IoT-enabled Smart Monitoring and Optimization for Industry 4.0

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Abstract: *In the last decades, forward-looking companies have introduced Internet of Things (IoT) concepts in several industrial application scenarios, leading to the so-called Industrial IoT (IIoT) and, restricting to the manufacturing scenario, to Industry 4.0. Their ambition is to enhance, through proper field data collection and analysis, the productivity of their facilities and the creation of real-time digital twins of different industrial scenarios, aiming to significantly improve industrial management and business processes. Moreover, since modern companies should be as "smart" as possible and should adapt themselves to the varying nature of the digital supply chains, they need different mechanisms in order to (i) enhance the control of the production plant and (ii) comply with high-layer data analysis and fusion tools that can foster the most appropriate evolution of the company itself (thus lowering the risk of machine failures) by adopting a predictive approach. Focusing on the overall company management, in this chapter we present an example of a "renovation" process, based on: (i) digitization of the control quality process on multiple production lines, aiming at digitally collecting and processing information already available in the company environment; (ii) monitoring and optimization of the production planning activity through innovative approaches, aiming at extending the quantity of collected data and providing a new perspective of the overall current status of a factory; and (iii) a predictive maintenance approach, based on a set of heterogeneous analytical mechanisms to be applied to on-field data collected in different production lines, together with the integration of sensor-based data, toward a paradigm that can be denoted as Maintenance-as-a-Service (MaaS). In particular, these data are related to the operational status of production machines and the currently available warehouse supplies. Our overall goal is to show that IoT-based Industry 4.0 strategies allow to continuously collect heterogeneous Human-to-Things (H2T) and Machine-to-Machine (M2M) data, which can be used to optimize and improve a factory as a whole entity.*

1 Introduction

The wide adoption of Internet of Things (IoT) technologies has lead to a greater connectivity in industrial systems, i.e., to the paradigm of Industrial IoT (IIoT). The recent literature provides several relevant definitions for IIoT, which can be summarized as a collection of Smart Objects (SOs), cyber-physical assets, together with generic information technologies and Cloud or Edge Computing platforms allowing real-time and intelligent access, collection, analysis, and exchange of information related to processes, products or services, within the industrial environment. The main objective of IIoT is to optimize the overall production value in terms of service delivery and productivity, cost reduction, energy consumption, and the definition of the build-to-order cycle [5]. Related to IIoT, the recent concept of Industry 4.0 identifies the ongoing fourth industrial revolution focusing on the manufacturing industry scenario and can be considered as a subset of IIoT. The terms IIoT and Industry 4.0 are often used as synonyms; however, there is a difference between them.

Industry 4.0 has been initially proposed to describe the developing German economy in 2011 [30, 37] and mainly focuses on the manufacturing industry. IIoT was first introduced in 2012 as industrial Internet entailing the adoption of IoT in general industrial context (both manufacturing and non manufacturing). This definition is backed by the Industrial Internet Consortium, which was formed in 2014 with the support of Cisco, IBM, GE, Intel, and AT&T. The primary actors in Industry 4.0 are academic institutions, whereas IIoT is more business-oriented and mostly driven by private companies and some academic institutions [1]. Both IIoT and Industry 4.0 aim at making systems robust, faster, and secure, and are characterized by the extensive use of Cyber Physical Systems (CPSs), digital twins, and heterogeneous data collection.

CPSs can be considered as the core of Industry 4.0, being focused on sensors and actuators, and, through the integration of computing, communication, and control, providing dynamic control, information feedback, and real-time sensing for complex systems. Hence, CPSs allow to fulfill the dynamic requirements of industrial production and improve the effectiveness and efficiency of the entire industry. Digital twins, instead, are more focused on the definition of a physical system's digital copy, in order to perform real-time optimization: this is done by creating virtual models of physical objects in virtual space, in order to simulate their real behaviors and provide feedback [36]. As a result, being more focused on models and data, digital twins enable companies to detect and quickly predict physical issues, and optimize processes. In the end, for both CPSs and digital twins, the physical part senses and collects data, and executes decisions based on the digital part, while this latter process and analyzes, thus making decisions [17]. Nevertheless, it is important to highlight that not every system that has entities in the cyber space corresponds to a CPS, since often cyber dynamics are not just a replica of some operational variables in the digital space (e.g., in the Cloud). In the context of CPSs and digital twins, communications play a key role, as efficient information flows from physical and cyber spaces is critical.

Hence, the Industry 4.0 leverages the integration of a set of complementary technologies and paradigms, including Enterprise Resource Planning (ERP), Internet of Things (IoT), Cloud Computing, and so on. Hence, the first change in industrial scenarios introduced by the Industry 4.0 corresponds to an advanced digitization process that, in combination with Internet-based and future-oriented technologies (including, as an example, Smart Objects (SOs) deployment), favors the vision of a production factory as a modular and efficient manufacturing system, in which products control their own manufacturing process.

In Figure 1, we show the main modules of an Industry 4.0-oriented infrastructure, which relies on a set of *data sources*, including: data provided by industrial machines; data collected by externally deployed IoT devices; information manually provided by

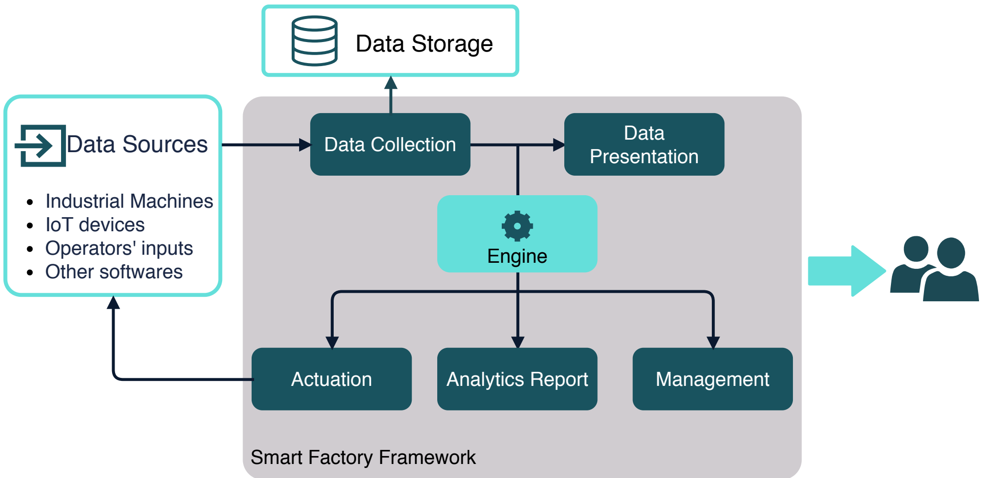

Figure 1: Industry 4.0 modules.

operators and employees in the company; and digital data imported from other third-party services, or pre-existent ERP. The framework building this Industry 4.0 scenario leverages the following main modules.

- A *data collection* module, integrating data from different sources and storing them in a coherent way, in order to efficiently perform queries and analyses.
- A *data presentation* module, devoted to the presentation of processed data to end-users, thus relying on clear and effective User Interfaces (UIs), in order to highlighting useful information.
- A customized *engine logic*, processing the collected raw data and performing different analyses in order to extract a higher knowledge level of the factory system.
- Different *high-layer interaction* modules, in which processed information can be employed to perform actuation tasks on industrial processes, as well as being presented in analytic reports or being employed to support factory employees in their activities, such as production planning, organization, optimization, and so on.

In this work, a description of the process, based on the Industry 4.0 IoT-oriented paradigm and implemented in a generic company C, in order to improve its "performance" in the overall departments, is presented. More in detail, we consider a realistic use case where company C is a successful company producing hoses, which follows high-quality standards for its products and services, and drives its constant attention to technological innovation and modern research, in order to continuously improve each stage of production and organization activities.

Even if the company C has defined a systematic and precise protocol to manage the quality of produced hoses and plan the activities on the production lines, these tasks cannot be considered *smart*, since they (i) do not involve any digitalized information and are performed through the usage of paper forms hand-written by operators, (ii) do not include any IoT-related technology to automatically collect data from industrial machines, and (iii) do not have a foundation of data that can be analyzed, in order to optimize and control the factory system has a whole. As a last consideration, the company C already relies on an ERP system, but not all processes are managed in a "smart" way.

In this work, the possible renovation steps for a company C, through the introduction of modern technologies in the business processes in both control quality and production planning tasks, are presented and discussed. The renovation process can be seen as based on the following applications: (i) the first application, denoted as *SmartFactory*, is a Web-based tool that has been developed in order to improve the production monitoring and the control quality activities; (ii) the second application corresponds to the introduction of planning capabilities aiming at supporting the production planning staff in the complex activity of scheduling the manufacturing orders on the production lines proper of the company C; and (iii) the third application relies on the introduction of an IoT-oriented infrastructure, to improve and enhance the overall activities in the company C. We then conclude discussing the introduction of predictive optimization-oriented approaches, to lower factory employees' risks and plant faults.

The rest of this work is organized as follows. In Section 2, a brief analysis on the context of Industry 4.0 is given, while in Section 3 a set of guidelines for the digitization of a target factory are presented. Section 4 is devoted to the analysis of different approaches to be applied for the monitoring of production lines and machines, while in Section 5 the positive impact of predictive optimization is discussed. Finally, in Section 6 conclusions are drawn.

2 Related Works and Motivations

The Industry 4.0 concept has recently gained particular attention, as it encompasses a heterogeneous set of research fields, being closely related not only to IoT, CPS, Information and Communications Technologies (ICT), and Cloud Computing, but also to Enterprise Architecture (EA) and Enterprise Integration (EI).

The work in [21] represents one of the first review on the content, scope, and findings of Industry 4.0 in ICT-oriented scenarios. In [21], the authors identify 5 main research categories: (i) concept and perspectives of Industry 4.0; (ii) CPS-based Industry 4.0; (iii) interoperability of Industry 4.0; (iv) key technologies of Industry 4.0; and (v) smart factory and manufacturing. In [24], it is highlighted how the benefits brought by Industry 4.0 are not available only to large companies, but they are accessible and attractive also for Small and Medium Enterprises (SMEs). More in detail, the authors of [21] adopt the definition provided in [16], considering Industry 4.0 as *"a new approach for controlling production processes by providing real-time synchronization of flows and by enabling the unitary and customized fabrication of products."* Finally, the authors conclude that applications are mostly related to monitoring of production processes and to the improvement of current capabilities and flexibility, through the introduction of new technologies, such as Cloud Computing and Radio-Frequency IDentification (RFID). However, at the same time, most of the possible opportunities (e.g., CPS, Machine-to-Machine (M2M), Big Data, or collaborative robots) are under-exploited, if not ignored, by SMEs.

Another key point is that the evolution process transforming a traditional company into a "smart industry" is generally smooth. One of the first steps relates to the digitization (or digital transformation process) which has been identified as one of the major trends changing society and business. Digitization, in fact, leads to changes in the companies in both organizational and operational environments through the introduction of new technologies. In [27, 45], it is highlighted how the changes introduced by the digitization cover different levels in a factory, such as: (i) the process level, in which processes are optimized reducing manual steps and adopting new digital tools; (ii) the organizational level, where obsolete practices are discarded and new services are integrated; (iii) the business domain level, in which value chains and roles inside ecosystems are changed; and (iv) the societal level (e.g., changing type of work). Moreover, in [14, 28], it is shown that replacing paper and manual processes with software-based solutions allows to automatically and quickly collect data that can be adopted to better understand the risk causes and the process performance. Finally, in [15, 40] the authors highlight the importance of User Interfaces (UIs) which a digitization process has to be equipped with, where real-time reports and dashboards on digital process performance allow managers to address problems before they become critical.

The current advancements in IoT, together with the development of new cost-effective and high-performance wireless communication systems, allow to connect devices and objects, thus giving them the possibility to share information related to the surrounding environment. This enables the creation of effective CPSs which can continuously monitor and control the environment in the industrial domain. Therefore, the second phase that can transform a traditional company into a smart industry is the introduction of new IoT technologies, in order to collect data inside the factory and monitor processes. This paradigm is also denoted as *Industrial IoT* (IIoT), which an example of is provided in [12], where it is highlighted how the general assessment of the machine operational condition is crucial for a smart and efficient industrial processes management. In [12], a prognostic approach to the detection of incipient faults of rotating machines, by means of their vibrational status monitoring, is proposed. Another IIoT-based solution is described in [8], where a particular mechanism, specifically designed to enable a pervasive monitoring of industrial machinery through battery-powered IoT sensing devices, is presented: the industrial scenario covered a time period of two months and was based on thirty-three IoT sensing devices performing advanced temperature and vibration monitoring tasks, while evaluating transmission delays and system operating life time through power consumption measures. The adopted IoT protocols guarantee that each node is reachable through IP addressing with an acceptable delay.

Another IIoT example is proposed in [23], in which the application of Low-Power Wide-Area Networks (LPWANs) in an industrial scenario is proposed. More in detail, the authors focus their work on the open LoRaWAN network standard [34], thus proposing a comparison with the IEEE 802.15.4 network protocol, which is another IoT protocol widely adopted in the industrial context. The authors conclude that LoRaWAN represents a strongly viable opportunity, providing high reliability and timeliness, while ensuring very low energy consumption.

After the digitization and monitoring through IIoT technologies phases, the last step for a smart industry is related to optimization of the company processes, leveraging the analysis of the collected information. In [29], the authors observe how the widespread adoption of IoT technologies is enabling a faster and more informative sensing, generating data abundance, more than ever. At the same time, technology advances provide also the computational resources needed to process this large amount of data, transforming them into actionable information in a reasonably short time. A critical overview of trends characterizing the industrial process monitoring activity since its appearance (almost 100 years ago) is provided, showing how this task has changed, from simple statistical analysis, to detection and, finally, to diagnosis and prognosis.

3 Digitization

3.1 Organization of the Company C

In order to discuss the evolution of a traditional company to an Industry 4.0-organized smart company, consider that the production activity of a generic company C is divided into N departments, each performing a specific production activity. Each produced article crosses consecutive departments, where semi-finished goods are manufactured with different machines' configurations, among the production processes of several articles. Moreover, each department has a variable number of lines L_{N} that can work simultaneously.

The three main classes of actors operating in the company C and involved in the activities are the following.

- **Production Scheduling Managers (PSMs)**: they are in charge of controlling and organizing the production schedule of all lines available in the factory, taking into account the stock policy and the commissions placed from customers.
- **Quality Inspectors (QIs)**: they are responsible to perform continuous checks on products and semi-finished products directly on the production lines in the factory, in order to guarantee conformity to quality standards. Then, QIs follow the schedule defined by PSMs and move between lines, in order to inspect the production process.
- **Line Operators (LOs)**: they are responsible for preparing and activating the production machines on the production lines, following the schedule. During the production, LOs take measurement to monitor the production, thus also performing quality checks on the hoses, which are then validated by QIs.

Moreover, consider that the company C has defined a precise protocol to follow in the hoses production process. More in detail, after the definition of the schedule for each line, performed by PSMs, each article to be produced is separated into a set of D Manufacturing Orders (MOs), one per department involved in the productive process. Each MO is then assigned to a specific line in the factory. In this way, a LO working on a production line is guaranteed to have a daily activity (namely, a list of MOs) to perform on the line which he/she is responsible for. The manufacturing monitoring task of the company C is performed through the use of MO Forms (MOFs) printed on paper sheets. Each department in C has a specific MOF layout, in terms of input information types and number of sections. Some of the sections are descriptive, aiming at showing some important information for the manufacturing process (i.e., configurations, measures, customizations); other sections are instead input sections that should be filled by LOs or QIs during the production with department-specific data or measurements. The possible

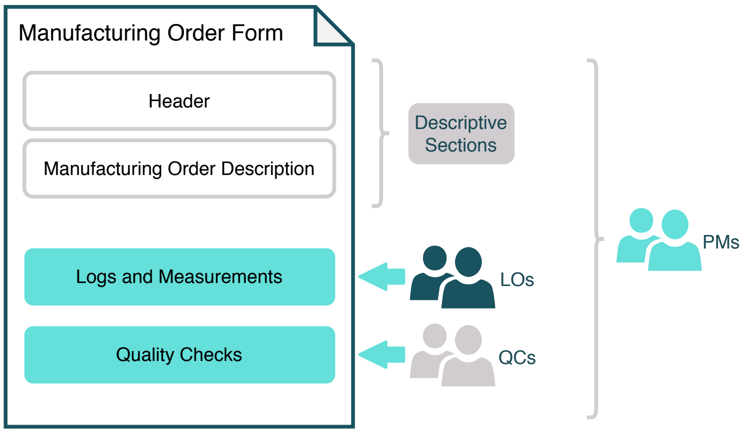

Figure 2: MOFs structure.

section types that can be identified for the production quality control of the company C are described in the following and depicted in Figure 2.

The *Header* section simply identifies the MOF type, among the available ones, through the title together with a start date and an order alphanumeric code. The *Manufacturing Order Description* section is another part containing a list of textual information describing the steps needed for order completion and machine configuration. The *Log and Measurements* is the part that has to be filled by LOs with the quantity of produced products, the quantity of raw materials employed on the line, the development status of a order (if it requires multiple work shifts) and all other measurements that are required during the production. The *Quality Checks* section contains the results of data surveys performed during the production process, in order to verify that the products comply with the required standards. This section can have a different layout depending on the MOF type, as different production articles require specific quality checks. This section is periodically filled out by QIs. The protocol adopted by the company C in order to monitor the productive process is based on the following daily steps.

1. Each morning, the PSM staff prints the MOFs corresponding to the MOs planned for the current work day and distributed to all factory departments, on each department's production line.

2. Each LO starts his/her work and, during the shift, fills out all MOFs received by his/her department supervisor.

3. Each QI starts his/her work and, moving among the lines, he/she periodically completes the quality section of the MOFs.

4. In the evening, each department supervisor collects the MOFs and delivers them to the PSM staff. Finally, all paper sheets are manually scanned and stored as digital images, where inputs are only hand-written.

The production planning of the company C is an extremely important and time-consuming task, as it strongly affects both results and performance of the subsequent activities. The planning, on one side, should fulfill the customer requirements and, on the other side, should try to efficiently use both machines and human resources on the lines. This activity, in the company C, is performed by the PSM staff and managed through the use of virtual spreadsheets, with different layouts and rules depending on the specific department. An example of structure spreadsheet is shown in [2].

A manual process for the planning activity can be extremely complicated and time-consuming for the PSMs, since it requires to take into account several factors (such as customers' orders, machine configurations and delay, employees availability), and is not exempt from possible errors during data insertion. A complete description of aspects related to digitization of control quality and planning processes in a real company are provided in [2]—in the following subsection, only some aspects are highlighted abiding by a general perspective.

3.2 Digital Quality Control

In order to replace the use of paper-based MOFs, the company C has integrated in its workflow a smart Web-based application, here denoted as *SmartFactory*, allowing to:

- collect data, related to the production, in a fast and easy way;
- get rid of costs related to the print-scanning process;
- facilitate the work of QIs and LOs in the different departments, through the adoption of both mobile devices (e.g., tablets) and PCs;
- efficiently manage updates and changes in the production process;
- save digital data through integration with the company IT and ERP systems.

The SmartFactory application, after a login process authenticating and authorizing users, should present different views for PSMs, QCs and LOs. This login phase can leverage on pre-existent technologies, like the operators' personal Near Field Communication (NFC) badges, if they are already employed in the company C to access to the buildings. After the login phase, SmartFactory can redirect the user to a separate home page, customized depending on his/her role with a custom data visibility and privileges on different modules (namely, Read-Only, RO, and Read-Write, RW). As an example, LOs can write on the Logs and Measurements section, and have RO privileges on the Quality Checks section.

Another essential feature required by the process of digitization of company C, is to simply find data of interest. For this reason, SmartFactory should include a research functionality for both QIs and PSMs allowing them to find, in real-time, data related to orders (both in production and historical). Another important functionality is the possibility to show orders requiring a supervision from the PSMs, in a separate and specific application view.

3.3 Digital Planning Management

The planning activity is generally assigned to highly qualified staff, with a deep knowledge of all mechanisms regulating the whole company workflow, from provision office to sales department. Since a second stage of the digitization process in a generic company C should include the production planning department, with the aim of replacing the spreadsheet-based method, the SmartFactory application should include a Web-based planning tool allowing to: (i) simplify and speed up the planning process for PMs; (ii) hide the complexity behind planning allocation calculations; and (iii) avoid planning errors. Moreover, this SmartFactory application's module is only used by PSMs through a PC and is integrated with the company IT and ERP systems through a software extension able to store all data related to the planning activity, which are not already registered. More in detail, the planning tool can include several modules. The *Scheduling Suggestions Module* is responsible for accessing the ERP system and retrieving, for the PSMs, a list of articles to be produced, thus representing the starting point onto which work. The *Shifts Manager Module* allows to manage all information related to LOs' shifts, such as the hours availability in the department of interest. Then, the *Planning Events Module* manages the Graphical User Interface (GUI) replacing the virtual spreadsheet used by PSMs, and allowing them to *drag-and-drop* manufacturing orders on a calendar-based view, in which columns show the working days and rows represent the production lines in the department subject to the planning activity (hence with representation similar to the spreadsheets ones). The SmartFactory application is also responsible for calculating the real duration of a MO event once it is placed on a specific cell. This calculation is performed considering: (i) the requested length of the hose; (ii) the production line's velocity, retrieved analyzing historical data from the ERP; (iii) the shift duration planned for the specific day; and (iv) configurations and setup delays. Finally, the *Production Manager Module* stores data inserted by PSMs and manages the interaction with the company C's ERP system, in order to move planned events to the production system, making digital MOs visible also in the quality control part of the SmartFactory application.

3.4 Main Advantages

The overall architecture of the SmartFactory application, with reference to the modules previously highlighted and their interactions, is shown in Figure 3.

It can be easily estimated that a first (and tangible) effect of the introduction of the SmartFactory application in a generic company C can be related to time saving aspects, due to the fact that forms are no longer printed on paper sheets nor manually scanned. Even the way to insert data from different actors may be certainly simplified, since SmartFactory allows a simultaneous access to MOFs, permitting QIs, LOs, and PSMs to input and view data on the same production order without interfering with each other. Another important aspect to be considered is the quantity of structured data, made available by the adopted digitization revolution, that are continuously collected and can be employed to monitor the status of the production in real-time, but also constitute a basis for further analysis. The last advantage is related to the reduction of errors and faulty products, as non-regular behaviors can be detected and recorded in real-time for further performance analysis.

Furthermore, with regard to the planning functionality that can be introduced in the SmartFactory application, the first advantage relates to the reduction of the number of hours directly spent by PSMs for the MOs' scheduling activity, but it is important to consider also the reduction of time needed to train a new person dedicated to planning activities. In fact, having the SmartFactory application hiding all aspects related to MOs'

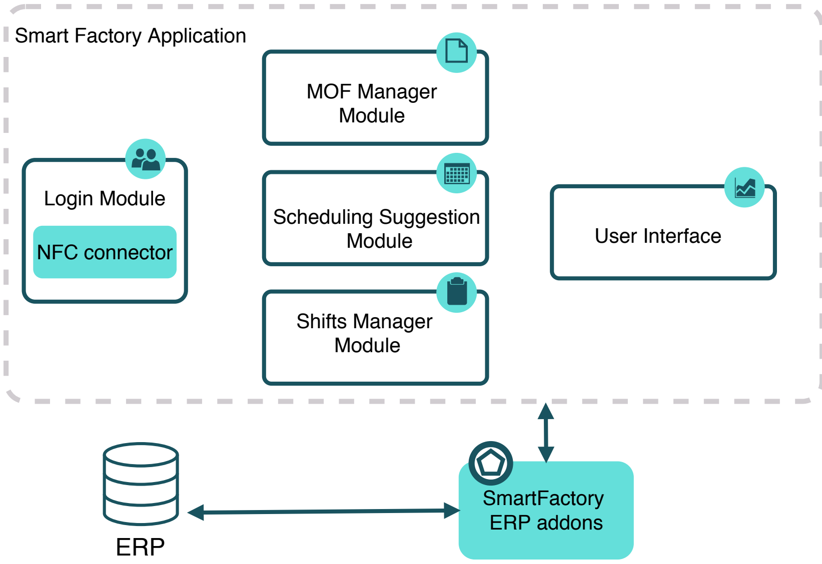

Figure 3: SmartFactory application overview.

duration calculations and providing the user with all required information in single view, a strong simplification of the work of PSMs is obtained, making possible for the company to assign this activity also to other people, with a minimized learning phase. Finally, the complete digitization and automation of the planning process allows to make the complete company plan available to all interested users.

4 Monitoring

On the basis of the concepts highlighted in Section 3, it has been clarified how a generic company C may benefit from a proper planning and quality control methodology, in order to improve its productivity and lower downtime and errors in resource allocation [44]. Looking at the company C as a *step-by-step* production chain, it is clear that data, on the basis of which planning is performed, should be as accurate and delivered *on-time* as possible.

This can be carried out in several ways. A first approach consists in extending the functionalities of the software tools described in Section 3, in order to create a framework of cooperating tools which also includes other aspects of the company C's management. More in detail, the proposed planning tool can be integrated with a more general Customer Relationship Management (CRM) tool, aiming at managing information related to customers orders and due dates, products' stock levels, and planned activities, as shown in Figure 4. As a second step, the company C's software framework can be extended with a Supply Chain Management (SCM) tool, allowing operators to have a clear representation of the status of the working supply chain, through the use of a dashboard showing running activities, production delays, warnings, and alarms related to working

Figure 4: Industry 4.0 monitoring with sensors on production machines, and planning and reporting dashboards.

machinery. This framework is generally built on top of a set of microservices, with its effectiveness strictly related to the quality of information collected from the company environment. This entails the introduction of IoT technologies, with the deployment of sensor networks—preferably Wireless Sensor Networks (WSNs) [19]—directly inside the factory environments and around each production machine, even involving different communication and processing technologies, in order to cover different needs [20].

In the case of a production machine characterized, for its internal manufacturing, by vibrations of some kind, it can be possible to equip the machine itself with some "sensing node" composed by a sensing element (e.g., a vibration sensor) connected with a 1-wire link to a "core" module, in charge of processing the incoming data (either analog or digital) and of doing additional tasks based on data themselves, such as sending the data to an upper-layer data collector, as well as internally storing the collected data for further analysis and as a safe backup. Even though this approach is general, the communication paradigm adopted for the harvested data forwarded to upper-layer systems may be addressed based on the specific characteristics representing the industrial environment in which the production machine is placed, as shown in Figure 4. In other words, this sensing module can forward its collected data through an IEEE 802.3 (Ethernet) connection, if this protocol is available and useful on the production line, as well as taking advantage of the availability of an IEEE 802.11 (Wi-Fi) connection, which several sensing nodes can attach to and participate as IEEE 802.11 clients.

As can be easily understood, a sensing node can be equipped with various types of sensors, able to detect different situations. An example can be a camera-based monitoring system, in which the sensor is video and its goal is to monitor a particular part of the production machine, as shown in Figure 5. In this scenario, the monitoring device provides several degrees of freedom, meaning that it can be customized with different setups and configurations (e.g., different types of cameras) based on the task that the IoT node should perform. In case the IoT system has to monitor with a certain accuracy a specific (and limited in space) region of the overall environment, then the camera should be chosen with certain characteristics (e.g., a High Quality (HQ) camera with an adequate frame ratio). If, instead, the IoT camera has to monitor with lower accuracy, then it can be a Low Quality (LQ) camera, thus lowering the overall price of the Industry 4.0 monitoring node.

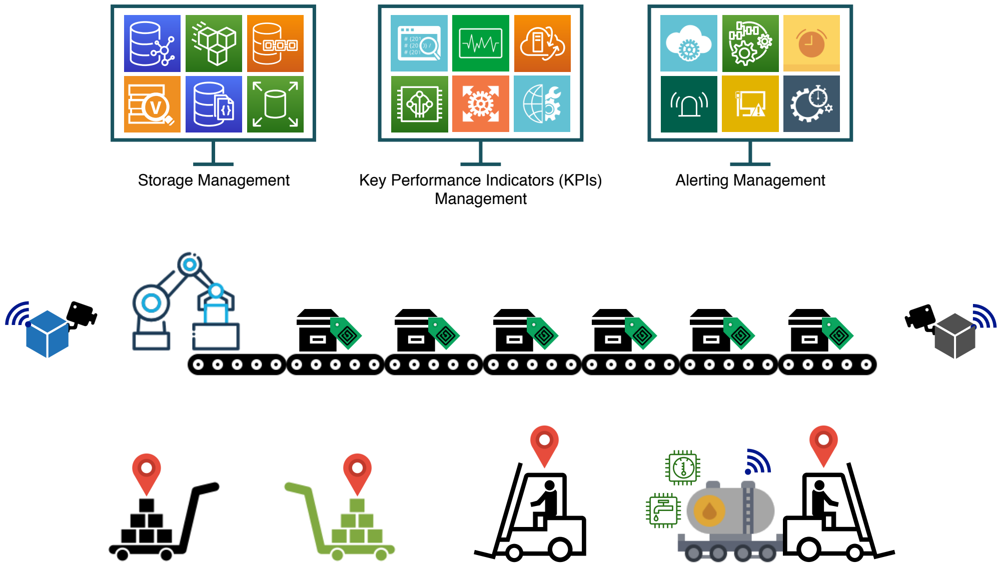

Figure 5: Industry 4.0 monitoring with camera sensors, vehicle positioning, and performance dashboards.

Obviously, these considerations certainly affect the core component of the sensing device, since it has to be defined on the basis of the need of analyzing a video stream, as well as a single frame taken by the camera. Moreover, in the case of a precise monitoring task, the processing element should perform proper processing, thus requiring a high amount of volatile memory (e.g., RAM), as well as a suitable Operating System, OS (possibly a real-time OS, RTOS). If monitoring should be less accurate, then processing can be carried out with more commercial (and less specialized) hardware.

Another way to monitor a machine involved in an Industry 4.0-oriented renovation process can be the definition and deployment of a network of IoT nodes organized with a proper topology, targeting the optimization of the communications inside the network itself and the reachability of the information from outside the network. An illustrative case study is given by a monitoring network composed by sensing nodes involving an *on-field* sensor, harvesting data from both the machine and the environment (as shown in Figure 4), and a processing module enabling the overall device to join and participate to a Bluetooth Low Energy (BLE)-based network [13]. Looking at topological level, in this scenario each sensing node acts as a BLE slave, while in the production plant a BLE master should be elected to own and manage the BLE network and, in turn, to collect data from its slaves. The BLE network topology can be selected depending on the needs and environment.

Another monitoring activity that an Industry 4.0-targeting company may consider is to exploit the possibilities "natively provided" by its production machines. The most relevant one is to access the Programmable Logic Controllers (PLCs) [3] managing the production machines, in order to collect (hopefully in a real-time mode) the production data exposed by the machine itself. This can be performed equipping each machine with a properly made "collector" node, composed of (i) a processing entity, in charge of collecting, storing, and forwarding *on-field* collected data to external—and high-layer—Supervisory Control and Data Acquisition (SCADA) systems [4]; and (ii) an *on-field* network interface, able to directly talk with the production machine. In relation to the latter component, the evolution that has taken place in the field of real-time production data collection, allows the company C to extend its *on-field* interfaces to support multiple communication protocols, ranging from ModBus (either through RS-485 or RS-232 cables) to Ethernet and CANBus [18]. Otherwise, if the data generated from the production machine needs to be restricted to a small amount of bytes (e.g., because they represent only an aggregated metric processed a few times in a certain time period), then the generic company C can consider to use some properly M2M-defined SIM cards, generally enabled to support a fixed traffic amount and low speed, but acceptable for this kind of industrial scenarios. With regard to wired technologies (such as ModBus, CANBus, and Industrial Ethernet), it is worth to specify that ModBus can be used as both fieldbus- and controller-level protocol, meanwhile CANBus is usually employed as fieldbus protocol only [39]. Moreover, both protocols work at application layer, leaving the possibility to adopt different low-level physical protocols (e.g., wired technologies, such as RS485 [41], but also wireless ones, such as the uprising 5G [25, 22]) for transmitting information on the field.

It is important to underline that M2M is related not only to cellular communications, but it generally identifies the interaction between heterogeneous smart devices, thus being one of the IoT's pillars. M2M can enable machines in the company C to exchange messages to each other, in order to achieve a predefined objective, to provide a specific service, or to complete a task [11, 6]. Abiding by this paradigm on monitoring devices in the company C's environment and making communication flows to converge in "collector" nodes, allows to create a M2M services layer, which can interact with SCM and planning tools. This can be useful in: (i) identifying problems, errors or breakdowns to be reported to operators; (ii) providing a real-time monitoring of company machinery status; and (iii) reducing the quantity of input required to operators working on production lines (e.g., during quality control activities).

Finally, for the company C it can be interesting to collect, in addiction to M2M-related data from the production machines, also data related to the interactions between employees and machines and, in general, with the industrial environment, in a Human-to-Machine (H2M)-oriented way. In this scenario, one could consider the introduction of localization-aware infrastructures for the sake of safety and security of the employees in their work environment. In detail, it can be advisable the adoption of *on-board* precise tracking technologies (e.g., based on Ultra-WideBand (UWB) technology [33]) on industrial vehicles which are in charge of moving materials (e.g., from warehouse to production lines, as well as among production plants). In this way, as shown in Figure 5, the resulting benefit is two-fold: on one hand, it is possible to plan vehicles' trajectories, thus better managing the good movements; on the other hand, workers can be aware of their surrounding vehicles' positions, thus increasing their safety and security. In order to improve these risk avoidance measures, the company C can define the adoption of additional sensors (e.g., proximity sensors) directly on the vehicles, thus reducing even further (and, hopefully, completely avoiding) accidents involving humans and/or fixed obstacles (e.g., shelving).

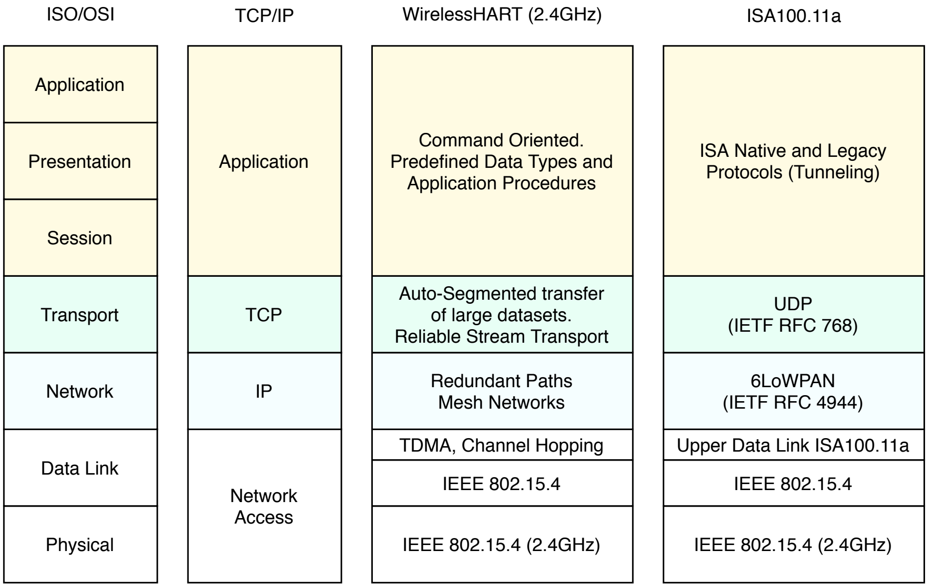

Figure 6: Layered stacks view of WirelessHART and ISA100.11a protocols.

As a conclusion, it is quite clear how, among all cited communication technologies, the wireless ones represent an essential business enabler for the industrial world, because of their reliability, fast deployment, flexibility, cost effectiveness, and capacity to be adequate in (i) pulling data from deployed devices and (ii) sending supervisory control commands to working machinery (e.g., open/close to a valve and start/stop to an actuator) [38]. To this end, the evolving SCADA technology continues to take advantage of emerging technologies at different layers, with the drawback of deploying various heterogeneous and fragmented wireless platforms. This is also due to a limited number of certified wireless instrumentation devices complying with WirelessHART or ISA100.11a [26, 10] specifications, whose layered protocol structures are shown in Figure 6 and directly compared with the 7-layer Open System Interconnect (OSI) model and TCP/IP protocol stack.

On the basis of their coverage area, industrial wireless technologies can be classified into three main categories: (i) WSNs, including ISA100.11a, WirelessHART, ZigBee, and IPv6 over Low-power Wireless Personal Area Network (6LoWPAN); (ii) backbone networks, dominated by IEEE 802.11a/b/g/n/ac protocol; and (iii) backhaul networks, involving Ultra High Frequency (UHF) radio and evolving toward 4G Long-Term Evolution (LTE)/5G, satellite, and microwave technologies. Referring to the ISA100 standard, wireless applications can be grouped into three classes: monitoring, control, and safety. As shown in Figure 7, wireless technologies should be used for noncritical control (Class 2 and Class 3) and monitoring (Class 4 and Class 5) applications, while safety applications, devoted to always-critical emergency situations, should be handled by certainly-available and reliable wired technologies.

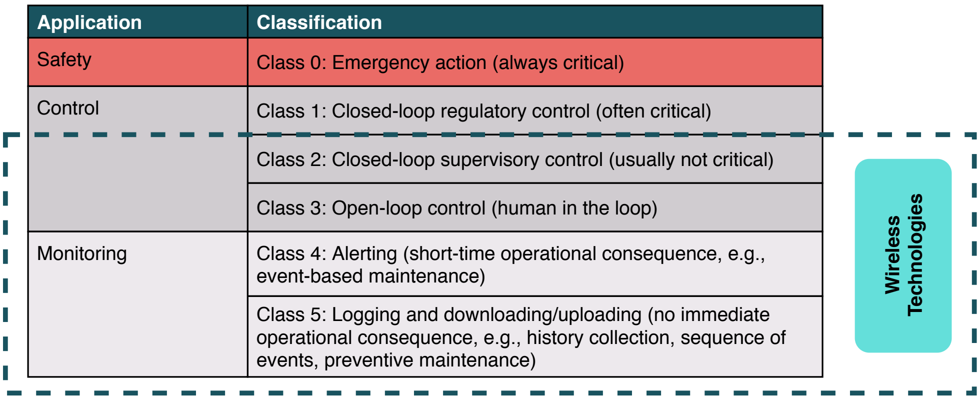

Figure 7: Wireless application classification.

5 Predictive Optimization

The techniques previously shown in Section 3 and Section 4 can be used by the company C to collect data from different (and heterogeneous) sources, targeting a more accurate overall situation monitoring of the company itself. As widely known, in the last years there is an increasing interest on the use of the large amount of data which can be collected in these scenarios, in order to extract relevant information. As shown in Figure 8, most companies have only recently started to take advantage of the possibilities introduced by both *on-premise* and *far-from-home* storage and processing mechanisms (e.g., Edge Computing, Fog Computing, Cloud Computing) for their large amount of collected data [31, 42].

Focusing on digitization activities, the quality control and planning tasks described in Section 3 can be enhanced giving to the technical departments more precise information that can help the staff in improving the planning of the activities to be performed inside the factory. These activities include, for example, the estimation of the warehouse stocks utilization over a certain time period (as well as on multiple time periods, for the sake of comparison), either predicting how a specific material employed during the production of hoses will be entirely consumed, as well as highlighting possible misuses or excessive utilization. The final goal is to optimize the use of resources, avoiding, or at least reducing, the waste of materials (which also has a relevant financial impact for the company C).

The data collected from the production machines can be exploited to forecast the productivity level of a certain product over a particular time interval. This, for sure, may help to optimize the utilization of materials required by an employee from the warehouse. The analysis of the *on-field* production data allows to optimize the maintenance of the production machines. In detail, the ability to collect data from production machines allows to timely perform specific part replacement before its actual fault. This can happen in two ways: (i) the part will be replaced in a *preemptive* way [7], knowing its exact lifetime; or (ii) the replacement will happen following a *predictive* approach [35, 9], based on a more accurate information processing and analysis, involving a more comprehensive dataset (possibly composed by heterogeneous data regarding different aspects of

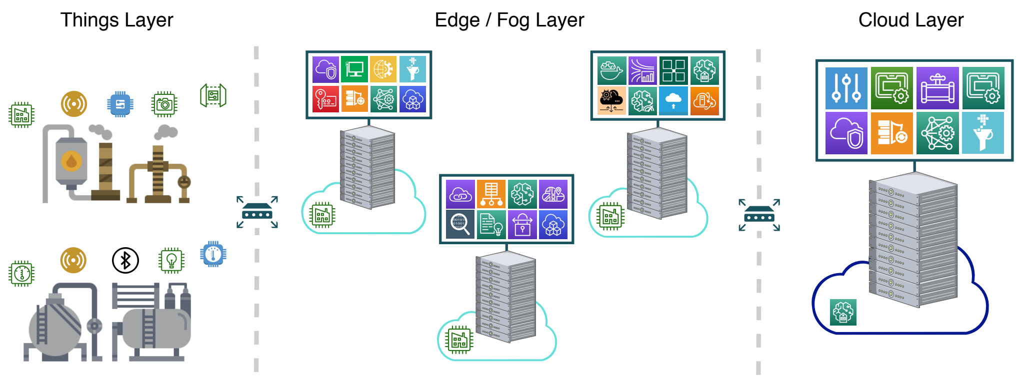

Figure 8: Industry 4.0 predictive optimization to be performed both *on-premise* and *far-from-home*.

the production machine) [32]. Both these maintenance strategies lead to a new concept, that can be denoted as Maintenance-as-a-Service (MaaS), in which the focus moves from sparse data to their aggregated meaning [46, 43]. This data aggregation and processing can be performed either inside the company (namely, company C) or by involving upper-layer systems, relying on the already recalled Edge Computing/Fog Computing/Cloud Computing paradigms.

6 Conclusions

In this work, we have presented an overview on how a generic company C can enhance its internal organization, from a traditional one to an IIoT-based one. Our experience shows that the best way for companies (especially for SMEs) to deal with this process is to face it gradually, integrating *step-by-step* the required set of technologies and know-how. More in detail, in order to drive a generic company C to become IIoT-oriented, the following three transformation stages have been identified: (i) *digitization* stage, aiming at digitally collecting and processing information already available in the company environment; (ii) *monitoring* stage, aimed at extending the quantity of collected data and providing a new perspective of the overall current status of a factory; and (iii) *prediction* stage, involving a set of heterogeneous analytical mechanisms to process the collected data. The last stage has the goal of highlighting problems, errors, or inefficiencies in the company environment, while, at the same time, performing actions on the company C itself through revisions or corrections on the planned tasks.

Acknowledgments

The work of Luca Davoli is partially funded by the University of Parma, under “Iniziative di Sostegno alla Ricerca di Ateneo” program, “Multi-interface IoT sYstems for Multi-layer Information Processing” (MIoTYMIP) project.

References

[1] Mohammad Aazam, Sherali Zeadally, and Khaled A Harras. “Deploying fog computing in industrial internet of things and industry 4.0”. In: *IEEE Transactions on Industrial Informatics* 14.10 (2018), pp. 4674–4682. DOI: 10.1109/TII.2018.2855198.

[2] Laura Belli et al. “Toward Industry 4.0 with IoT: Optimizing Business Processes in an Evolving Manufacturing Factory”. In: *Frontiers in ICT* 6 (2019), p. 17. ISSN: 2297-198X. DOI: 10.3389/fict.2019.00017.

[3] William Bolton. *Programmable Logic Controllers*. 4th ed. Newnes, 2015. 292 pp. ISBN: 978-0-7506-8112-4.

[4] Stuart A Boyer. *SCADA: Supervisory Control And Data Acquisition*. 4th ed. International Society of Automation, 2009. 257 pp. ISBN: 978-1-9360-0709-7.

[5] Hugh Boyes et al. “The industrial internet of things (IIoT): An analysis framework”. In: *Computers in Industry* 101 (2018), pp. 1–12.

[6] Jim Brodie Brazell et al. *M2M: the wireless revolution*. Tech. rep. 2005.

[7] Donato Catenazzo, Brendan O’Flynn, and Michael Walsh. “On the Use of Wireless Sensor Networks in Preventative Maintenance for Industry 4.0”. In: *2018 12th International Conference on Sensing Technology (ICST)*. Limerick, Ireland, Dec. 2018, pp. 256–262. DOI: 10.1109/ICSensT.2018.8603669.

[8] Federico Civerchia et al. “Industrial Internet of Things Monitoring Solution for Advanced Predictive Maintenance Applications”. In: *Journal of Industrial Information Integration* 7 (2017), pp. 4–12. ISSN: 2452-414X. DOI: 10.1016/j.jii.2017.02.003.

[9] Michele Compare, Piero Baraldi, and Enrico Zio. “Challenges to IoT-enabled Predictive Maintenance for Industry 4.0”. In: *IEEE Internet of Things Journal* (2019), pp. 1–1. ISSN: 232-2541. DOI: 10.1109/JIOT.2019.2957029.

[10] Marcio S. Costa and Jorge L. M. Amaral. *Analysis of wireless industrial automation standards: ISA-100.11a and WirelessHART*. https://tinyurl.com/isa100whart. Accessed: 2020-04-05. Nov. 2012.

[11] Mathias Santos De Brito et al. “Towards programmable fog nodes in smart factories”. In: *2016 IEEE International Workshops on Foundations and Applications of Self* Systems (FAS* W)*. IEEE. Augsburg, Germany, 2016, pp. 236–241. DOI: 10.1109/FAS-W.2016.57.

[12] Giuseppe Dinardo, Laura Fabbiano, and Gaetano Vacca. “A Smart and Intuitive Machine Condition Monitoring in the Industry 4.0 Scenario”. In: *Measurement* 126 (2018), pp. 1–12. ISSN: 0263-2241. DOI: 10.1016/j.measurement.2018.05.041.

[13] Carles Gomez, Joaquim Oller, and Josep Paradells. “Overview and Evaluation of Bluetooth Low Energy: An Emerging Low-Power Wireless Technology”. In: *Sensors* 12.9 (2012), pp. 11734–11753. ISSN: 1424-8220. DOI: 10.3390/s120911734.

[14] Mark Huberty. “Awaiting the Second Big Data Revolution: From Digital Noise to Value Creation”. In: *Journal of Industry, Competition and Trade* 15.1 (Mar. 2015), pp. 35–47. ISSN: 1573-7012. DOI: 10.1007/s10842-014-0190-4.

[15] Marika Miriam Iivari et al. “Toward Ecosystemic Business Models in the Context of Industrial Internet”. In: *Journal of Business Models* 4.2 (2016), pp. 42–59. ISSN: 2246-2465. DOI: 10.5278/ojs.jbm.v4i2.1624.

[16] Dorothée Kohler and Jean-Daniel Weisz. *Industrie 4.0: Les Défis de la Transformation Numérique du Modèle Industriel Allemand*. La Documentation française Paris, 2016. 176 pp. ISBN: 978-2-1101-0210-2.

[17] C. Koulamas and A. Kalogeras. “Cyber-Physical Systems and Digital Twins in the Industrial Internet of Things”. In: *Computer* 51.11 (Nov. 2018), pp. 95–98. ISSN: 1558-0814. DOI: 10.1109/MC.2018.2876181.

[18] Wolfhard Lawrenz. *CAN System Engineering. From Theory to Practical Applications*. 2nd ed. Springer-Verlag London, 2013. 353 pp. ISBN: 978-1-4471-5612-3.

[19] Xiaomin Li et al. “A Review of Industrial Wireless Networks in the Context of Industry 4.0”. In: *Wireless Networks* 23.1 (Jan. 2017), pp. 23–41. ISSN: 1572-8196. DOI: 10.1007/s11276-015-1133-7.

[20] Chun-Cheng Lin et al. “Key Design of Driving Industry 4.0: Joint Energy-Efficient Deployment and Scheduling in Group-Based Industrial Wireless Sensor Networks”. In: *IEEE Communications Magazine* 54.10 (Oct. 2016), pp. 46–52. ISSN: 1558-1896. DOI: 10.1109/MCOM.2016.7588228.

[21] Yang Lu. “Industry 4.0: A Survey on Technologies, Applications and Open Research Issues”. In: *Journal of Industrial Information Integration* 6 (2017), pp. 1–10. ISSN: 2452-414X. DOI: 10.1016/j.jii.2017.04.005.

[22] M. Luvisotto et al. “Real-time Wireless Extensions of Industrial Ethernet Networks”. In: *2017 IEEE International Conference on Industrial Informatics (INDIN)*. Emden, Germany, Nov. 2017, pp. 363–368. DOI: 10.1109/INDIN.2017.8104799.

[23] Michele Luvisotto et al. “On the Use of LoRaWAN for Indoor Industrial IoT Applications”. In: *Wireless Communications and Mobile Computing* 2018 (2018). ISSN: 1530-8669. DOI: 10.1155/2018/3982646.

[24] Alexandre Moeuf et al. “The Industrial Management of SMEs in the Era of Industry 4.0”. In: *International Journal of Production Research* 56.3 (2018), pp. 1118–1136. DOI: 10.1080/00207543.2017.1372647.

[25] A. Neumann et al. “Towards Integration of Industrial Ethernet with 5G Mobile Networks”. In: *2018 IEEE International Workshop on Factory Communication Systems (WFCS)*. Imperia, Italy, June 2018, pp. 1–4. DOI: 10.1109/WFCS.2018.8402373.

[26] Mark Nixon. *A Comparison of WirelessHART and ISA100.11a*. Tech. rep. Accessed: 2020-04-04. Emerson Process Management, Sept. 2012, pp. 1–39. URL: https://www.emerson.com/documents/automation/white-paper-a-comparison-of-wirelesshart-isa100-11a-en-42598.pdf.

[27] Päivi Parviainen et al. “Tackling the Digitalisation Challenge: How to Benefit from Digitalisation in Practice”. In: *International Journal of Information Systems and Project Management* 5.1 (2017), pp. 63–77. ISSN: 2182-7788. DOI: 10.12821/ijispm050104.

[28] Sarah Quinton and Lyndon Simkin. “The Digital Journey: Reflected Learnings and Emerging Challenges”. In: *International Journal of Management Reviews* 19.4 (2016), pp. 455–472. DOI: 10.1111/ijmr.12104.

[29] Marco S. Reis and Geert Gins. “Industrial Process Monitoring in the Big Data-Industry 4.0 Era: from Detection, to Diagnosis, to Prognosis”. In: *Processes* 5.3 (2017), p. 35. ISSN: 2227-9717. DOI: 10.3390/pr5030035.

[30] Vasja Roblek, Maja Meško, and Alojz Krapež. “A Complex View of Industry 4.0”. In: *SAGE Open* 6.2 (2016), pp. 1–11. DOI: 10.1177/2158244016653987.

[31] Radhya Sahal, John G. Breslin, and Muhammad Intizar Ali. “Big Data and Stream Processing Platforms for Industry 4.0 Requirements Mapping for a Predictive Maintenance Use Case”. In: *Journal of Manufacturing Systems* 54 (2020), pp. 138–151. ISSN: 0278-6125. DOI: 10.1016/j.jmsy.2019.11.004.

[32] Erim Sezer et al. “An Industry 4.0-Enabled Low Cost Predictive Maintenance Approach for SMEs”. In: *2018 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*. Stuttgart, Germany, June 2018, pp. 1–8. DOI: 10.1109/ICE.2018.8436307.

[33] Kazimierz Siwiak. “Ultra-Wide Band Radio: Introducing a New Technology”. In: *IEEE VTS Vehicular Technology Conference, Spring 2001. Proceedings (Cat. No. 01CH37202)*. Vol. 2. Rhodes, Greece, Greece, May 2001, pp. 1088–1093. DOI: 10.1109/VETECS.2001.944546.

[34] Nicholas Sornin et al. *LoRaWAN Specification*. https://tinyurl.com/loraspecv10. Accessed: 2019-01-27. Jan. 2015.

[35] Lukas Spendla et al. “Concept of Predictive Maintenance of Production Systems in Accordance with Industry 4.0”. In: *2017 IEEE International Symposium on Applied Machine Intelligence and Informatics (SAMI)*. Herl'any, Slovakia, Jan. 2017, pp. 405–410. DOI: 10.1109/SAMI.2017.7880343.

[36] Fei Tao et al. “Digital Twins and Cyber–Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison””. In: *Engineering* 5.4 (2019), pp. 653–661. ISSN: 2095-8099. DOI: 10.1016/j.eng.2019.01.014.

[37] Birgit Vogel-Heuser and Dieter Hess. “Guest Editorial Industry 4.0—-Prerequisites and Visions”. In: *IEEE Transactions on Automation Science and Engineering* 13.2 (Apr. 2016), pp. 411–413. ISSN: 1558-3783. DOI: 10.1109/TASE.2016.2523639.

[38] Soliman A. Al-Walaie. *Industrial wireless evolution - The next-generation process automation wireless technology*. https://www.isa.org/intech/20151001/. Accessed: 2020-04-03. Sept. 2015.

[39] S. Wang et al. “An Integrated Industrial Ethernet Solution for the Implementation of Smart Factory”. In: *IEEE Access* 5 (Nov. 2017), pp. 25455–25462. DOI: 10.1109/ACCESS.2017.2770180.

[40] Andreas Wank et al. “Using a Learning Factory Approach to Transfer Industrie 4.0 Approaches to Small- and Medium-sized Enterprises”. In: *Procedia CIRP* 54 (2016). 6th CIRP Conference on Learning Factories, pp. 89–94. ISSN: 2212-8271. DOI: 10.1016/j.procir.2016.05.068.

[41] Xuepei Wu and Lihua Xie. “Performance Evaluation of Industrial Ethernet Protocols for Networked Control Application”. In: *Control Engineering Practice* 84 (2019), pp. 208–217. ISSN: 0967-0661. DOI: 10.1016/j.conengprac.2018.11.022.

[42] Jihong Yan et al. “Industrial Big Data in an Industry 4.0 Environment: Challenges, Schemes, and Applications for Predictive Maintenance”. In: *IEEE Access* 5 (2017), pp. 23484–23491. ISSN: 2169-3536. DOI: 10.1109/ACCESS.2017.2765544.

[43] Theodore Zahariadis et al. “Preventive Maintenance of Critical Infrastructures using 5G Networks Drones”. In: *2017 IEEE International Conference on Advanced Video and Signal Based Surveillance (AVSS)*. Lecce, Italy, Aug. 2017, pp. 1–4. DOI: 10.1109/AVSS.2017.8078465.

[44] Ray Y. Zhong et al. “Intelligent Manufacturing in the Context of Industry 4.0: A Review”. In: *Engineering* 3.5 (2017), pp. 616–630. ISSN: 2095-8099. DOI: 10.1016/J.ENG.2017.05.015.

[45] Alfred Zimmermann et al. “Adaptive Enterprise Architecture for Digital Transformation”. In: *Advances in Service-Oriented and Cloud Computing*. Ed. by Antonio Celesti and Philipp Leitner. Taormina, Italy: Springer International Publishing, 2016, pp. 308–319. ISBN: 978-3-319-33313-7. DOI: 10.1007/978-3-319-33313-7_24.

[46] Marian Zoll, Daniel Jack, and Marcus Vogt. “Evaluation of Predictive Maintenance-as-a-Service Business Models in the Internet of Things”. In: *IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*. Stuttgart, Germany, June 2018, pp. 1–9. DOI: 10.1109/ICE.2018.8436272.