2008).

3. PRACTICAL CASE: STUDY AND DESIGN OF A MES

3.1 Context goals and methods

The case study in this article was carried out based on a company belonging to the chemical industry, whose business focus is flush toilets. Its production area has two zones, the injection and the assembly areas, the former becoming mostly the supplier of the second. The assembly area is the one that, until now, requires more human labour and where there is a greater flow of paper. In this way, the automation of the various stations and their proper sensing will allow the constitution of an MES information system capable of monitoring performance and carrying out processes that are

currently executed manually, but which with the introduction of MES can be supported by the software.

The paper's main goal is to model, using the UML notation, an architecture MES system capable of supporting the processes of the assembly area of the company under study. For the modelling to be idealized in the most effective way possible, informal interviews and observation techniques were carried out on the factory floor. Also, before the final construction of the model was elaborated, the several fragmented data repositories (programs scattered across the manufacturing floor not connected to each other) were analysed and so that in the end a completely integrated solution could emerge.

3.2 Results and discussion

For the modelling, two types of diagrams were used, the class diagram and the use case diagram, which are part of the UML notation.

The use case diagram aims to highlight the features of the system and which actors in the process are allowed to access them. The class diagram is intended to represent the structure that the MES database should acquire, with all relevant data to be saved.

Considering the use case diagram (Figure 2) first, the assembly operator should be able to enter shop orders ("Enter shop order"), and immediately must add his employee number / number of all team members to the cell ("Insert operator allocated to the station") where the manufacturing order will be produced. Thus, there will be tracking of who performed the assembly, something that will be necessary for a later performance analysis. Before all the production be launched, and in cases it is a workstation cell, the operator must validate all the components that are in the line edge ("Validate components at the work cell's line edge"), using for that a code bar system.

When a station stops, the system issues a warning so that the justification of it can be done ("Stop justify warning"). Therefore, when possible, he must justify, accessing for that purpose a list of those stops that are missing justify ("View stops without justification"). Some of these justifications can be accessed by the machines' PLC and put it automatically in the system. After the shop order is completed, the assembly operator must confirm the production, with the record of the same, printed immediately afterward ("Print production log"). Note that the rectification functionality is present, for possible errors in the data ("Rectify production value"). The assembly team leader has the possibility to "Register work order requests", which are sent as a warning to the maintenance so that it can proceed with the repair of faults. Also, he/she must be able to register kanbans ("Register kanban"), where, depending on the shop order he is working on, he can consult the components that make it up, before proceeding ("View components that make up the shop order"). Each time a kanban is registered, the dashboard of the Mizusumashi (cell supply train) is updated and whenever

there is a batch construction of a missing item, the supplier's dashboard is also updated (with a batch construction notice right away). Both the assembly team leader and the area manager can consult performance reports for the stations, as well as consult non-conformity failures.

The Mizusumashi can, through its dashboard, visualize warnings of the cells (replacement or lack of components), active kanbans (to supply cells), which may suffer (through Mizu) changes in their status (active, inactive, supplied, for example). The supplier is also able to view orders that can be made to them (they are also kanbans but whose "type" attribute (in class diagram) varies, such as priority). The option to change status is also presented here so that the orders are being fulfilled.

The class diagram (Figure 3) brought together processes such as the use of kanban (signal card that controls production or transport flows in an industry), audits, quality control, work order requests for maintenance and even execution and planning of work, maintenance actions, whether routine or urgent. Added to this, the question of automatic records (Record table and Stops_Record), in order to save stops and even calculate cycle times, were safeguarded by the data structure.

Starting with the Kanban system, knowing that a shop order (ShopOrder table) has several components, each component (Component table) needed will correspond to a kanban (Kanban table) that, with the accumulation, will make batch construction (Batch Construction table), this already having a maximum number of pre-defined accumulation articles. In the follow-up, it is important to emphasize that both audits (Audit table), as well as stop recording (Stop_Record table) and quality control (Quality_Record table), are connected to tables that function as information repositories (Audit_Bank, Stops_Bank and Quality_Bank). In this way, for example, to justify the reason for the stop, the user easily accesses a list of various reasons, leaving him only to select the most opportune one. The same is true with audits and quality control. Each device has access to a maintenance plan (Maintenance Plan table), which consists of several actions (Maintenance Action table), carried out by operators. These same actions can be requested by work orders requests (Work Order Request table) that arise from possible failures that are associated with the Shop Orders.

It is essential to mention that in this structure, knowledge management was taken into account too, since a task repository (Tasks_Bank table) was associated. In this way, when carrying out any task, it will be possible to search for employees with the most favourable skills (since there is a connection between Collaborator and Tasks_Bank), as well as the steps of the same can be investigated (since there is a precedence situation as attribute in Tasks_Bank table). In addition to the class diagram presented with more granular data, it was necessary, for data about the performance of the stations to be saved, to create a view (Report – Figure 1) above the level of the data structure represented in Figure 2. In this view, data from Overall Equipment Effectiveness is saved, so that shift performance is easily accessed. Also included here, is data about the stops, which are divided into total stops, programmed and micro stops.

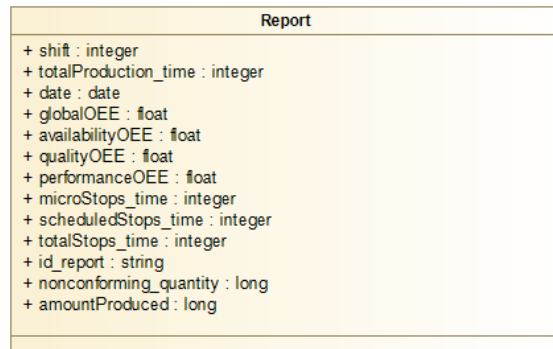


Figure 1- Report Class Diagram (View)

The MES's architecture presented in this paper offers an integration of the processes on the shop floor, decreasing in an abrupt amount the paper flow, which was previously used for example to signal station stops, for later calculation of OEE. With this approach, it is possible to establish a more continuous flow of information in the company, which originated almost in real-time.

The MES architecture and specification outlined here highlight some of the features previously considered to be crucial in such a monitoring system. They are the ability to support the saving of data in real-time (Real-time characteristic) (Arica & Powell, 2018; Coito et al., 2019), as well as its subsequent visualization (Visualization characteristic) (Arica & Powell, 2018) using analytics (Analytics characteristic), where performance indicators are calculated (OEE) (Govender et al., 2019). In this way, decentralized decision making (Decentralization characteristic) is possible to be sustained (Makarov et al., 2019). In addition, knowledge management is provided (Knowledge Management characteristic), with the possible distribution of relevant information at the right time and in the right place (through information repositories) (Naedele et al., 2015). With this architecture, it is also possible to establish a vision of the digital twin of the shop floor, in which data from the equipment (mostly sensors and actuators) is collected and subsequently treated with a view to its monitoring and historical view (Park et al., 2020; Schmetz et al., 2020). In this way, it is possible to have a pre-structure capable of leveraging the first moment of the Smart Factory, which can be improved by artificial intelligence algorithms capable of predict future machines' behaviours.

The two major deficiencies of the production systems listed above, such as the capture of data in real-time and the existence of islands of information (Yao et al., 2019), are addressed in this approach, since all the processes in this section of production were previously mapped and integrated into the architecture. At the same time, the equipment with integrated sensors capable of generating data that was previously stored only on the machine's PLC was used. This is a basic software architecture for a factory floor, being able to be flexible to the introduction of other modules.

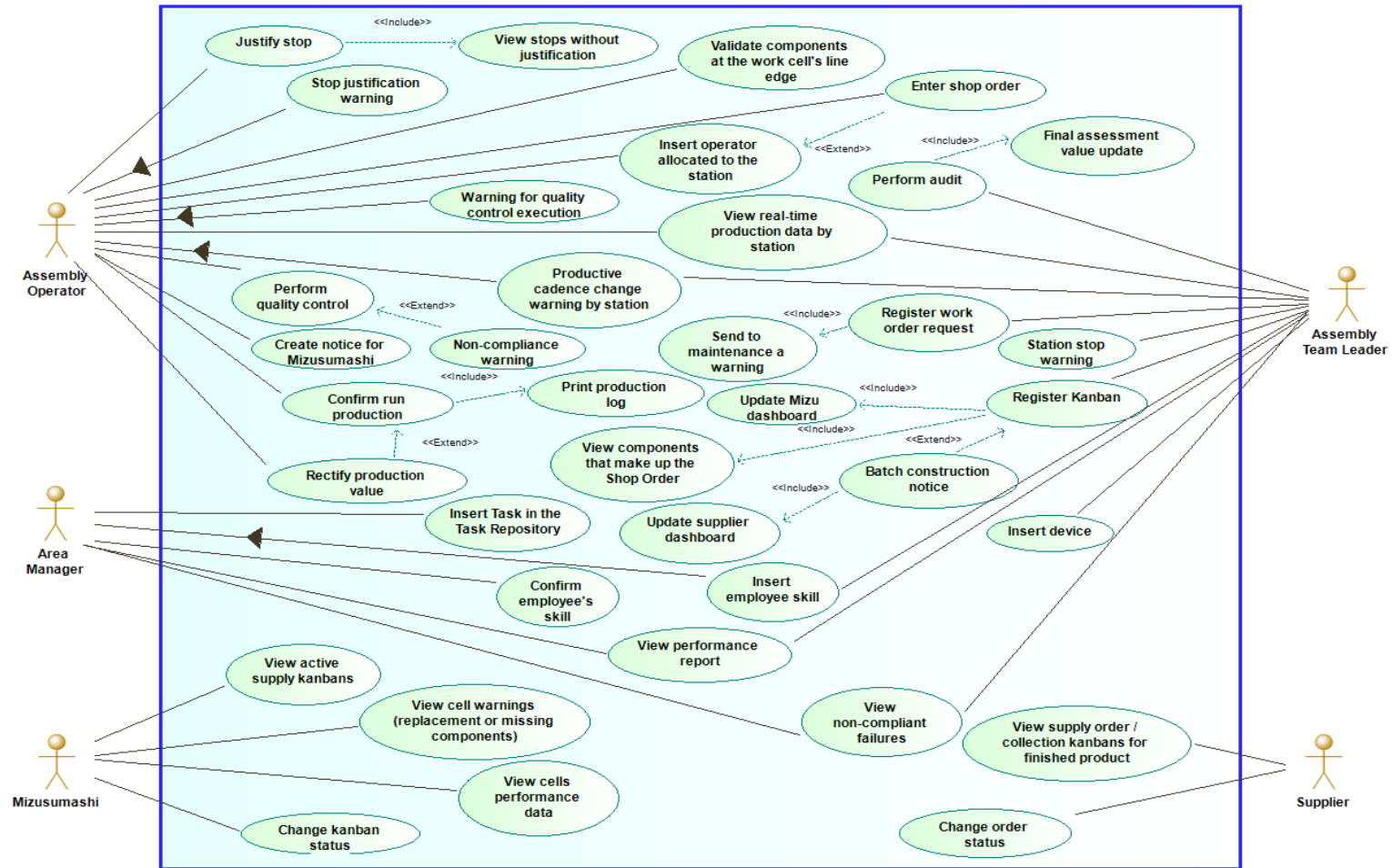


Figure 2- MES Use Case Diagram

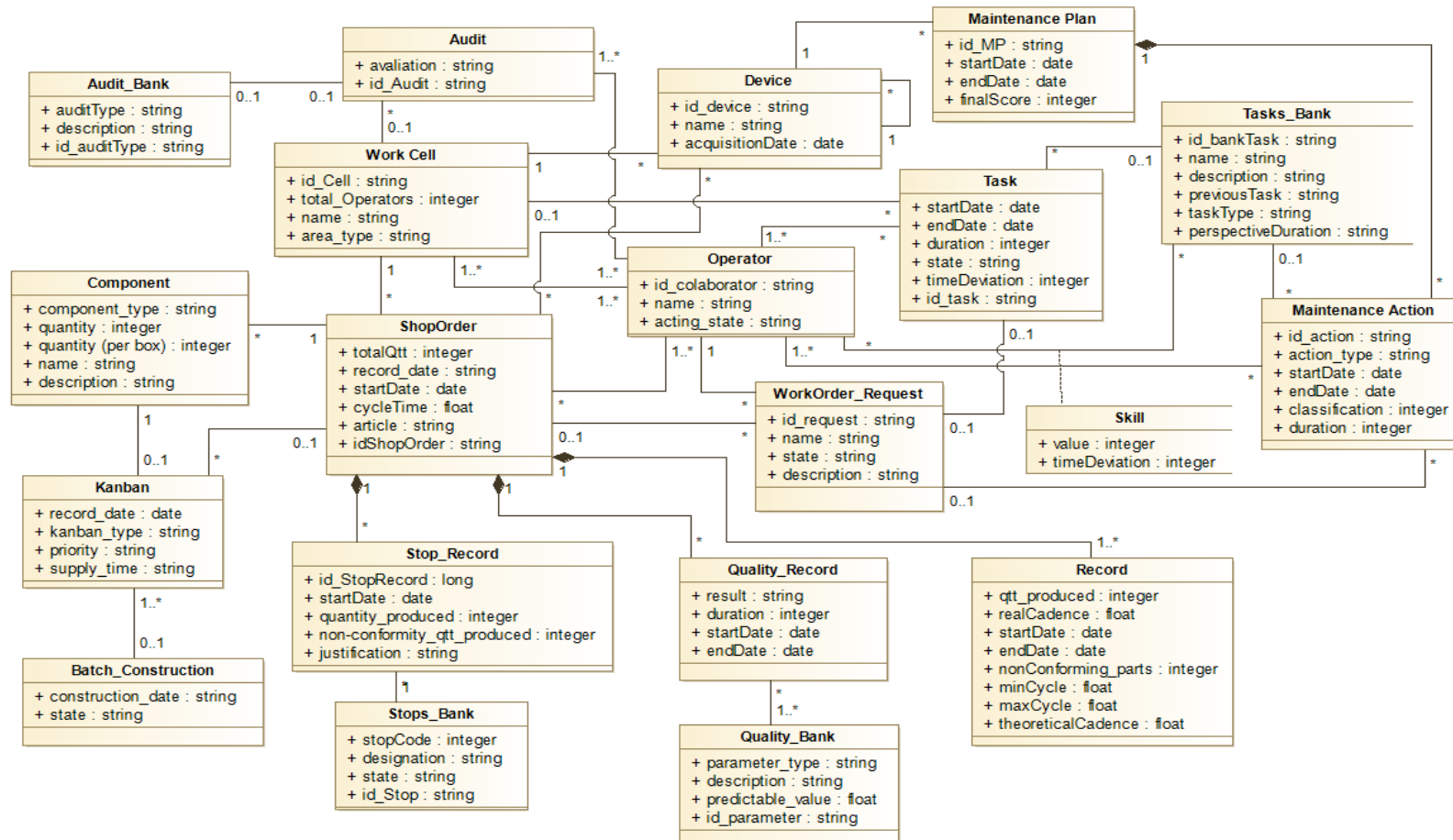


Figure 3- MES Class Diagram

4. CONCLUSION

The constant changes in the market have been asking companies to adapt their way of working and the consequent fever of the moment to apply I4.0 technologies. Information systems will be crucial in this regard as they will enhance the flow of information in the company promoting decentralized decision-making processes.

The modelling phase of an information system (using UML) appears to be one of the most essential tasks since the system requirements are designed so that all relevant processes are supported. Thus, and for the modelling to be properly idealized, previously a study focused on the company's processes was carried out, as was its mapping (using another language, the Business Process Model Notation).

A Manufacturing Execution System with the mentioned approach intendeds to solve the problem associated with the existence of fragmented and scattered sources of information on the factory floor. Thus, the creation of a data structure (through the UML class diagram) was essential in order to bridge this phenomenon and to acquire a broader view of what data sources a company owns and what use it can consequently make of them .

In addition, the same approach aims to solve the difficulty of establishing a software architecture capable of leveraging the concepts of Smart Factory and Digital Twin. It is suitable for the basic processes of a factory floor and facilitates the introduction of topics such as knowledge management and data visualization. The flow of information with an architecture of this type flows more easily through the company and decision making is easier and faster.

For future work, it is suggested to implement the above specification of MES and complete this approach with modules that answer to artificial intelligence methods capable of predicting possible anomalies in equipment, as well as the application of this architecture in another type of business structure, with a view to its generalized validation.

Acknowledgments

This work was supported by Portuguese funds through the Institute of Electronics and Informatics Engineering of Aveiro (IEETA) and Foundation for Science and Technology, in the context of the project UIDB/00127/2020.

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