POLITECNICO DI MILANO

School of Industrial and Information Engineering

Master of Science in Management Engineering

The emerging role of the Industrial IoT in the Smart Factories: overview of the major applications and development of a qualitative framework

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To my parents Anna and Pietro, for allowing me to undertake this journey.

To my girlfriend Francesca, for all the love and support she always gives me.

To my brother Davide, for his recurring encouragements throughout my studies.

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EXECUTIVE SUMMARY

PREMISE

Smart and connected products are increasingly present in people's home today, but the Internet of Things paradigm has recently predated an industry which, over the course of history, experienced several disruptive transformations: the industrial sector. The rise of the Industrial IoT enables enterprises to equip physical assets with connected sensors and generate a network of intelligent products, processes and services that communicate with each other over the Internet. The application domain of the Industrial IoT stretches from the Smart Factory to the Smart Supply Chain and the Smart Lifecycle. The research conducted in this work focuses only on the analysis of the first application domain, though. Within a Smart Factory, the Industrial IoT is suitable for plenty of adoptions, including production management, predictive maintenance, material handling, quality assurance, workplace safety and energy management. The broad range of benefits offered include the improvement of the overall operating efficiency, the reduction of workplace accidents, the management of the quality control processes, the accurate monitoring of the production flow. Although, the adoption of the Industrial IoT poses also various challenges enterprises must cope with, amongst which certainly stands out the threat of cyberattacks.

OBJECTIVES

In accordance with the scope of activities to which the IoT Observatory of Polytechnic University of Milan focuses, the research questions around which this work is founded are:

- Which is the current state of adoption of the Industrial IoT in Italy?
- Which are the major IoT trends that are expected to impact the manufacturing sector?
- Which are the main benefits that manufacturing companies seek to achieve by implementing IIoT-enabled solutions?

- Does the Industrial IoT create new business models driving new revenue opportunities?
- Can the Industrial IoT merge with other disruptive technologies impacting the industrial sector and bring additional benefits?
- Does the existing academic literature provide a framework to examine the Industrial IoT application?

On the basis of the research questions listed above, this work undertakes to pursue two different objectives:

1. Analysis of the current state of art and the major trends of the Industrial IoT in the Smart Factories, from a demand-side perspective;
2. Development of a qualitative framework to map and analyse the different applications of the Industrial IoT in a Smart Factory.

METHODOLOGY

With the purpose of reaching these two objectives, the following activities have been carried out:

1. *Review of the existing literature*. The first phase of this work consisted of reviewing the existing academic literature about the Industrial IoT and its wide range of applications. As the examined topic extends to the broader concept of Industry 4.0, the accomplishment of this activity required a major effort. In fact, 44 academic papers including 27 Articles, 13 Conference papers, 3 Reviews and 1 Short survey, have been carefully read and analysed. The selected papers were selected according to the recency of their publication date, the relevance of the investigating topic within them and the number of citations.
2. *Analysis of secondary sources*. In addition to the analysis of the academic papers, various material from secondary sources was examined. This includes white papers, web articles, studied certified by third parties and reports drafted by the most recognized consulting firms. Moreover, the attendance to two events organized by the IoT Observatory of Polytechnic University of Milan constituted a great opportunity to gather original information from experts closely operating with the discussed themes and recognized the forces at stake.

3. *Survey*. In July 2018 the IoT and the Industry 4.0 Observatories of Polytechnic University of Milan launched a survey aimed at studying the diffusion among the Italian industrial enterprises of Industrial IoT-enabled projects. The survey was submitted to 987 companies out of which 129 answered, with a response rate equal to 13%. After the closure date, the collected answers entered into a specifically created database and a fair number of charts was delivered in order to effectively communicate the obtained results.
4. *Telephone interviews*. According to the answers they provided during the survey, the companies that launched the most interesting Industrial IoT-enabled projects were contacted for a follow-up call interview. During these discussions, the 17 participating companies explain some responses given in the survey and provided a detailed description of the projects they undertook. Moreover, they gave their expert opinion on further curiosities of the researchers.
5. *Framework creation*. Once processed the information collected during the previous activities, a qualitative framework was created. It is a matrix composed by two dimensions that refer to key aspects of the Industrial IoT, limited to its adoption in a Smart Factory context. The development of this framework permitted to analyse the research subject of this work under an original and comprehensive perspective. In addition to these two dimensions, a third variable has been added in order to provide an even more wide picture of the underlying topic. The generated results are presented in a bubble chart.
6. *Analysis of real-world projects*. In order to test the goodness and the robustness of the proposed framework, twelve projects of industrial enterprises that successfully implemented an Industrial-IoT enabled solution in their Smart Factories, have been presented and studied in relation to it. These best practices have been found by navigating on the Internet from reliable online articles. Later, these cases have been grouped according to the Industrial IoT application to which they referred enabling to raise original considerations about the discussed topic.

RESEARCH RESULTS AND DISCUSSION

The analysis of the 'Smart Factory Survey 2018-19' enabled to raise interesting considerations concerning the adoption by industrial enterprises of IoT-enabled solutions in their Smart Factories. First, 62% of 127 sampled projects that leverage the IoT as main enabling technology was implemented to obtain benefits within the production facility perimeter, proving the great interest of manufacturers to invest in this type of solutions (Fig. I). Concerning the use that companies make of the Industrial IoT in their manufacturing facilities, instead, with a reference sample of 94 projects, 'Production management' resulted the most popular application, leveraged by 22% of the implemented IoT-enabled projects. To follow, great results were obtained also by 'Preventive/Predictive maintenance' and 'Energy management' applications, respectively related to 19% and 18% of the sampled projects. Finally, the remained projects were implemented for 'Quality assurance' (16% of the sampled projects), 'Material handling' (14%) and 'Workplace safety' (11%) purposes (Fig. II).

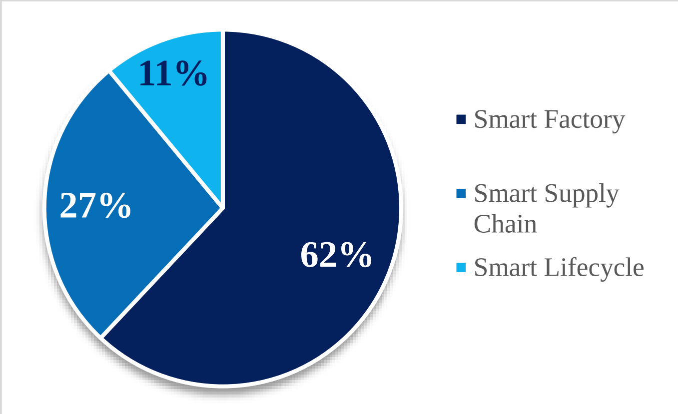

Fig. II. Scope of sampled projects *(sample: 127 projects)*

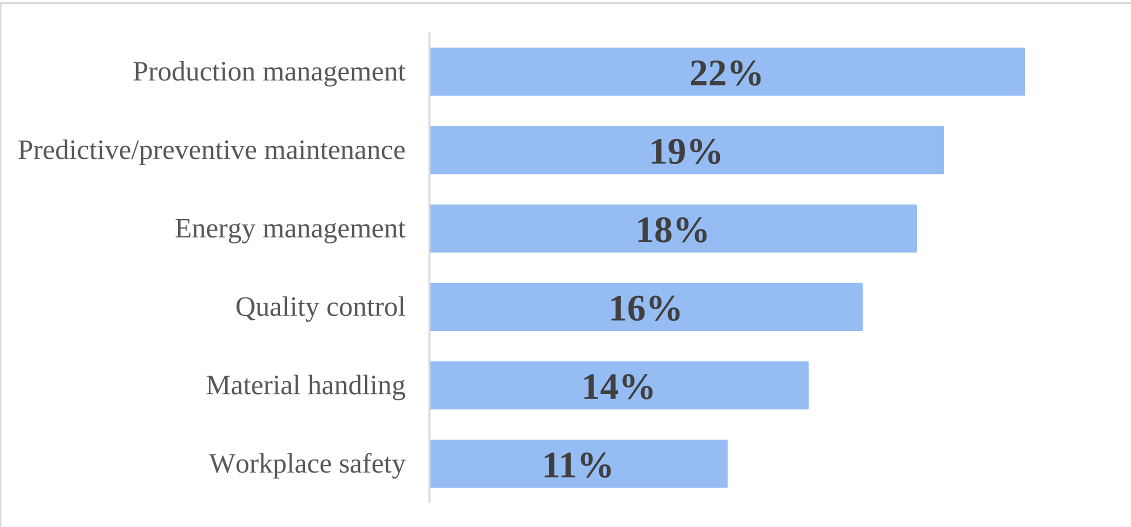

Fig. I. Industrial IoT application of sampled projects *(sample: 94 projects)*

With respect to the main forces that drive companies to undertake this kind of projects, with a reference sample of 113 responding companies, the vast majority of them stated that they implemented IoT-enabled solutions in their factory to gain advantages in terms of efficiency (75% of the participants) and effectiveness (58%). In relation to the barriers, instead, different answers have been collected according to the size of the corresponding companies. In fact, if 67 responding large-sized companies indicated as main barriers encountered the 'Insufficient knowledge and the lack of internal competences' and the 'Incomprehension of the real value of the solutions' (respectively chosen by 60% and 54% of the large-sized respondent firms), 14 responding small-sized enterprises, immediately after the lack of knowledge and internal competences (indicated by 71% of the small-sized respondent companies), consider the limited availability of financial resources to be a great barrier to the implementation of this kind of projects (57%). In response to the level of use of the data collected thanks to the implementation of the IoT-enabled solutions, one third of 83 responding companies stated to have intensively and profitably used the available data (Fig. III). It is important to underline that a great portion of companies that stated not to have fully leveraged the collected data justified the choice explaining that they recently launched the project and they could not collect a significant base of data to perform a robust data analysis. Finally, with respect to the activation of additional services, as expected, 42% of 114 responding companies claimed to have added push notification services to the implemented IoT-enabled solution in order to be informed in case of occurrence of specific events. Only 6% of responding companies, instead, activated pay-per-use services, even though the leasing model is expected to hugely impact the industrial market (Fig. IV).

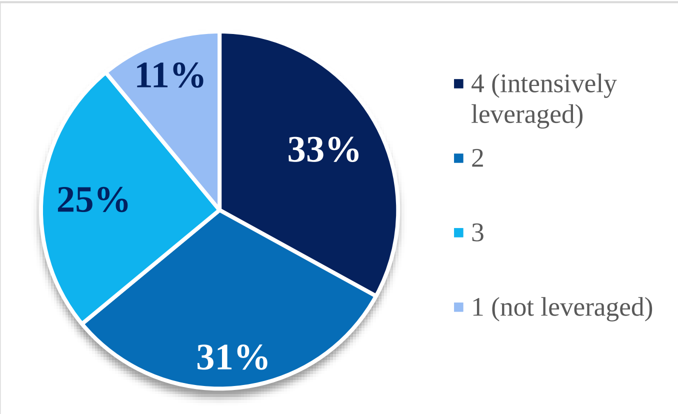

Fig. III. Level of use of collected data *(sample: 83 companies)*

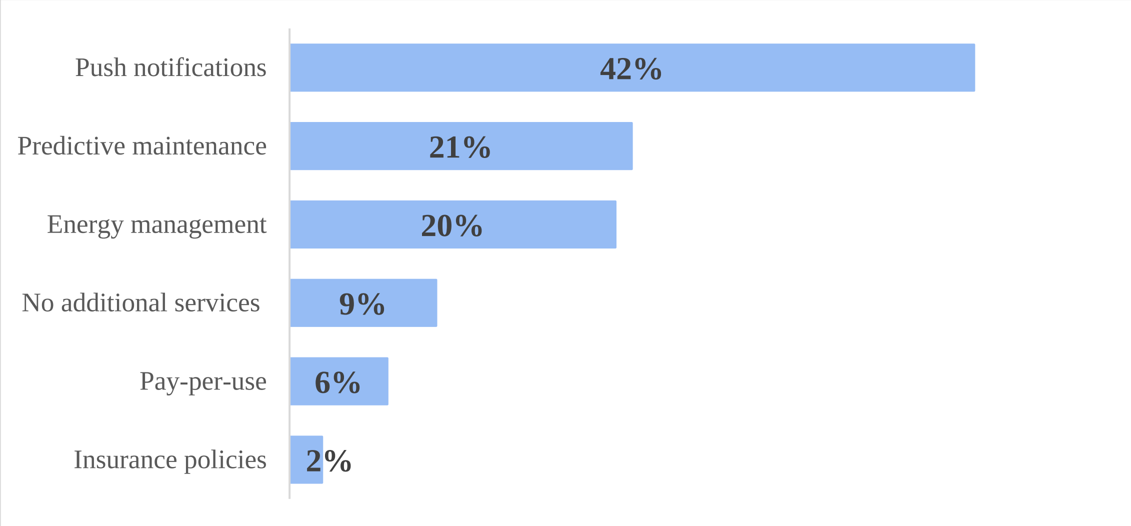

Fig. IV. Activation of additional services (sample: 114 companies)

The major topics that emerged from the individual interviews are:

- the main obstacles to the success of an IoT-enabled project are represented by the need to rearrange the organizational structure and integrate departments (IT and OT) that previously worked independently and the lack of workforce properly skilled for the Industry 4.0;
- the fiscal incentives provided by the Industry 4.0 National Plan certainly represent an attractive opportunity to save money and, therefore, enlarge the scope of the project;
- the solutions currently available on the marketplace are inadequate to satisfy the increasingly complex requirements of the manufacturers.

FRAMEWORK

In order to study in greater detail how companies operating in the industrial sector are leveraging the IoT to gain benefits of different nature in their Smart Factories, a qualitative framework has been developed. It consists of a matrix composed by two dimensions which represent two key aspects of the Industrial IoT.

- *Network Complexity*. It indicates the level of geographical dispersion and interaction that exists among the end nodes of the system that generates from the Industrial IoT adoption. For the evaluation of this variable, both the connected devices and the actors involved are considered 'end nodes'. In this way, IIoT-enabled solutions whose resulting network consists of a considerable number of connected devices or involves many actors into the system will be classified with high values of 'Network Complexity' within the proposed matrix.

- *Synergism*. It indicates the extent to which the solution in question combines the Industrial IoT paradigm with the other Industry 4.0 enabling technologies, namely the Industrial Analytics, the Cloud Manufacturing, the Advanced Automation, the Advanced HMI and the Additive Manufacturing. In order to reap the greatest return from the Industry 4.0, in fact, all these enabling technologies might be integrated into interconnected and autonomous systems. This dimension has not been evaluated as the number of 'Smart Technologies' that work together with the Industrial IoT but, rather, as the level of interaction and cooperation that exists between them.

With the purpose of enlarge the scope of analysis of the proposed framework, in addition to the two variables explained above, the model has been provided with a third numeric dimension, named 'Diffusion'. It indicates the current state of adoption of each Industrial IoT application in a Smart Factory environment and it has been calculated by means of the results obtained during the 'Smart Factory 2018-19' survey. Graphically, the IoT applications are plotted into a bubble chart, where the size of the bubbles enlarges as the 'Diffusion' variable increases.

RESULTS

The development of the framework and the representation on it of the six Industrial IoT applications enabled to outline different aspects (Fig. V).

First, 'Workplace safety' and 'Predictive maintenance' applications employ a considerable number of end devices to interconnect various kinds of actors and leverage the Industrial IoT in tandem with other Industry 4.0 'Smart Technologies'. In the first application, in fact, an interconnected system is created among the workers operating at the line level, the industrial equipment, the production supervisors and the emergency equips which intervene in case of necessity. In these solutions, the Industrial IoT cooperates with the Advanced HMI, as the potential warning signals are displayed on wearable devices, and the Industrial Analytics, providing preventive and predictive indications about the occurrence of hazardous scenarios. By means of the 'Predictive maintenance' application, instead, the Industrial IoT enables to connect the shop floor machineries to the facility supervisors and the maintenance service providers. These solutions exemplary leverage the IoT with the Industrial Analytics technology that enables smart machines to autonomously predict breakdowns or dangerous operating conditions and proactively trigger maintenance service requests when needed.

Second, the adoption of the Industrial IoT for 'Material handling' and 'Quality assurance' purposes turned out to be the one to watch the most with respect to the future scenarios and their positions within the proposed framework are expected to go through major advancements. Manufacturing companies, in fact, are increasingly equipping entire fleets of AGVs robots with IoT-connected sensors raising the overall complexity of the network of end nodes and exploiting the synergies between the Industrial IoT and the Industrial Automation. For the 'Quality assurance' application, instead, IoT-connected sensors will be increasingly applied to machineries and line tools in order to promptly detect any quality conformance issue of the processing products. The introduction of these solutions, that uses the Industrial IoT in tandem with the Advanced HMI and the Industrial Automation, is destined to blow up the market, extending the range of connected nodes adopted and, therefore, the complexity of the generated network of devices.

Finally, the analysis of the experiences of companies that adopted Industrial IoT-enabled solutions for 'Energy management' purposes enabled to highlight that, with regards to this application, the IoT is currently used as a stand-alone technology limiting its potentialities to simply reporting the functioning parameters of the line machineries. Companies that adopt solutions that leverage the Industrial IoT in cooperation with other Industry 4.0 enabling technologies, in particular integrating computational capabilities so as to preventively detect the sources of energy waste and avoid power outage from happening, are still few.

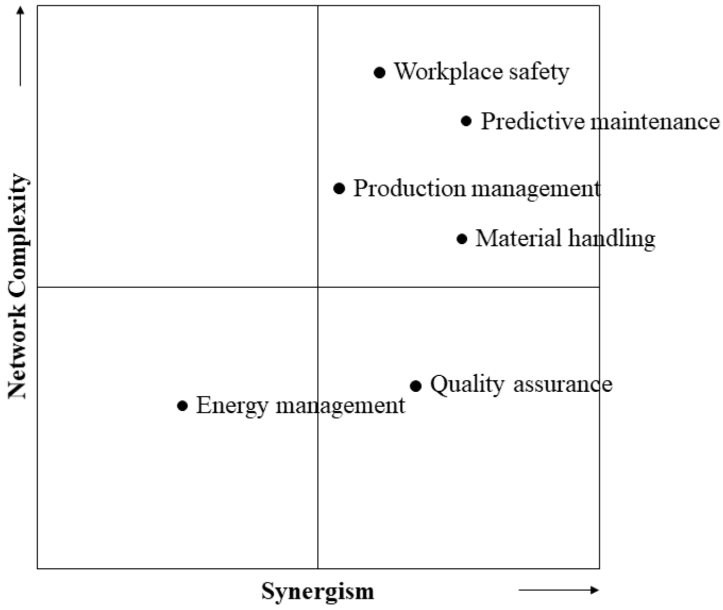

Fig. V. Analysis of the IIoT applications in a Smart Factory in comparison with the proposed framework

LIMITATIONS AND FURTHER DEVELOPMENT

Inevitably, the work conducted so far, and the framework developed suffer from some limitations. First, because of its qualitative nature, the framework founds its results on the individual judgement and sensitivity of the researcher and the raised considerations can constitute ground of disputes and opposite views. Second, the twelve real-world projects examined do not constitute a consistent and robust sample of observations. Finally, as extracted from secondary sources, the analysis of the twelve experiences suffer from low accuracy and adaptability. All these limitations constitute prolific ground for future enhancements.

1 INTRODUCTION

1.1 INDUSTRY 4.0: SMART MANUFACTURING

Over the course of history, the industrial sector experienced major changes that fundamentally transformed and evolved the society in all its aspects, including even non-industrial spheres. These changes caused radical transformations to such an extent that they are defined Industrial Revolutions (Fig. 1).

The First Revolution started in the 18th century and enabled the development of the first forms of mechanization by means of the energy generated by water and steam. The Second took place in 1870 and, with the help of electrical energy, allowed companies to increase their production capacity giving rise to the mass production and the division of labor in assembly lines. The Third, the "Digital Revolution", occurred during the last century and, leveraging the advancements in the Information Technology and the use of electronics, brought automation and robotics into the factories.

Ultimately, in the last few years manufacturing is going through a further transformation, called the Fourth Industrial Revolution, or Industry 4.0. It refers to the introduction of the Internet of Things (IoT) and Internet of Services concepts into manufacturing facilitating the vertical and horizontal integration and interoperability of the production systems [1]. In some ways, it has taken what was started during the Third Revolution with the adoption of computers and automation and enhanced it with smart and autonomous systems fueled by data and machine learning[1]. The level of maturity achieved by digital technologies such as Industrial IoT, Industrial Analytics and Cloud Manufacturing has enabled the paradigm shift from automated towards intelligent manufacturing.

[1] https://www.forbes.com/sites/bernardmarr/2018/09/02/what-is-industry-4-0-heres-a-super-easy-explanation-for-anyone/#725b43459788

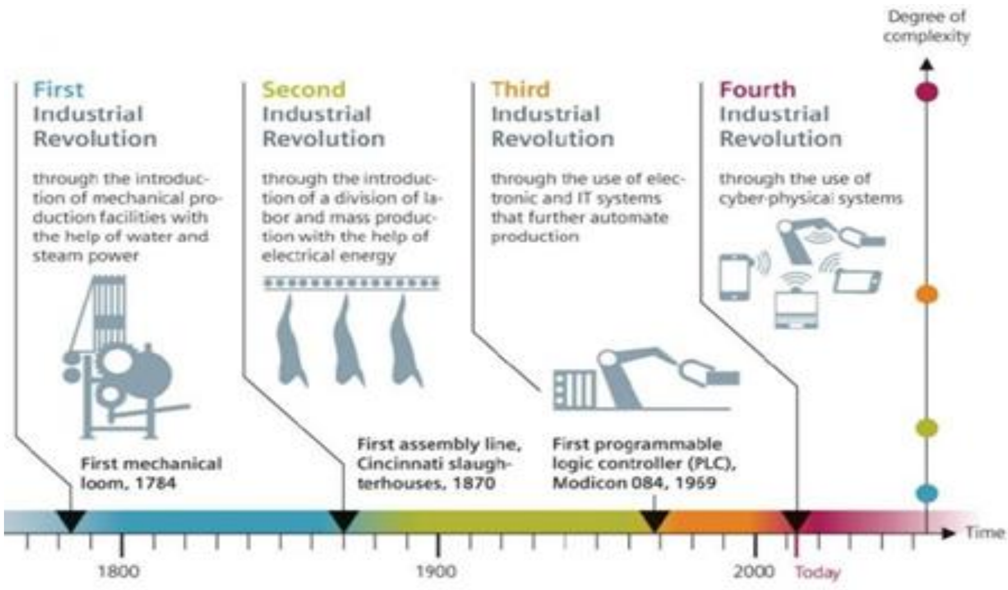

Fig. 1. The transition from the First to the Fourth Industrial Revolution

1.1.1 ENABLING TECHNOLOGIES

In the context of Industry 4.0, manufacturing systems are raised to an intelligent level. The competitive nature of today's industry forced companies to implement a digital transformation of their factories transforming machines into interconnected, self-learning and self-aware systems. Smart Manufacturing refers to the use of cutting-edge Information and Communication Technology (ICT) and advanced data analytics to improve manufacturing operations at all levels of the supply network, be it the shop floor, the factory or the Supply Chain [2]. All the available information is captured in real time, made accessible to many people in the organization and turned into actionable insights in an agile and responsive manner. This leads to a shift from centralized factory control systems to decentralized intelligence [3] [4].

The paradigm demanded a strategic innovation from management that contributed to reconfigure the production systems converging Information Technology (IT) and Operational Technology (OT). It enables companies to cope with the challenges of delivering increasingly individualized products with shorter lead-time and higher quality [5]. Moreover, it enhances the production efficiency helping enterprises to save on raising labour costs and supporting real-time decision making in a big data environment.

According to a research conducted by Ray Y. Zhong et al. [6], the key technologies used in smart manufacturing are: the Internet of Things, the Cyber-physical systems, the Cloud computing, the Big data analytics and other ICTs.

- THE INTERNET OF THINGS

It enables the creation of a network of physical objects (devices, vehicles, buildings and any item embedded with electronics, software, sensors and network connectivity) that allows these objects to collect and exchange data [7] [8]. The integration among the digital and the physical world can be accomplished in two ways: make physical objects ‘intelligent’ by embedding computing and communication facilities into them and connecting these to the Internet; attach tags to physical objects so that sensors that are connected to the Internet can read these tags and generate information about the objects [9].

The scope of application of IoT is extremely wide. According to the Internet of Things Observatory of Polytechnic University of Milan, it is possible to identify 12 main application fields of the IoT: Smart City & Smart Environment, Smart Metering & Smart Grid, Smart Home, Smart Building, eHealth, Smart Car, Smart Logistics, Smart Asset Management, Smart Factory, Smart Lifecycle, Smart Agriculture, Smart Retail. The application of the IoT in manufacturing is the subject of the research and it will be extensively discussed in the next paragraphs.

- CYBER-PHYSICAL SYSTEMS

The main driving technology of smart manufacturing is Cyber-Physical System (CPS) (Fig. 2). It provides seamless integration between computational capabilities and physical assets enabling different components to interact with each other to exchange information. In the manufacturing environment, any adjustment to the production process can be tested in virtual simulations and, if successful, implemented into the actual production line without any physical intervention. This translates into improved operational processes with reduced lead time and increased productivity, thus making the enterprise more competitive and robust against changing customer needs [10] [11].

A CPS consists of two main functional components: advanced connectivity that ensures real-time data acquisition from the physical world and information feedback from the cyber space; intelligent data management, analytics and computational capability that translate raw data gathered into predictive and prescriptive operations and valuable actions [12].

In CPS-based production systems a prominent role is played by the Digital Twin (DT) technology that is the virtual and computerized counterpart of a physical system along its lifecycle. Exploiting a real-time synchronization of sensed data coming from the field, the virtual representation reflects the current state of the system and can be used to perform simulations, real-time optimizations, decision making and predictive maintenance [13].

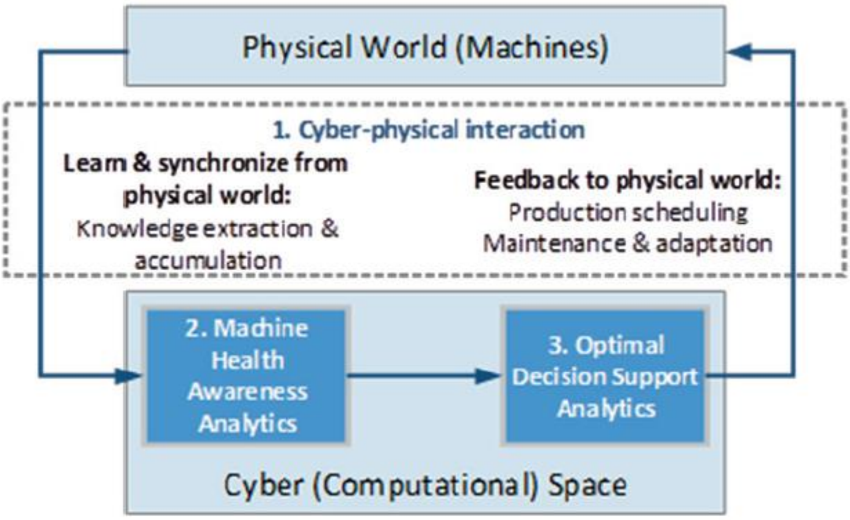

Fig. 2. Cyber-physical system framework for self-aware and self-maintenance machines

- CLOUD COMPUTING

The National Institute of Standards and Technology (NIST)[2] defines Cloud computing as "a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources that can be rapidly provisioned and released with minimal management effort or service provider interaction". The model is composed by five essential characteristics (On-demand

[2] https://csrc.nist.gov/publications/detail/sp/800-145/final

self-service, Broad network access, Resource pooling, Rapid elasticity, Measured service), three service models (Software as a Service, Platform as a Service, Infrastructure as a Service), and four deployment models (Public clouds, Private clouds, Hybrid clouds, Community Cloud). The technology is extremely attractive to businesses as it eliminates the need for users to plan ahead for provisioning and allows enterprises to increase resources only when necessary and without investing in licensing new software, incorporating new infrastructure or training new personnel. This enhances firms' competitiveness through greater flexibility, cost reduction, elasticity and optimal resource utilization. Three distinct fields of application for cloud computing in the industrial sector can be observed: product development, manufacturing process and manufacturing systems and networks management [14]. By means of Cloud computing, with the support of the IoT, virtualization and service-oriented technologies, manufacturing resources are transformed into services that can be comprehensively distributed and shared to form temporary, reconfigurable production lines. The resulting benefits are: enhanced efficiency, reduced product lifecycle costs and resource loading optimization [15].

- BIG DATA ANALYTICS

The declining costs of storage and the increasing computing power made Big Data extremely attractive for businesses that recognized the opportunity to increase their efficiency and gain competitive advantage over competitors. In manufacturing, companies operating in process-based industries are using advanced analytics to mine operational and shop-floor data in order to correct process flaws, increase yields and reduce costs[3]. The increasing adoption in the industrial sector of devices equipped with sensors and connected by the IoT entails the creation of massive amounts of information that require to be properly managed. The abundance of real-time available data generates an information overload forcing manufacturers to adopt data-driven strategies and develop continuous processes for gathering,

[3] https://www.mckinsey.com/business-functions/operations/our-insights/how-big-data-can-improve-manufacturing

processing and interpreting data [16]. Sensor data fail without an analytics platform to help make sense of them. The main challenge for manufacturers is to extract actionable value from the vast amount of data gathered. There are two ways an enterprise can increase the value of its data: first, sell the "private" data or, secondly, to become a data re-user [17].

The concept of Industry 4.0 embraces also other technologies, including mobile computing, Artificial Intelligence, autonomous robots, simulation, cybersecurity, additive manufacturing and augmented reality.

1.1.2 DISSOLVING THE AUTOMATION PYRAMID

Often, in a manufacturing company functions are carried out independently, in different departments, using different sets of software tools. The control architecture of automated manufacturing systems (AMSs) is typically modelled according to the ISA-95 pyramid standard. It defines five functional hierarchical levels, each with specific automation tasks and interaction rules.

The first level ("field level") comprises the physical devices existing at the machine and the production line levels such as actuators and sensors. The second level ("control level") includes logical devices such as the PLC ("Programmable Logic Controller") that receives as input the information from sensors and triggers outputs based on pre-programmed parameters. The third level ("supervisory level") corresponds to control and data acquisition systems (the SCADA, that stands for "Supervisory Control And Data Acquisition") that allows the company to monitor and control production processes. The fourth level ("planning level") refers to the Manufacturing Execution Systems (MES) that controls all the activities occurring on the shop floor. The top of the pyramid ("management level"), in conclusion, consists of the company's integrated management system (the Enterprise Resource Planning, abbreviated to the acronym 'ERP') which ties together all the different applications necessary to run day-to-day business activities.

This architecture has the advantages of predictability and robustness for production plans in stable conditions, as well as good global optimization due to the accessibility to global information from a single source. Nevertheless, because of its rigid and top-down communication flows, it does not fit the dynamic environments of the market and does not allow the vertical and horizontal integration of the Industry 4.0 vision [18]. Therefore, the traditional hierarchical structure is no longer adequate to map the levels of automation existing in a manufacturing domain. It needs to be enforced and evolved into more decentralized and flexible paradigms able to dynamically react to the continuous changes of the business environment.

The introduction of the Internet of Things, the Edge Computing and the Cyber-Physical Systems technologies in the automated manufacturing context completed the changeover from the existing hierarchical control architecture to a more collaborative and distributed ecosystem where data processing and control functions are placed at the edge of the network and systems and devices at the different levels of the pyramid seamlessly communicate each other with no interaction rules (Fig. 3).

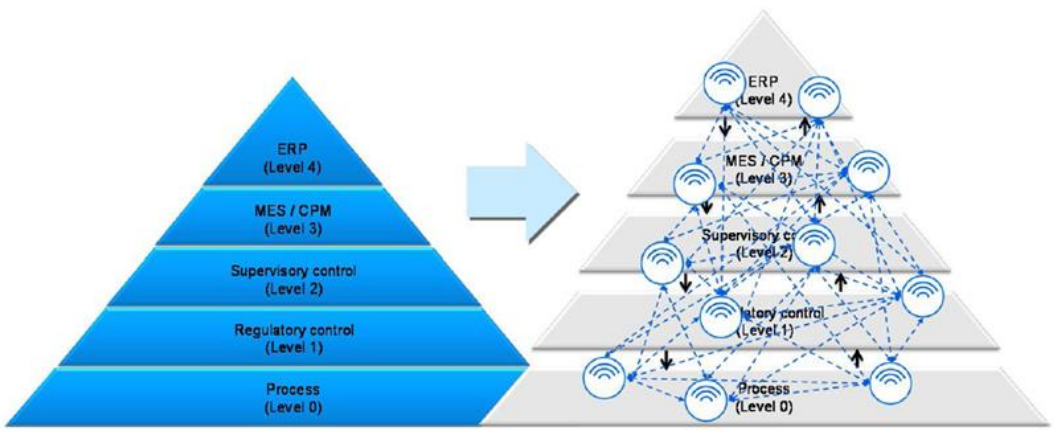

Fig. 3. The evolution of control architectures for automated manufacturing systems

1.1.3 THE SITUATION IN ITALY

In Italy, an increasingly amount of attention is being paid to the phenomenon of Industry 4.0. In February 2017, in order to promote the digitisation of the manufacturing sector, the Italian Ministry of Economic Development has launched the Industry 4.0 National Plan[4]. For Italian companies operating in the manufacturing sector, it represents a major opportunity to win the challenges set by the digital transformation and take advantage of the opportunities offered by the Fourth Industrial Revolution. Thanks to the Plan, the Government provides access to considerable tax incentives for those manufacturing companies investing in technological and digital transformation in accordance with the established measures. The financial incentives offered concern the hyper-depreciation on tangible operating assets and the super-depreciation on intangible operating assets, the tax credits for R&D, the facilitations for SMEs and innovative start-ups, etc.

According to the Industry 4.0 Observatory of the Polytechnic of Milan, in 2017 the Industry 4.0 market in Italy was worth between €2.3 and €2.4 billion, with a 30% growth compared to the previous year. Nevertheless, the results that emerge from a study conducted by the Ministry of economic development (MiSE) [19] prove that the way to go is still long: the vast majority of Italian companies (equal to the 86,9%) does not adopt any “4.0” technologies and is not planning to launch future projects aimed at enhancing the digitalization of the production processes.

1.2 THE INDUSTRIAL INTERNET OF THINGS

1.2.1 DESCRIPTION

The Industrial IoT (IIoT) is the application of the IoT to the industrial sector. It enables the creation of a network comprising autonomous industrial assets and machines embedded with sensors and interconnected via communications technologies to form a single coherent system able to ingest data from the networked devices, analyse them in real-time and use them to optimize operations. Each connected object represents a node in the resulting virtual network and automatically communicates its state with the other objects and automated systems within the same environment [20] enabling industrial companies to boost productivity and improve operational efficiency.

[4] https://www.sviluppoeconomico.gov.it/images/stories/documenti/INDUSTRIA-40-NATIONAL%20PLAN_EN-def.pdf

The adoption of IIoT-enabled solutions opens plenty of opportunities. One of the greatest benefits is predictive maintenance. It enables companies to limit equipment downtime increasing the overall equipment effectiveness (OEE) and improve safety of workers. Other relevant benefits include quality control, production flow monitoring, energy management, traceability of tools, equipment and finished goods along the Supply Chain and within the production plant. However, companies might face several challenges when implementing networked sensors and intelligent devices into their processes. These hurdles can compromise the success of the project and include security and privacy of data exchanged, integration of information technologies (IT) and operational technologies (OT), workforce transformation.

Although the manufacturing industry represents by far the largest market, the IIoT application domain is extremely broad and covers a diverse range of industries, including logistics, agriculture, healthcare, financial services, retail and utilities. The IIoT paradigm, in connection with Big Data analytics, Cloud computing, Human-Machine Interface (HMI), Artificial Intelligence (AI) and robotics, are the pivotal technologies pushing manufacturing towards Industry 4.0.

The IIoT is driving unprecedented disruption and a growing number of innovative companies have already started to implement it to reap the resulting benefits and enhance their competitiveness. In this regard, Accenture expects the IIoT market to reach $123B in 2021, attaining a CAGR of 7.3% through 2020[5].

1.2.2 REFERENCE ARCHITECTURE

From a technological standpoint, only few integrated models on Industrial IoT architectures exist in literature. A reference standard is extremely important for vendors and implementers to build safe, secure and reliable IIoT systems at reduced effort and risks, lower costs and shorter time to value. Recently, the Industrial Internet Consortium (IIC) addresses the need for a common architecture framework and developed the Industrial Internet Reference Architecture (IIRA)

[5] https://www.forbes.com/sites/louiscolumbus/2018/06/06/10-charts-that-will-challenge-your-perspective-of-iots-growth/#33ff41743ecc

[21]. It summarizes the common elements of IIoT systems into three tiers: the Edge tier, the Platform tier and the Enterprise tier (Fig. 4).

The *edge tier* collects data from sensors, actuators, devices, control systems and assets, collectively called the edge nodes. The architectural characteristics of this tier, including the breadth of distribution, location, governance scope and the nature of the proximity network, vary depending on the specific use cases.

The *platform tier* receives, processes and gives control commands from the enterprise tier to the edge tier. It consolidates processes and analyzes data flows from the edge tier and provides management functions for devices and assets. It also offers non-domain specific services such as data query and analytics.

The *enterprise tier* implements domain-specific applications, decision support systems and provides interfaces to end-users including operation specialists. The enterprise tier receives data flows from the edge and platform tier. It also issues control commands to the platform tier and edge tier.

The three tiers are connected by three networks: the proximity network, the access network and the service network.

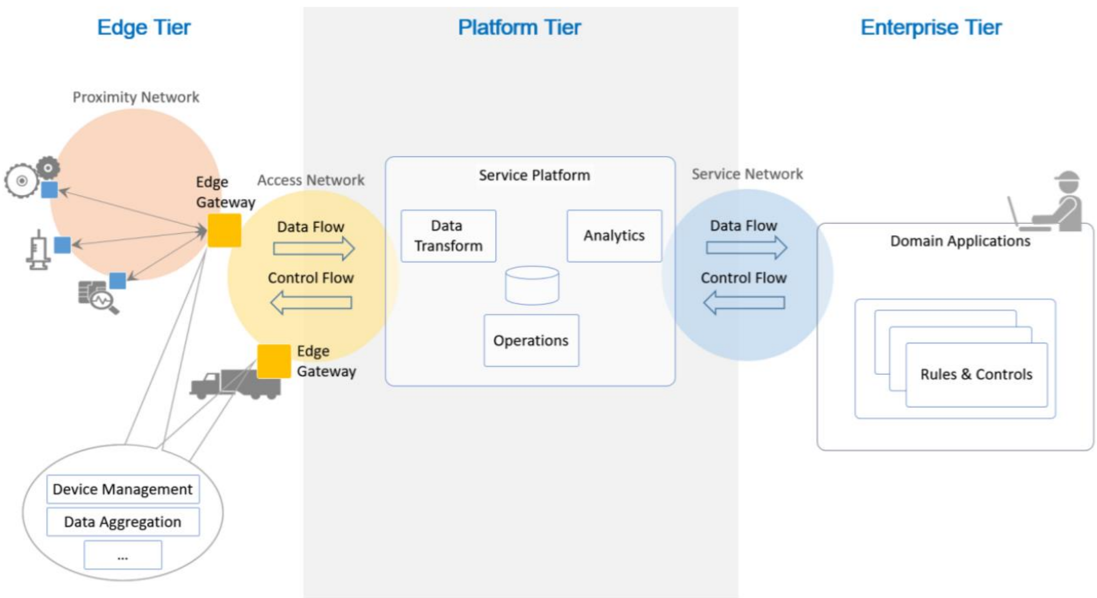

Fig. 4. Three-Tier IIoT System Architecture

1.2.3 ENABLING TECHNOLOGIES: THE KEY ROLE OF SENSORS

Generally, an industrial IoT system consists of three components [22]: front-end edge devices (sensors, actuators and other low-level devices) that are responsible for collecting data; connectivity technologies that enable smart devices to communicate and exchange information; data analytics tools that transform the gathered data into business information. In this system sensors play a significant role collecting continuous streams of data that, once processed, can provide actionable insights [23] [24]. To improve their operational efficiency, industrial systems rely on increasingly innovative sensors for reliable, consistent and accurate data. According to the specific industrial application, sensors measure ambient parameters such as temperature, humidity, air quality, pressure as well as the presence of near objects, the heat emitted by machines, the movement of assets etc. An evolving trend refers to the development of wearable and embedded sensors ensuring safety and health of workers and decreasing injuries in industrial workplaces.

Similarly to the broader concept of IoT, the key enabling technologies that make the Industrial IoT work can be classified as follows [25].

- IDENTIFICATION AND TRACKING TECHNOLOGIES

They include RFID systems, barcode and intelligent sensors. A Radio-Frequency Identification (RFID) identifies and tracks tags attached to the physical objects providing precise real-time information about the involved devices. It is composed of three components: Transceiver (Tag Reader), Transponder (RFID tag), Antenna. Two types of tags are used: passive and active tags. Passive tags are not battery-powered but rely on radio frequency energy generated by the reader to power the tag. Active tags have their own internal battery supply and are more reliable than passive tags due to their ability to establish communication with a reader.

- COMMUNICATION AND NETWORK TECHNOLOGIES

The devices and the industrial equipment contained in the IIoT system have different communication and networking capabilities. The presence of gateways, standards and protocols of communication enable “things” to exchange information and facilitate their interaction across the network [26, p. 0]. The IIoT greatly benefits by leveraging existing Internet protocols such as IPv6, 6LoWPAN, Zigbee.

- SERVICE MANAGEMENT TECHNOLOGIES

The dynamic nature of the industrial IoT applications requires the connected devices to provide reliable and consistent services. The IIoT implements Quality of Service (QoS) requirements such as performance, energy efficiency and security to meet the needs of users and applications [27, p. 0]. The implementation and management of a service-oriented IoT allows each component to perform its functionalities as standard services leading to significantly increase the efficiency of both devices and networks involved in the system.

The IoT is not a technology per se. Rather, it is the combination of several technologies such as IP-based connectivity, cloud and big data analytics as well as mobile devices, RFID, wireless networks and plant-floor IT applications such as MES (Manufacturing Execution System) and PLM (Product Lifecycle Management).

1.2.4 IOT-AIDED SERVITIZATION

Manufacturing enterprises are rethinking their offerings adopting service-oriented strategies through which they add the service component to tangible goods to reinforce their competitive edge and avoid the commodity trap, which jeopardize the economies with lower production costs (Fig. 5). Many services are enabled by ICT solutions that support product-services (P-S) not only in the delivery and execution, but also in the ideation and creation. This makes ‘Servitization’ a data intensive process [17] whose main challenge is to derive value from a series of distributed sources of unstructured and structured data.

In this regard, the concept of smart and connected products, strengthened through the advent of the Internet of Things, plays a representative role enabling companies to get closer to their end customers. Companies leverage the data obtained by the IoT-based solutions to gain knowledge about how customers really use their products and improve their service offerings [28]. This translates into improvements in fulfilling and even exceeding customer needs and, consequently, increased profitability. According to Lee and Lee [29], IoT applications aimed at enhancing customer value can be summarized in three categories: monitoring and control, big data and business analytics, information sharing and collaboration.
In manufacturing field, the use of sensors and IoT-enabled machine-to-machine communication allows the implementation of the condition-based maintenance (CBM), a maintenance strategy through which the repair or replacement decisions are dependent on the current or predicted condition of the assets. The equipment is outfitted with built-in sensors so that the owner can monitor it remotely and deliver maintenance, repairs and upgrades automatically only in case of necessity [30]. This allows manufacturing companies to ensure the operational reliability of the equipment and focus on the work at hand decreasing maintenance frequency and, consequently, maintenance costs and improving productivity.

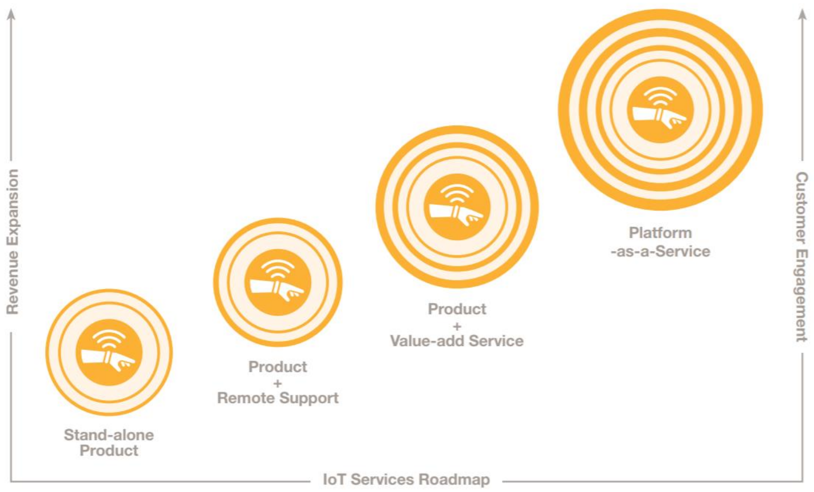

Fig. 5. Companies moving from product-based to service-based offerings by building platforms

1.2.5 MAIN CHALLENGES

Even though the adoption of the paradigm offers attracting opportunities, it also poses various challenges enterprises must cope with. Below some of the major challenges are discussed. The list does not pretend to be exhaustive, but it aims at offering a clearer picture of the underlying phenomenon.

- SECURITY AND PRIVACY

Industrial IoT systems generate, process and exchange large amounts of sensitive data in the Internet, which makes factories particularly vulnerable to malicious attacks aimed at illicitly access and alter this information. The threat to the cybersecurity of the companies' information systems is continuously escalating also due to the reduction of costs to sustain cyber-attacks and the increase of available bandwidth [31]. Nowadays, many enterprises still lack structured control framework to ensure the integrity, the authenticity and the privacy of the information and the service availability of the system.

Smart factories consist of cyber and physical abstraction layers, both exposed to violations from hackers and other cyber criminals. Electronics are subject to physical attacks, including invasive hardware attacks, side-channel attacks, and reverse-engineering attacks. Software can be compromised by malicious code, such as Trojans, viruses, and runtime attacks. Communication protocols are subject to protocol attacks, including man-in-the-middle and denial-of-service attacks [32].

Cyber-attacks on IIoT systems constitute a danger also for humans operating on the production lines. In fact, not only they are subject to social attacks, such as phishing and social engineering, also their physical safety is endangered when looking at the man-machine interaction and the future development of collaborative robots[6].

[6] https://www.ilsole24ore.com/art/tecnologie/2018-10-08/cybersecurity-buone-pratiche-nell-industria-40-124545.shtml?uuid=AEFgNCJG

The introduction of IoT increased the potential attack surfaces of a cyber-physical system (CPS) (Fig. 6). A study conducted by HP[7] reveals that the 70% of IoT devices are vulnerable to attack containing several security issues: privacy concerns, insufficient authorization, lack of transport encryption, insecure web interface, inadequate software protection.

In such a threatening context, it is imperative for businesses to integrate rigid countermeasures against cyberattacks. The main objective of an industrial production system is preventing any unnecessary delay in production. To achieve this aim, the company must defend itself against denial-of-service (DoS) attacks that make the system unavailable keeping it busy with useless operations. This leads to loss of productivity and revenues.

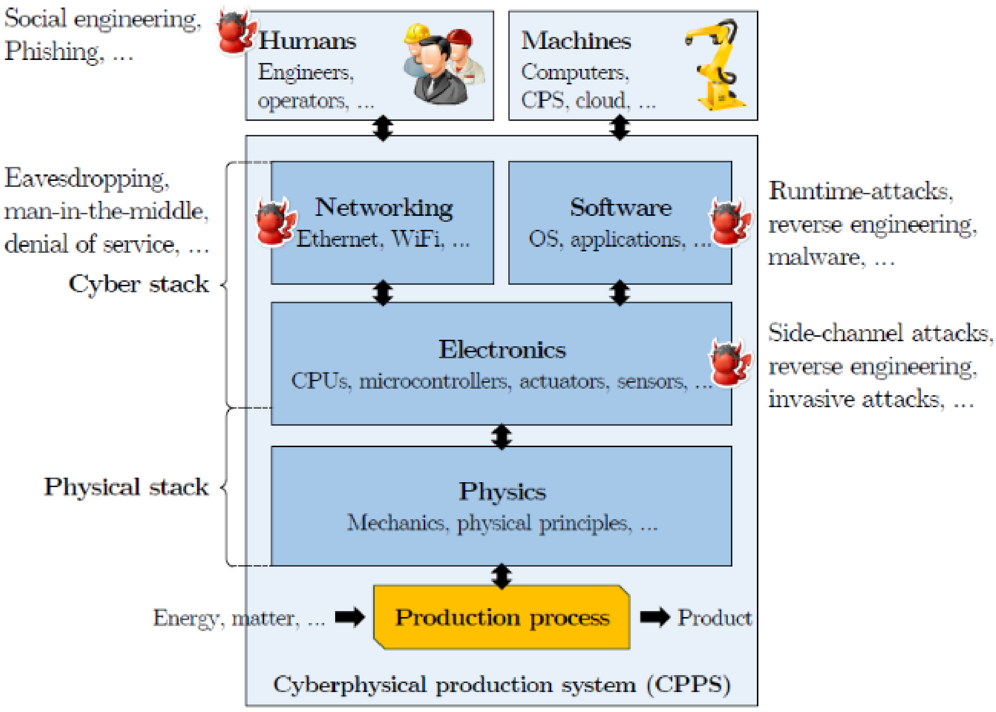

Fig. 6. Cyber-physical production system (CPPS) architecture and potential attack surfaces

[7] http://www8.hp.com/us/en/hp-news/press-release.html?id=1744676#.W74bvWgzY2w

- TECHNOLOGICAL COMPLEXITY

As distributed systems, Industrial IoT solutions have to face the common difficulties of the distributed systems that is interoperability, scalability, and dependability [33]. They have to interoperate with existing infrastructures complementing and integrating legacy applications in a single coherent system. Another requirement for industrial IoT systems is scalability, that is the ability of a system to perform well even when it grows of a few orders of magnitude. The systems must be properly designed to prevent performance degradations when the number of users or machines grows significantly (size scalability), when their components are spread over a larger geographic area (geographic scalability) or when they are managed by multiple parties (administrative scalability). Moreover, they have to be dependable, that is, reliable, safe, available, maintainable, and secure, all at the same time in order not to damage the surrounding environment.

- DATA HANDLING

The use of IoT in manufacturing increases the total amount of available information transforming the industrial data into industrial Big Data [34]. Information collected by sensors embedded in machines, vehicles and tools are of paramount importance for enterprises as they can support companies optimizing their performance and increasing their competitiveness. To fully exploit the potential of the collected data a major role is played by Big Data analytics that enable companies to spot hidden patterns and transform information into actionable insights[8]. However, data captured come from heterogeneous data sources and need to be validated and transformed before starting the analysis. This originates one of the main challenges of analytics: the management and the visualization of data gathered to provide knowledge and make effective and timely decisions [35].

[8] https://hbr.org/sponsored/2016/12/why-iot-analytics-are-a-manufacturers-most-important-tool

- COSTS

A significant hurdle that deters companies from initiating an IIoT project is represented by the high cost of implementation. Even though the price of sensors is drastically reducing (in 2004 the average cost of an IIoT sensor amounted to 1.3 U.S. dollars, whereas in 2016 it dropped to 0.50 U.S. dollars[9]), costs still play a significant role in determining the feasibility of developing IoT solutions. The expenses to be sustained refer to costs of the initial investment, the hardware, the connectivity per month, the power, the software license, the cloud platform usage fees etc. An industrial IoT project involves providing industrial equipment with IoT sensors updating legacy processes and tools or acquiring greenfield installations with completely new equipment. In a recent study, Jasper grouped the operational expenses for Industrial IoT deployments into three categories[10]: Network communication (one-third to one-half of the operational expenses for industrial IoT deployments), that is the cost of providing a data connection for the devices; Administrative labor (20-50% of the operational expenses for industrial IoT deployments), that is the cost of managing and monitoring devices, and creating reports from their data; Technical support (10-33% of operational expense for industrial IoT deployments), that is the cost of fixing technical problems and making repairs to devices in the field. Because of the high investment costs and the potential but uncertain benefits, firms need to carefully assess every IoT-induced opportunity and challenge to ensure that their resources are spent judiciously [29].

- TECHNOLOGY IMMATURITY

The technology is still at an early stage of the maturity curve and the lack of a defined protocol or standardization is restraining the growth of global IIoT market. For manufacturing companies, whose essential requirements are operational flow and responsiveness, implementing a solution that is not perfectly tested and still

[9] https://www.statista.com/statistics/682846/vr-tethered-hmd-average-selling-price/
[10] https://www.businessinsider.com/breaking-down-operational-expenses-for-industrial-iot-deployments-2016-4?IR=T

immature constitutes a challenging and a high-risk scenario, differently from consumer IoT where the extent of a potential failure is certainly lower [36]. Let's consider the case in which a company implements a man down system where devices detect whether an employee is down either from injury or not responsive, and that system does not send out a notification at the proper time. A failure of the system can cause serious damages in terms of workers' safety. Another issue for which companies hesitate to embrace the Industrial IoT is that the infrastructure, intended as the ecosystem of partners including system integrators, cloud providers, network providers, microprocessor vendors etc., is still inadequate and fragmented. Moreover, according to a recent survey launched by Penton[11], promoters of IoT-related products and services do not provide to organizations enough knowledge about available solutions, which prevent them from carefully select the most suitable option. In order to facilitate the development of the market, where the global demand for the Industrial IoT is expected to report a considerable growth in the next years, improvements in interoperability and common standards are needed.

- CHANGE MANAGEMENT

Another typical pitfall that can compromise the success of an Industrial IoT project is failing to properly manage the organizational change it implies in terms of culture, process and workforce. Industrial companies that decide to deploy an IIoT solution need to foster a digital culture across the organization, educate people involved in the project and develop specific skills and competencies in the company's workforce. This can cause the emergence of resistances to change from employees organizations must deal with. According to a recent study performed by Accenture [37], IT professionals will be in high demand in the emerging IIoT service sector. Manufacturers seek technologists who write applications, connect and repair equipment and integrate the information coursing through machinery, factories and supply chains; data scientists who can interpret the insights from analytics programs; intelligent equipment operators who operate robots and

[11] https://www.iotworldtoday.com/2016/04/20/top-10-reasons-people-aren-t-embracing-iot/

equipment on site or from remote locations; and security experts who ensure the integrity and the protection of exchanged data. Moreover, IIoT demand incessant collaboration from cross-functional teams. For decades, Information Technology (IT) and Operations Technology (OT) teams have operated in silos, with very different objectives and priorities and little need to collaborate. The emergence of the Industrial IoT has facilitated the convergence of the two departments that collaborate and communicate sharing relevant information. The transition process is arduous to the point that many industrial companies look outside to consulting firms to help them build a strategy for digital transformation.

1.2.6 APPLICATION DOMAIN

An increasing number of industrial firms are beginning to embrace the IIoT paradigm on a big scale attracted by the opportunity to drive down costs and increase competitiveness. The ramifications of the Industrial IoT go well beyond manufacturing only. Li Da Xu in his review paper named 'Internet of Things in Industries: A Survey' [25] discusses some of the major IoT applications in industries.

- *Healthcare service industry*. Thanks to the IoT's ubiquitous identification, sensing and communication capabilities the vital functions of a patient are constantly monitored, and the caregiver can remotely perform diagnosis and make suitable treatment recommendation [38].

- *FSC (Food Supply Chain)*. The IoT paradigm allows the virtualization of the main FSC stages and processes from precise agriculture to food production, distribution and consumption (the so-called farm-to-plate). This enables companies to better understand the inside dynamics of the ecosystem and the interdependencies between the flow of resources [39].

- *Mining production*. To enhance working conditions of underground miners and prevent fatal accidents from happening, mining companies use IoT-compatible devices to monitor the safety of the necessary equipment (such as boring machines, conveyors, elevators, fans) and analyse critical environmental parameters.

- *Transportation and logistics*. Both vehicles and physical objects are more and more equipped with bar codes, RFId tags or sensors so that companies can conduct real-time monitoring of their movement across the entire supply chain from the manufacturing to the shipping and distribution phases. Moreover, IoT is playing a major role in the automotive industry evolving cars from connected to fully autonomous able to independently avoid obstacles and drive without needing any interaction from the driver.

- *Firefighting*. Firefighting authorities leverage IoT technology to detect potential fire, provide early warning and arrange emergency rescue services as needed.

In addition to the list provided above it should be noted that even in other industries, including farming, retail, hospitality, smart buildings, advertising, financial services, energy and utilities, firms started implementing IIoT-enabled solutions (Fig. 7). But no other sector is expected to be more impacted by this technological revolution than manufacturing. Strongly driven by the increasing need for agile production, operational efficiency, centralized control and demand-driven supply chain and connected logistics, manufacturers are heavily investing in IoT devices. BI Intelligence[12] expects the installed base of manufacturing IoT devices to grow to 923 million in 2020. By that year, manufacturers will spend approximately $267 billion on the IoT. The adoption of the Industrial IoT in manufacturing, especially within the factory perimeter, is the overall purpose of the study and it will be largely discussed in the following sections.

[12] https://www.businessinsider.com/internet-of-things-in-manufacturing-2016-10?IR=T

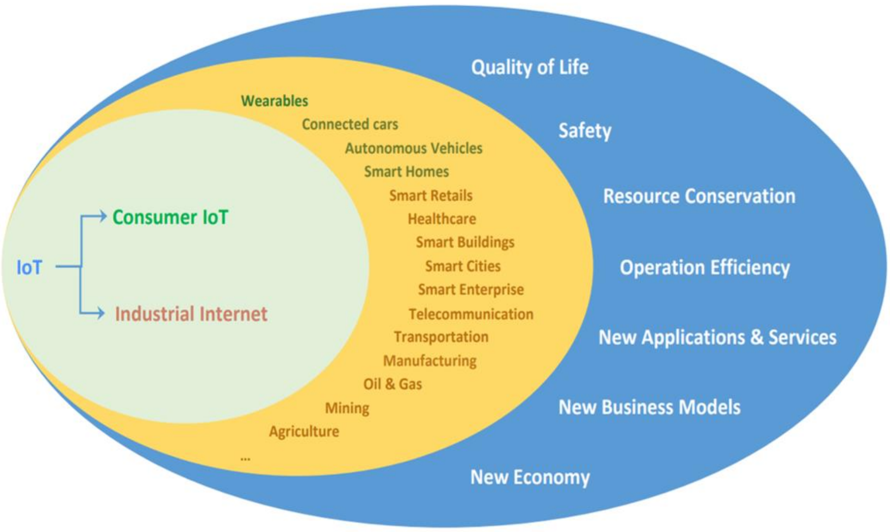

Fig. 7. The broad applicability of the Industrial IoT

1.3 THE INDUSTRIAL IOT IN THE INDUSTRY 4.0

1.3.1 SCOPE OF APPLICATION

According to the Internet of Things Observatory of Polytechnic University of Milan, in the context of Industry 4.0 the Industrial IoT has three major applications: Smart Factory, Smart Supply Chain and Smart Lifecycle.

- SMART FACTORY

The IoT technology provides real-time visibility of shop-floor production performance enabling manufacturers to remotely monitor and manage assets, processes, resources and dynamically schedule production plans [40]. IoT-enabled smart factories replace the hierarchical structure of the shop floor with a flatter and interconnected model supporting decentralized operations and making the information accessible to any worker and supervisor operating on the line. By installing various sensors across the production site, quality issues and process errors can be promptly detected and fixed during the manufacturing stage resulting in increased productivity and customer satisfaction. Predictive maintenance is a top manufacturing trend whereby machines are able to autonomously predict failures and trigger maintenance services if needed thus preventing production breakdowns, improving asset utilization and reducing maintenance costs. At the production level the IoT technology is also adopted to improve energy efficiency and drive energy-aware data driven decisions.

- SMART SUPPLY CHAIN

The IoT had a considerable impact on supply chain management as it enabled to create connection between the entities and the processes involved, automatically identify and track products and goods across the chain as well as within the manufacturing facility, efficiently manage fleet and provide complete information and full transparency at all the nodes of the chain [41]. The introduction of the IoT in the SC management maximizes the transparency of inbound and outbound logistics mitigating risks and accelerating decision-making process and facilitates plan, control and coordination of processes of supply chains [42]. Smart and connected products are challenging traditional buyer-supplier relationship redistributing bargaining power [43]. Product-as-a-Service business models applied to machinery and industrial equipment increase manufacturers' bargaining power by reducing the costs of switching provider. Sensors, connectivity, data storage and analytics and other parts of the technology stack are becoming essential to product differentiation and their cost has a considerable incidence to the total product cost. The providers of these components also possess substantial resources and expertise and can capture a great share of the overall product value.

- SMART LIFECYCLE

The information gathered from sensor-embedded products provide manufacturers a design feedback and a better understanding of product performance and usage enabling them to tailor offerings to more-specific segments of the market. This translates into persisting improvements in fulfilling and even exceeding customer needs relieving customer pains, and consequently, improved profitability [28]. Manufacturing firms are able to diagnose product performance in real-time and automatically activate field services if needed moving from reactive to predictive.

1.3.2 IOT-BASED SMART FACTORY

The IoT paradigm is the main enabler technology for smart factories and played a major role in stimulating manufacturing companies to embrace the fourth stage of industrialization. Through the IoT physical assets become active participants in business processes communicating in real time information about their production status, their location, the surrounding environment, the maintenance schedule and even more. The creation of a connected network of people, devices, machines and assets enables the end-to-end visibility of the operations within the production facilities and across the entire supply chain allowing manufacturers to achieve higher levels of agility and responsiveness.

The paper "Smart Factories in Industry 4.0: A Review of the Concept and of Energy Management Approached in Production Based on the Internet of Things Paradigm" [44] presents a reference architecture for IoT-based smart factory in Industry 4.0 (Fig. 8). It consists of smart objects able to self-organize to fulfil a certain task interacting each other via semantic services [45]. The main characteristics of such factories are: factory visibility allowing optimized decision-making in the area of production and improving factory efficiency; possibility to create new valuable services from big data collected and adopt new planning methods; remote monitoring by third parties; proactive maintenance, by which machines are able to predict failures and autonomously trigger maintenance processes; connected Supply Chain based on information sharing and transparency; energy management based on real time energy consumption data provided by IoT-connected smart meters [46].

The pervasive use of sensors and networked devices at the shop floor level allows field engineers and factory heads to: monitor the production flow in (near) real-time; remotely manage production machineries to reduce energy consumption and improve the overall workers' safety and security; collect aggregate product data during various stages of its development cycle to identify and correct quality defects; implement condition-based maintenance alerts to avoid production breakdowns and increase manufacturing throughput [47].

Companies are also exploiting the potential that the Internet of Things can offer outside the manufacturing facility. Real-time data gathered from connected products concerning their usage and performance throughout the lifecycle offer manufacturing companies the opportunity to better define customers' behaviours and needs and increase the value proposition by enhancing the current offering or providing new valuable and tailored solutions [43]. Moreover, the IoT technology allows companies to build transparent and sustainable relations with suppliers. By connecting the production line and the plant equipment to suppliers, all parties involved in the supply chain can access the related information and trace the interdependencies, the material flow and the manufacturing cycle times [48].

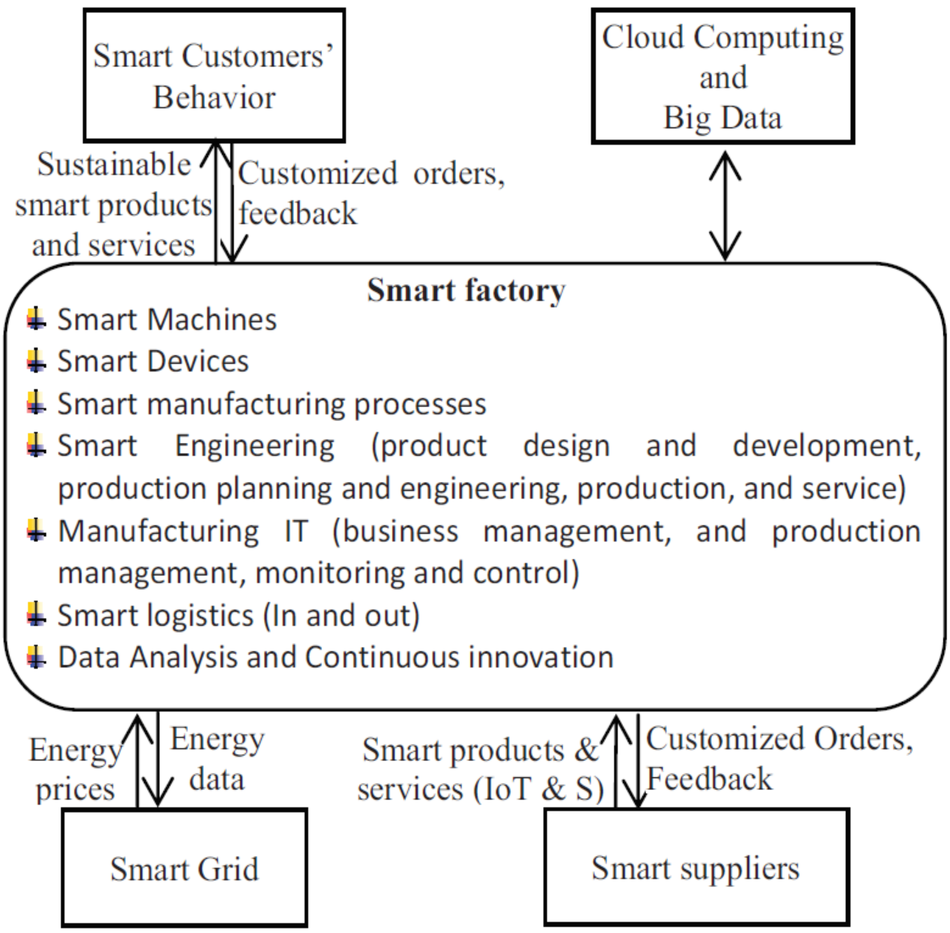

Fig. 8. Reference architecture for IoT-based smart factory

1.3.3 BUSINESS BENEFITS

The IIoT paradigm is an enabler of incremental improvements in the major organizational processes and promises to deliver several business benefits: improved productivity in day-to-day operations, reduced time-to-market, improved process optimization, improved product quality, reduced operational costs, quicker and better decisions making[13]. According to the Internet of Things Observatory of the Polytechnic University of Milan, the possible applications of the IIoT in a Smart Factory environment can be summarized as follows.

- ENERGY MANAGEMENT

In the current manufacturing scenario, the rising energy prices, the increasing ecological awareness about the environmental footprint of production processes and the changing consumer behaviours are driving decision-makers to prioritize green manufacturing and adopt energy-efficient practices in production management to reduce energy consumption. The IoT technology, by means of smart meters and sensors at the machine and the production line levels, enables the collection and the monitoring of real-time energy consumption data from manufacturing processes. The data collected are then stored, analysed and integrated in the company's information systems to improve energy-aware decision-making. Thanks to the adoption of the IoT technology to manage energy consumption at the operational level companies can achieve plenty of benefits [49]. The real-time availability of energy consumption patterns enables managers to make an efficient load balancing reducing energy usage at peak times and improves negotiation position when dealing with energy providers thus reducing energy consumption costs. Manufacturers can reduce energy consumption by spotting energy waste sources and taking actions to remove them or by optimizing production scheduling selecting the most efficient array of machines to produce the job. Moreover, the adoption of the IoT technology helps manufacturing companies decentralize decision-making at the production level so that workers

[13] http://techgenix.com/industrial-iot/

and supervisors on the shop floor can monitor almost in real-time energy usage and take decisions accordingly.

- QUALITY ASSURANCE

By capturing, analysing and communicating product and process data from IoT sensors in real time, manufacturers can obtain effective metrics to support statistical process control (SPC) and Six Sigma methodologies[14] with the aim of providing customers with goods of high quality and personalization and realizing the full potential of production processes. The IoT offers the opportunity to automate manual quality-control tasks and early identify nascent quality problems turning to real-time, actionable closed-loop feedback systems to ensure conformance with contracted specifications. In a networked manufacturing environment, the machine can communicate its output variation to downstream equipment, which automatically makes adjustments to ensure the final product complies with determined requirements[15]. Line operators, quality specialists and product managers can access the stream of metrics from the production floor so that they can take quick data-driven decisions to solve any conformance issues.

- PRODUCTION MANAGEMENT

The IoT promises the utmost operational accuracy and drives a greater overall efficiency of manufacturing processes. Manufacturers monitor in real-time the flow of individual products and components throughout the production line and quickly detect bottlenecks having better insights into the root causes of any manufacturing issue. The information collected by the IoT devices support managers to make better decisions and quick alert when faults or tolerance variances occur. By adding a real-time connection to field devices and sensors manufacturers have a real-time visibility into manufacturing operations and manage the shop floor assets remotely, even beyond the immediate facility perimeter. The integration and interoperability of the Supply Chain enabled by the

[14] https://www.qualitymag.com/articles/94260-capitalizing-on-the-convergence-of-manufacturing-quality-iot-and-lean
[15] https://www.industryweek.com/IoT-boosts-quality

IoT allows for the improvement of the production planning process (PPP) in all its phases [50]: plan developing, execution and control. The basic information required to schedule production plans – basically, the customer demand, the supply capacity of suppliers, the production capacity of the company and the status of inventories – are automatically collected and forecasted by the system so that the necessary shop-floor activities are dynamically planned, allocated and executed in real-time. The resulting production scheduling is agile and able to swiftly and effectively adjust to any changes in customer demand [51].

- PREDICTIVE MAINTENANCE

Manufacturing companies use IoT-enabled sensors and real-time data analytics to continuously monitor the performance of the industrial equipment and, applying machine learning techniques, predict potential breakdowns or malfunctions before they impact production. When organizations move from reactive to predictive maintenance, they optimally schedule maintenance process and time avoiding loss of resources due to unplanned or routine maintenance events and significantly extending the life expectancy of the assets [52]. Thanks to the IIoT, OEMs and third-party service providers gain visibility into manufacturers' field assets and can remotely monitor the equipment status anticipating and preventing failures early. This leads companies to increase their asset availability and utilization, optimize the supply chain management and ensure workers' health and safety. The potential of predictive maintenance is real saving up to 12 percent over scheduled repairs, reducing overall maintenance costs up to 30 percent and eliminating breakdowns up to 70 percent [53] .

- MATERIAL HANDLING

The RFID and barcode technologies enable manufacturers to track the location and the movements of the items throughout the facility. Material handling systems are more and more integrated and connected and employ sensors, communication protocols, RFID tags and IoT tracking technologies to sense the surrounding environment and autonomously manage pick, drop, stack and move operations. A properly designed system can help a company improve customer service, reduce inventory, shorten delivery time, speed order fulfilment and lower overall handling costs[16]. The Internet of Things helps manufacturing businesses manage their inventories as it provides real-time data on the available stock level and enables the automatic reordering when the stock level falls to a certain quantity. Moreover, the IoT enables material handling teams to deploy their forklift fleet more efficiently by providing instant information on where the vehicles are needed[17].

- WORKPLACE SAFETY

Several industrial organizations are undertaking IoT-related projects using connected devices and analytics to boost employee safety. The advent of wearables and sensors embedded in personal protective equipment and industrial machines helped manufacturing companies monitor in real-time the wellbeing of workers operating in hazardous conditions[18] preventing work injuries and fatalities from happening. The connected devices and sensors track metrics concerning workers' health (heart rate, skin temperature, blood oxygen level, brain activity, fatigue, etc.) and environmental conditions (temperature, humidity, noise levels, air quality, etc.) and alert workers or supervisors to take actions accordingly if these parameters go out-of-tolerance. For employers, work safety is of absolute importance as, in addition to the distress of an employee suffering from injury, occupational accidents negatively affect productivity and can constitute significant financial losses.

[16] http://www.mhi.org/fundamentals/integrated-material-handling
[17] https://blog.hyster.eu/how-the-internet-of-things-is-transforming-materials-handling/
[18] https://www.ibm.com/blogs/internet-of-things/ibm-employee-wellness-safety-solution/

2 OBJECTIVES AND METHODOLOGY

2.1 OBJECTIVES

Despite the several challenges they pose, such as the complex integration or the threat of cyber-attacks, IoT-enabled solutions are increasingly adopted by industrial enterprises to facilitate improvements in productivity and efficiency as well as gain economic benefits of different nature. The Internet of Things Observatory of Polytechnic University of Milan intends to investigate how manufacturing companies are leveraging the Industrial IoT in their Smart Factories and the major advantages or barriers incurred during the implementation of this kind of projects. In the course of 2018-19, in fact, it set the objective of studying the framework of IoT applications intended for Smart Factory projects, analysing the most representative cases of success[19]. As a result, it centred its research activity around the following questions:

- Which is the current state of adoption of the Industrial IoT in Italy?
- Which are the major IoT trends that are expected to impact the manufacturing sector?
- Which are the main benefits that manufacturing companies seek to achieve by implementing IIoT-enabled solutions?
- Does the Industrial IoT create new business models driving new revenue opportunities?
- Can the Industrial IoT merge with other disruptive technologies impacting the industrial sector and bring additional benefits?
- Does the existing academic literature provide a framework to examine the Industrial IoT application?

As part of the research program of the Internet of Things Observatory of Polytechnic University of Milan, the focus of this work goes along with the scope of the above-mentioned Observatory's activities. The first activity of this project

[19] https://www.osservatori.net/ww_en/observatories/internet-of-things

consisted of the definition of the objectives to achieve. In compliance with the research questions listed above, this work undertakes to pursue two different aims:

1. Analysis of the current state of art and the major trends of the Industrial IoT in the Smart Factories, from a demand-side perspective;
2. Development of a qualitative framework to map and analyse the different applications of the Industrial IoT in a Smart Factory.

To successfully reach these objectives, a large number of sources was consulted, both primary, internal and external secondary. Certainly, in the fulfilment of the first objective, mainly secondary sources were examined. Examples of internal secondary sources are: the reports and the publications confidentially provided by the IoT Observatory of Polytechnic University of Milan, the "Smart Factory 2018-19" survey, the following telephone interviews performed to obtain further details about the implemented projects and the two events organized by the above-mentioned Observatory whose purpose was to investigate the current state of adoption of Industry 4.0 IoT-enabled projects and the major IoT trends expected to impact the manufacturing sector. Examples of external secondary sources, instead, are the consulted academic papers and the reports drafted by the major consulting firms. As regard the second objective, instead, the three dimensions that model the framework has been developed starting from the analysis of secondary sources and originally elaborated to provide up-to-date information that reinterpret and visually explain the discussed topic. In the end, a set of real-world projects collected from external secondary sources have been presented and studied in relation to the proposed framework to practically explain its functioning and assess its effectiveness.

In the table below (Table 1), it is shown the level of contribution that each source had in the achievement of the two objectives. In this analysis, a distinction has been made between primary and secondary sources. An additional distinction has been performed between internal and external secondary sources to discern the cases in which the source in question directly derived from the IoT Observatory's information system or belonged to third parties.

	Primary sources	Secondary sources	
		Internal	*External*
Objective 1	/	High	High
Objective 2	High	Low	Medium

Table 1. Contribution of each type of source in the achievement of the two objectives

2.2 METHODOLOGY

With the purpose of reaching the two objectives mentioned above, the following activities have been carried out:

1. Review of the existing literature;
2. Analysis of secondary sources;
3. Survey;
4. Telephone interviews;
5. Framework creation;
6. Analysis of real-world projects.

2.2.1 REVIEW OF THE EXISTING LITERATURE

Once defined the two goals of the research, the starting activity consisted of carefully reviewing the existing academic literature about the Industrial IoT topic. As the Industrial IoT topic belongs to a broader concept that includes, first, the Fourth Industrial Revolution, or Industry 4.0, and then, the Smart Factory, the accomplishment of this phase required a major effort. In fact, 44 academic papers, including 27 Articles, 13 Conference papers, 3 Reviews and a Short survey (Annex), have been carefully read and analysed. The consulted papers have been found by means of some of the best online search engines for scientific publications, that are Scopus[20], Web of Science[21], ResearchGate[22] and Google Scholar[23]. The selection of the papers has been performed according to the following two criterions: the recency of the publication date, considering only documents published after 2014 (included), and the relevance of the searching topic in them. However, with regards to the first criterion, an exception has been made for 6 papers that have been examined because they represent milestones within the existing academic literature. Other two elements that constituted a preference reason resulted the high number of citations and the ‘Politecnico di Milano’ affiliation. The adopted searching keywords include the following terms: “IIoT”, “Industrial IoT”, “Industrial Internet of Things”, “IoT”, “Internet of Things”, “Predictive Maintenance”, “Smart Manufacturing”, “Industry 4.0”, “Servitization”, “Smart Factory”, “Big Data”, “Cloud”. All the consulted papers are free and written in English language. In the ‘Introduction’ chapter of this work, whenever the text refers to one of these papers, a proper citation has been added. The accomplishment of this initial activity allowed to understand the relevance of the topic, but also the lack of a reference architecture and the existence of a plurality of definitions concerning the Industrial IoT, holding opposite views especially in relation to the boundaries of its application domain. Some of these definitions, in fact, state that the Industrial IoT is the application of the IoT to the manufacturing industry; others, instead, argue that the potential ramifications of the Industrial IoT applications extend to the entire industrial sector.

2.2.2 ANALYSIS OF SECONDARY SOURCES

In addition to the analysis of the academic papers, the introductory chapter of this work has been written collecting information from secondary sources of different nature, including white papers, web articles, studies certified by third parties and consulting firms’ reports. The integrated analysis of academic papers and

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[20] https://www.scopus.com/search/form.uri?display=basic

[21] http://apps.webofknowledge.com/WOS_GeneralSearch_input.do?product=WOS&search_mode=GeneralSearch&SID=F3zqGk7KkyEd696AD6v&preferencesSaved=

[22] https://www.researchgate.net/

[23] https://scholar.google.it/

secondary sources enabled to identify three major aspects of the adoption of the Industrial IoT in the Industry 4.0 field. First, it facilitated the convergence of the Information Technology (IT) and Operations Technology (OT) departments, that previously operated in silos, with very different objectives and priorities and little need to collaborate. Second, the introduction of the Internet of Things, the Edge Computing and the Cyber-Physical Systems technologies in the automated manufacturing context led to the dissolution of the hierarchical levels of the ISA-95 Standard Automation Pyramid in favour of a more collaborative and distributed ecosystem. Finally, thanks to its advent, manufacturing companies are rethinking their offerings adopting service-oriented strategies to enhance the customer engagement and avoid the commodity trap.

The opportunity to attend two events organized by the Internet of Things Observatory of Polytechnic University of Milan represented an important opportunity to gather original information from experts actively operating on the field and identify the most relevant forces affecting the discussed subject. In chronological order, the events in question were the "Workshop Smart Factory" and the "Workshop Industrial IoT", both held at the Bovisa Campus of the Polytechnic University of Milan. The first event, held on the 9th of October 2018, consisted of a round table in which twelve experts, representing as many companies currently dealing with the debating topic, took part, arguing about the main benefits and the major barriers of implementing a Smart Factory project. Moreover, they openly presented the projects their companies undertook answering the curiosities of other participants. The second event, held on the 12th of December 2018, consisted of a conference in which the Internet of Things and the Industry 4.0 Observatories of Polytechnic University of Milan shared the results they obtained throughout the year thanks to their research activities regarding the Industrial IoT. During the event, some companies were asked to present their projects and the strategies they adopted to successfully leverage the Industrial IoT paradigm in their Smart Factory, Smart Supply Chain or Smart Lifecycle.

2.2.3 SURVEY

In July 2018 the Internet of Things and the Industry 4.0 Observatories of Polytechnic University of Milan launched a survey aimed at studying the diffusion in Italy of Industry 4.0 projects in which the Internet of Things paradigm fulfils the role of key enabling technology. The survey was sent to 987 companies headquartered in Italy out of which 129 answered, with a response rate equal to 13%. It consisted of a set of questions about Industry 4.0 IoT-enabled projects. in particular, researchers were interested to investigate many aspects ranging from the level of knowledge of these solutions, the actual or past commitment to these projects, the field of application, the progress status, the principal objectives pursued, the major barriers faced, the level of use of the data available, the activation of additional services, etc. After the date of closure of the survey, occurred the 21st of September 2018, the collected answers entered into a specifically created database and were properly analysed according to specific guidelines. At the end, a set of graphs, including pie charts, bar charts and histograms, were created in order to effectively communicate the results obtained in the occasion of the conference held the 12th of December 2018 at the Bovisa Campus of the Polytechnic University of Milan. An in-depth discussion of the results achieved thanks to the survey is provided in the third chapter of this work.

2.2.4 TELEPHONE INTERVIEWS

After the above descripted survey, the companies that launched the most interesting projects and provided the most impressive answers were selected and contacted. 17 companies out of these gave their availability for a follow-up call interview. During these interviews, companies justified the answers provided in the survey, detailed the projects they launched and gave their expert opinion on further curiosities of the researchers. All the interviews were performed between September 2018 and October 2018. The interviews were recorded and transcribed in order to easily analyse them. The major topics that emerged from the telephone interviews are discussed in the third paragraph of this work.

2.2.5 FRAMEWORK CREATION

At this stage, after having collected and processed the information gathered by means of the activities described above, it has been possible to proceed with the development of the framework. The aim of this latter is to provide a personal reinterpretation of the discussed topic and ambitiously contribute to enhance the existing literature about the Industrial IoT paradigm and its different applications within a Smart Factory. The selection of the three dimensions constituting the proposed framework has been performed considering all the information collected during the previous activities.

2.2.6 ANALYSIS OF REAL-WORLD PROJECTS

With the aim of evaluating the goodness and the robustness of the framework, twelve real-world projects, two for each Industrial IoT application within a Smart Factory, have been presented and studied in relation to the proposed model. They refer to both Italian and foreign manufacturing companies that successfully implemented an Industrial IoT-enabled project in their Smart Factories. Later, the set of data items has been grouped by the belonging Industrial IoT application and, for each cluster of observations, the corresponding centroid has been qualitatively fixed. In this way, some interesting considerations concerning the adoption of the Industrial IoT in a Smart Factory have been raised and integrated into the analysis carried out so far. The twelve best practices have been found by navigating on the Internet from online articles, always verifying the reliability and credibility of the source and truthfulness of the reported information. The list of cases has been inserted into a DB in which a huge number of IoT-enabled projects are collected.

In the graph provided below (Fig. 9), the six phases across which the work has been developed are shown in relation to the two objectives that it aims at pursuing.

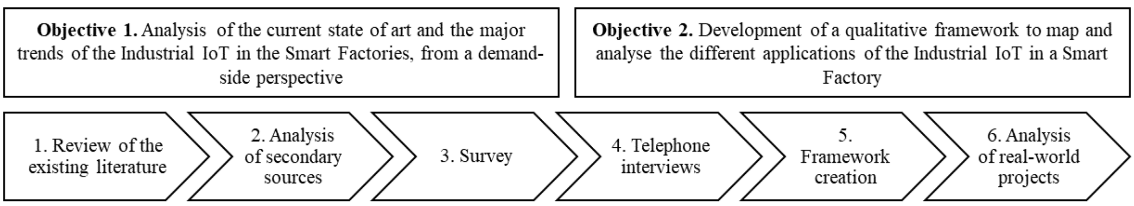

Fig. 9. Objectives and methodologies

2.2.7 RESEARCH QUESTIONS-METHODOLOGIES MATRIX

The methodologies adopted in this work differently contributed to answering the research questions on which the study focuses. The survey and the telephone interviews, along with the analysis of real-world projects, resulted particularly useful to evaluate the current state of adoption of the Industrial IoT in Italy. To answer the question about the IoT trends that are expected to impact the manufacturing sector in the next future, this work resorted mainly to the analysis of secondary sources. Even the expert opinions provided by companies participating to the telephone interviews and comprehension of future plans of companies that implemented the examined projects were helpful to this purpose. With the aim of highlight the main benefits that manufacturers can gain by implementing IIoT-enabled projects in their Smart Factory, several methodologies were useful, including the review of the existing literature, the analysis of secondary sources, the analysis of the survey and the telephone interviews. The potentiality of the Industrial IoT to drive companies to create new business models was deepen thanks to the existence of online reports and articles discussing about this topic. The creation of the framework and the analysis of real-world projects, along with the analysis of secondary sources, enabled to stress the fact that the Industrial IoT is increasingly adopted in tandem with other Industry 4.0 enabling technologies. Finally, with regards to the last research question, the first activity of review of academic papers allowed to prove the lack in the existing literature of a framework to examine the IIoT application within a Smart Factory, whilst the activity of framework creation aimed to remedy this shortcoming.

In the table provided in the next page (Table 2), for each research question, it is reported the corresponding methodology that enabled to answer to it.

	Review of the existing literature	Analysis of secondary sources	Survey	Telephone interviews	Framework creation	Analysis of real-world projects
RQ1			X	X		X
RQ2		X		X		X
RQ3	X	X	X	X		
RQ4		X				
RQ5		X			X	X
RQ6	X				X	

Table 2. Research Questions - Methodologies Matrix

3 RESEARCH RESULTS AND DISCUSSION

3.1 SMART FACTORY SURVEY 2018-19

In July 2018 the Internet of Things and the Industry 4.0 Observatories of Polytechnic University of Milan performed a survey aimed at studying the diffusion in Italy of Industry 4.0 projects in which the Internet of Things (IoT) represents the key enabling technology. The final results were presented during a conference held the 12th of December 2018 at the Polytechnic University of Milan in which various companies argued about the Industrial IoT and the potential benefits that it can deliver. An increasing number of Italian manufacturing companies, in fact, is making the move to the Fourth Industrial Revolution driven by the desire to improve the production efficiency and increase the overall profitability. In addition to this, the adoption of the National Industry 4.0 Plan by the Italian Government further encouraged industrial organizations to embrace the digital transformation providing access to fiscal advantages in the case of fulfilment of specific requirements. In this paragraph, the section of the survey dealing with the application of the Industrial IoT in a Smart Factory environment will be discussed in detail.

3.1.1 SAMPLE DESCRIPTION

The survey was sent to 987 companies headquartered in Italy out of which 129 answered, bringing the response rate to 13%. 17 companies among those that answered to the survey gave their availability for a follow-up call interview during which they explained in detail the Industry 4.0 projects they undertook and gave their expert opinion on further curiosities of the researchers.

The companies that answered the survey were grouped in different categories according to their size (enterprises that employ fewer than 50 people were classified as ‘Small’, those that employ between 50 and 250 people were classified as ‘Medium’, those that employ more than 250 people were classified as ‘Large’)[24], the sector in which they operate and the location of the plant in which

[24] https://data.oecd.org/entrepreneur/enterprises-by-business-size.htm

the project was implemented (if this information was not possible to find, it was considered the location of the corporate headquarters). In the majority of the cases the respondent companies were large-sized (61% of the sampled companies) and headquartered in Northern Italy (84% of the sampled companies). The list of sectors in which they operate, instead, ranges from automotive (13% of the sampled companies), energy and utility (12% of the sampled companies), home appliance (11% of the sampled companies) to food (6% of the sampled companies) and construction (3% of the sampled companies) (Fig. 10).

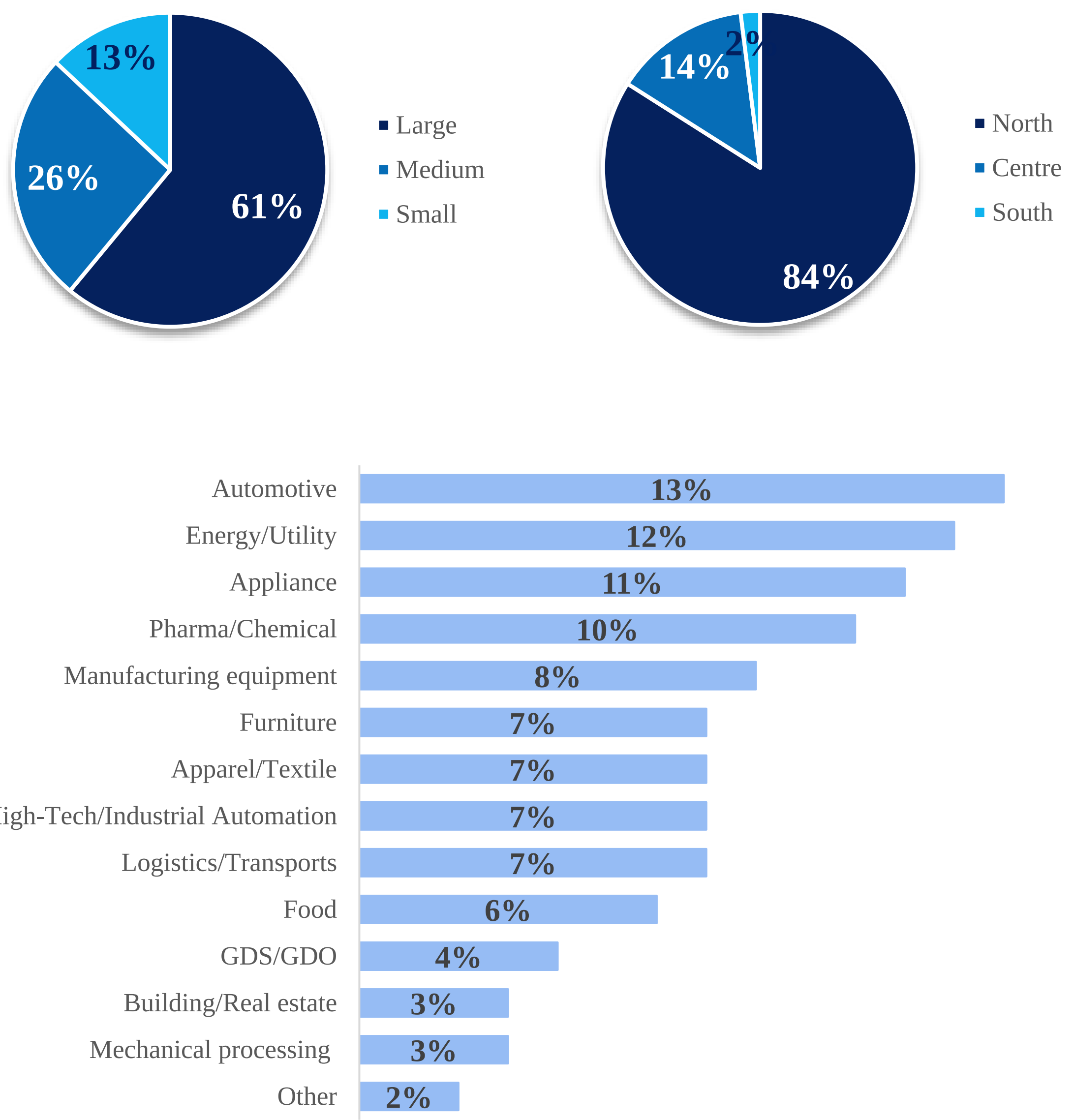

Fig. 10. Sample description by company size, location and sector *(sample: 129 companies)*

3.1.2 KNOWLEDGE OF THE DISCUSSED TOPIC

In recent years Industry 4.0 and Internet of Things (IoT) have increasingly become buzzwords in the production field and manufacturers started paying much more attention to the main challenges and benefits inherent in implementing Smart Manufacturing. A great credit must be recognized to the Italian Government that, by the means of the tax incentives allocated to companies able to satisfy the requirements set out in the National Plan, raised awareness about the topic among manufacturers. This observation is confirmed in the survey as 95% of the respondents stated to be aware of the existence of IoT-enabled solutions for Industry 4.0. This figure is even more meaningful if compared with the one registered during the survey launched in 2016 when only 73% of the respondents stated to have already heard about this type of solutions. The majority of the cases (54% of the sample) learned about it by reading newspapers or press articles concerning Industry 4.0 and related topics, another substantial proportion of respondents (46% of the sample) became aware of it being actively involved in Industry 4.0 projects in the company they work for.

Taking into consideration the characteristics of the companies, the results suggest that the medium-sized and the large-sized companies are more informed than the small-sized ones, having registered an average knowledge level of the topic respectively of 6,55/10 and 6,37/10 against 5/10 of the small enterprises. Therefore, although almost the totality of the respondents stated to have already heard about solutions intended for the manufacturing sector that leverage the IoT as key enabling technology, the level of detail to which they examined the subject is just sufficient as the average knowledge level of all the respondents resulted 6,21/10 with the majority of responses gathering between 6/10 and 7/10.

3.1.3 IMPLEMENTED INDUSTRY 4.0 IOT-ENABLED PROJECTS

The survey highlighted that an increasing number of companies are moving to the Fourth Industrial Revolution: almost 7 manufacturers out of 10 (67% of sampled companies) stated to have launched at least an Industry 4.0 project in which the IoT played a leading part. In the survey launched in 2016 this figure stopped at

41%, as proof that enterprises are increasingly confident about the potential offered by the Industrial IoT solutions.

As already mentioned in the 1.3.1 paragraph, in the context of Industry 4.0 the Industrial IoT has three major applications: Smart Factory, Smart Supply Chain and Smart Lifecycle. In the survey, the overwhelming majority of the respondent companies (62%) leveraged the IoT technology to gain advantages within the Smart Factory perimeter, while the remaining part of projects concerned the Smart Supply Chain and (27% of the sampled projects) and the Smart Lifecycle (11% of the sampled projects) (Fig. 11).

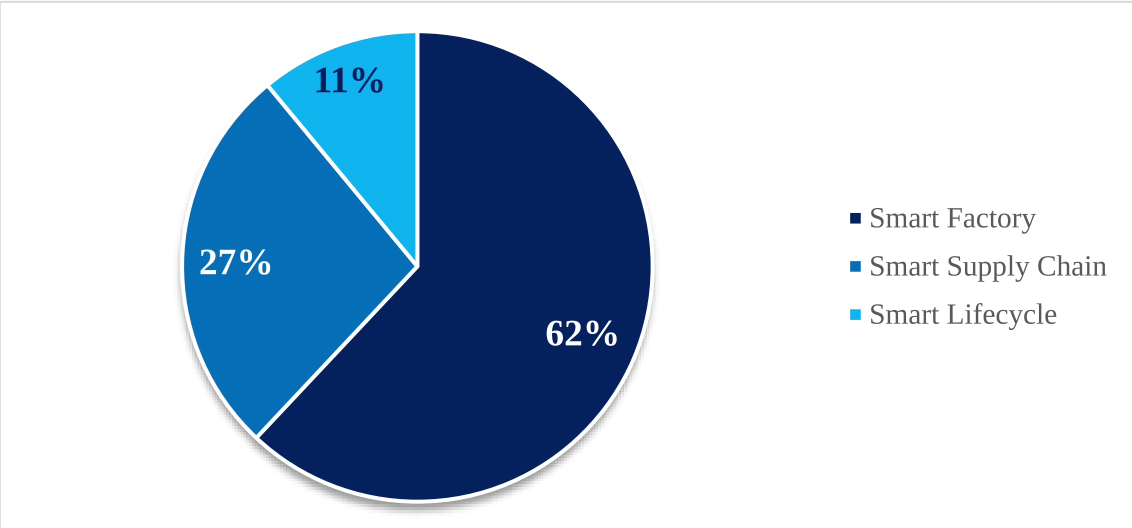

Fig. 11. Scope of application of sampled projects *(sample: 127 projects)*

Looking at the productive sectors, the companies operating in the automotive and home appliance industries proved to be the most active in terms of this kind of investments. In fact, 86% of the companies operating in the automotive industry and 75% of the companies operating in the home appliance industry affirmed they executed at least an IIoT-enabled project to drive productivity improvements and mitigate geographical risks. In reference to the business size, instead, large-scale companies revealed to be the most involved ones, having obtained that 68% of the implemented projects belongs to large-sized companies and 76% of the large companies declared to have invested in, at least, an Industry 4.0 IoT-enabled project. Nevertheless, it is necessary to make this consideration reminding that the majority of the sampled companies (61%) were large-sized.

Even though the survey allowed to realize that an increasing number of companies decided to adopt IIoT-enabled solutions, in the majority of the cases the projects are still at early stages of their life cycle. Only 42% of 127 sampled projects, in fact, was indicated as 'Executive' while the remaining part is divided almost equally among preliminary analysis (30% of the sampled projects), in which the different alternatives still have to be validated and the guidelines defined, and pilot projects (28% of the sampled projects), in which experimental trials are conducted to evaluate the feasibility of the idea.

3.1.4 SMART FACTORY IOT APPLICATIONS

Concerning the IIoT applications in the Smart Factory environment, largely discussed in the 1.3.3 paragraph, 'Production management' turned out to be the most popular application since it was the pursued benefit of 22% of the 94 sampled projects. Among the most widespread functionalities, it is worthwhile to mention even 'Preventive/Predictive maintenance' and 'Energy management', respectively related to 19% and 18% of the sampled projects. To follow, the Industrial IoT was adopted to help manufacturers performing quality control activities in 16% of the cases, monitoring material handling activities in the 14% of the cases and ensuring workplace safety only in the 11% of the cases (Fig. 12). About their progress status, the percentage of executive projects rises to 45% whereas the amount of pilot projects and preliminary analyses is respectively of 29% and 26%.

With respect to the technologies used, at the end, in 54% of 63 sampled Industry 4.0 projects cabled solutions were adopted to build the IoT-based platform. Other technologies that received great approval by the respondent companies were cellular network (13% of the sampled projects) and RFId technologies (11% of the sampled projects).

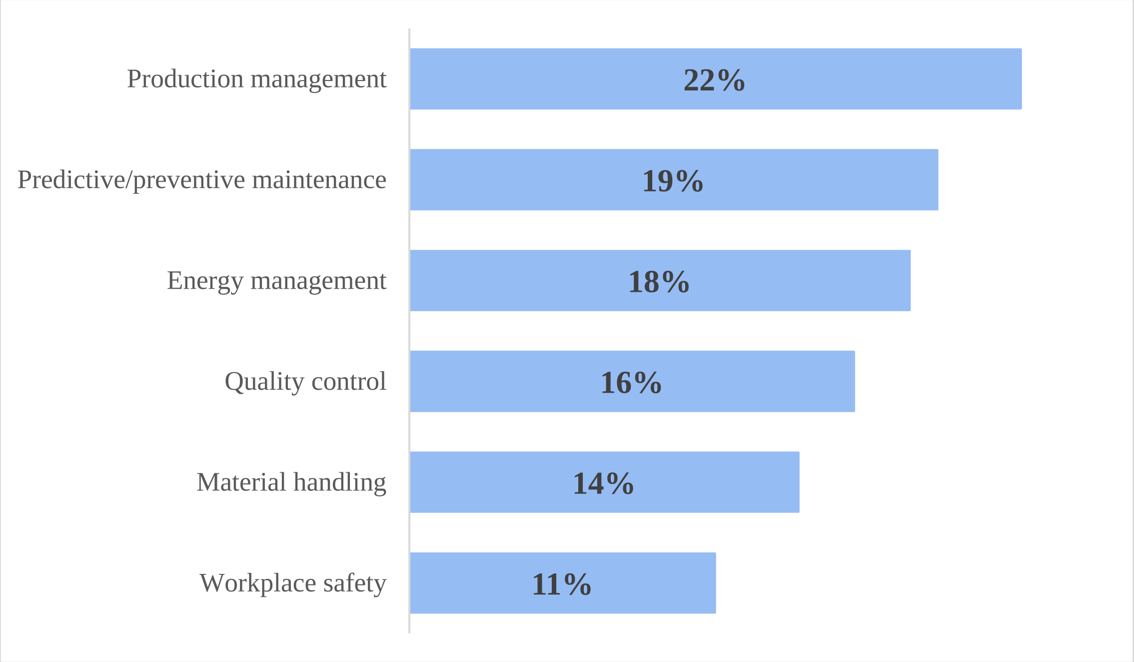

Fig. 12. Rate of diffusion of the Industrial IoT applications in a Smart Factory environment *(sample: 94 projects)*

3.1.5 DRIVING FORCES

The companies that stated to have undertaken an Industry 4.0 IoT-enabled project were also asked to indicate the major factors that led to their decision to launch such a project. As for every innovation project, the forces that drive an organization to change can be of different nature: internal, if the innovation arises from a strategic and managerial need, or external, if instead the change is imposed by market dynamics and technological opportunities. As expected, the vast majority of the respondent companies affirmed that, by means of the underlying project, they seek to increase and improve the efficiency (75% of the sampled answers) and the effectiveness (58% of the sampled answers) of their operations. It is surprising, instead, to observe that 45% of the sampled companies decided to undertake this type of project with the aim of accessing the tax incentives provided by the Government by the Industry 4.0 National Plan (Fig. 13). This figure proves the leading role played by the Italian Government in encouraging businesses to make their move towards the digital transformation of their manufacturing activities and invest in Industry 4.0 technologies and capabilities.

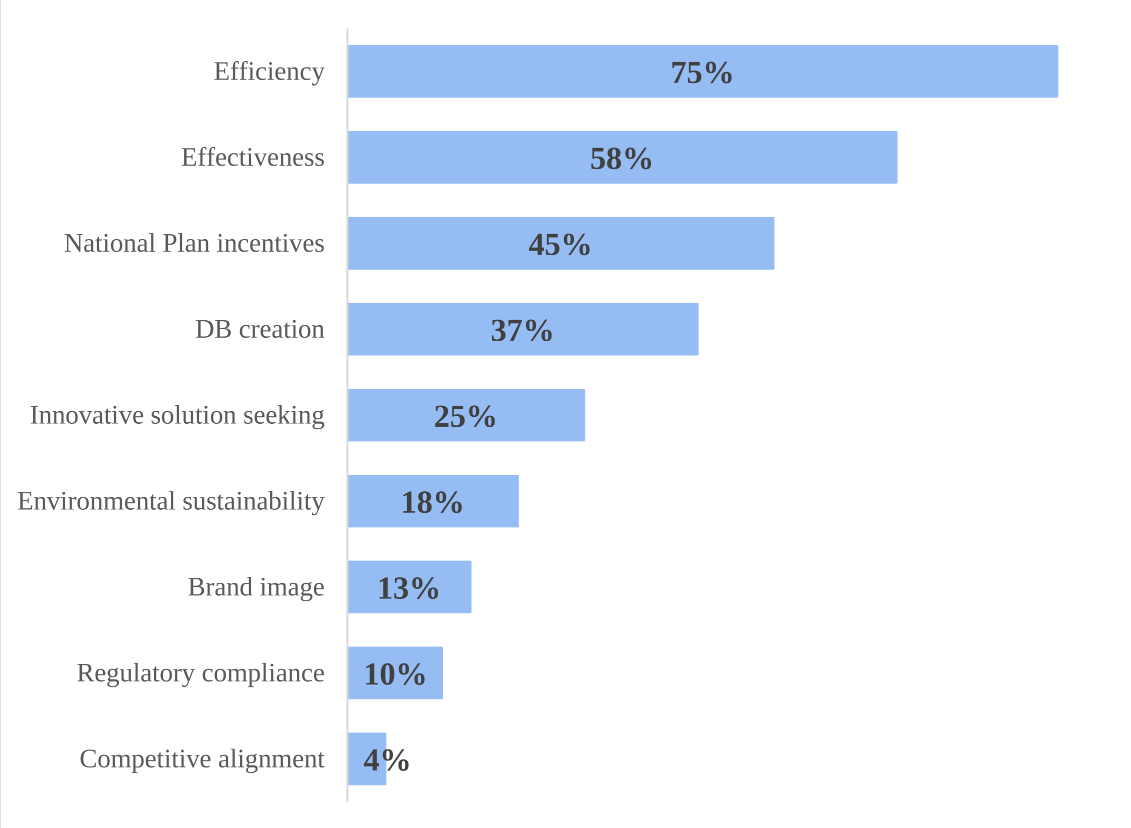

Fig. 13. Major drivers to launch an Industry 4.0 IoT-enabled project *(sample: 113 companies)*

3.1.6 MAIN BARRIERS

Later, all the participants to the survey were asked to indicate the main hurdles that a company could face during the development of Industry 4.0 projects in which the Industrial IoT plays the role of main enabling technology. For many organizations, the biggest challenge is represented by the lack of experienced talents and internal competences needed to plan and execute the digital innovation initiatives. With continued strain on IT budgets, organizations struggle to both manage the priorities of today and invest in the talent needed to help them transform their business[25]. The obtained results allow to get back to the subject previously discussed about the superficial knowledge of manufacturers about the existence of IoT-enabled industrial solutions. The most selected items by respondents, in fact, were 'Insufficient knowledge about the topic related to the Smart Factory and/or lack of internal competences able to manage this kind of

[25] https://www.insight.com/en_US/learn/content/2018/03132018-the-industrial-iot-why-building-your-smart-factory-cant-wait.html

projects' that was selected by 60% of the respondent firms and 'Lack of comprehension of the real value of the solutions that have to be implemented' that was picked, instead, by 53% of the answering companies. Considering the size of the firms that answered this question, some interesting observations can be highlighted. In fact, if large-sized companies indicated as main barriers the 'Insufficient knowledge about the topic related to the Smart Factory and/or lack of internal competences able to manage this kind of projects' and the 'Lack of comprehension of the real value of the solutions that have to be implemented' (respectively chosen by 60% and 54% of the large-sized respondent firms), small-sized enterprises, immediately after the lack of knowledge and internal competences (indicated by 71% of the small-sized respondent companies), consider the limited availability of financial resources to be a great barrier to the implementation of this kind of projects (57% of the small-sized companies selected the item 'Limited availability of financial resources') (Fig. 14). Cost concerns, in fact, play a significant role in determining the feasibility of developing Industrial IoT solutions and often deter manufacturers from deploying IoT solutions. If compared with manufacturing giants, small-scale businesses encounter more difficulties in implementing IIoT-based solutions. Even though the prices of IIoT components have fallen, undertaking projects of this type remains an highly capital-intensive activity and often small enterprises don't have sufficient resources to sustain it. In addition to the costs of the IoT components (including hardware, infrastructure, mobile or wearable applications and certificates) it is necessary to take into account the monetary losses originating from the production downtime required to replace or retrofit the legacy infrastructure.

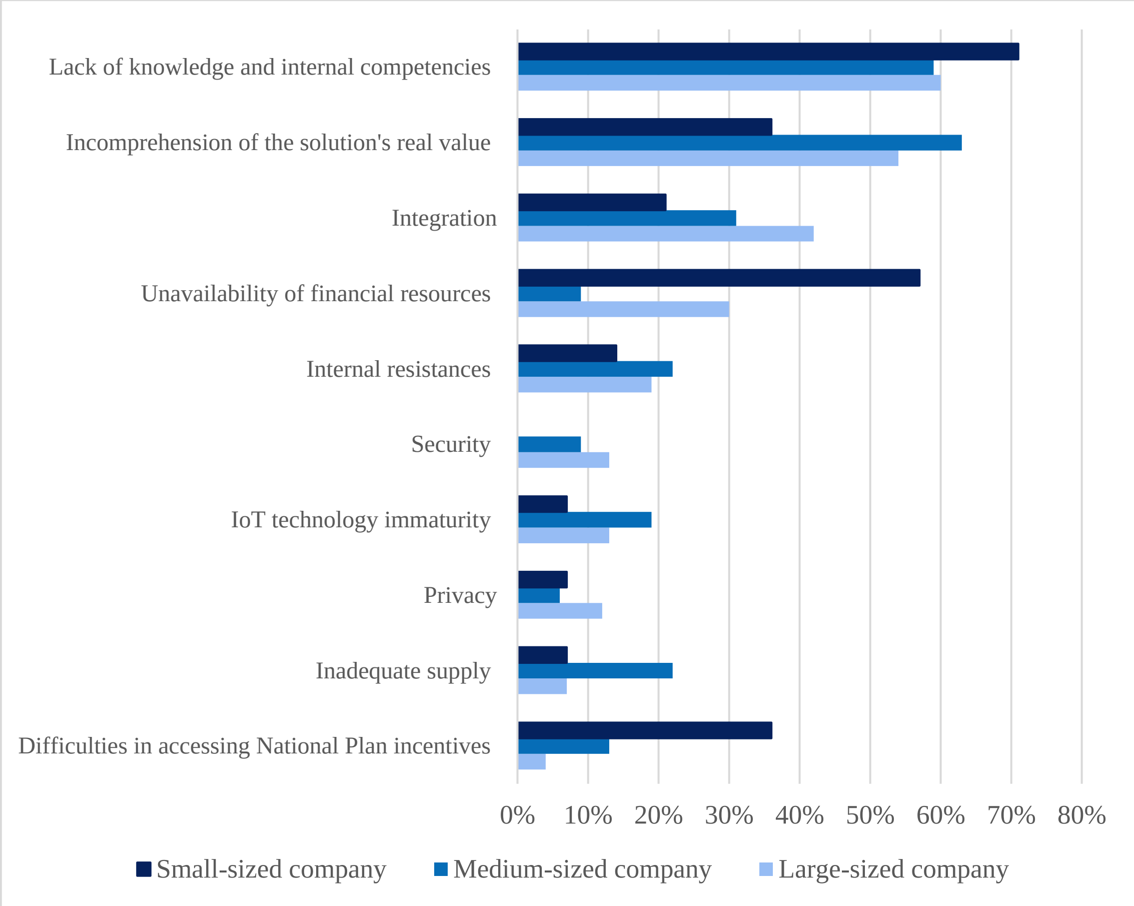

Fig. 14. Major obstacles to Industry 4.0 IoT-enabled projects, divided by company size *(sample: 67 large-sized companies, 32 medium-sized companies, 14 small-sized companies)*

3.1.7 USE OF COLLECTED DATA

Interesting insights emerged also from the results obtained in response to the question about the level of use of the data collected thanks to the implemented solution. The adoption in the industrial sector of devices equipped with IoT-connected sensors, in fact, led to the generation of massive amounts of real-time data from multiple sources that, with the purpose of creating actionable value, require to be properly processed and managed by means of advanced analytic techniques. During the survey, participants were asked to indicate on a scale from 1 to 4 (1 meant that the company did not use the generated data, 4 meant that the company profitably leveraged the generated data) the extent to which they leveraged the data gathered by means of the launched projects. The results obtained seem to prove that a successful project can not abstain from accurately collecting available data and performing ad-hoc analyses of them. One-third of the answering companies, in fact, stated to have profitably used the available data, whereas only 11% of the sampled companies declared they did not used this data (Fig. 15). It is important to underline that a great portion of those companies that stated not to have leveraged the collected data, that is they answered indicating ‘1’ or ‘2’, justified the choice explaining that they recently launched the project and they could not collect a significant base of data to perform a robust analysis.

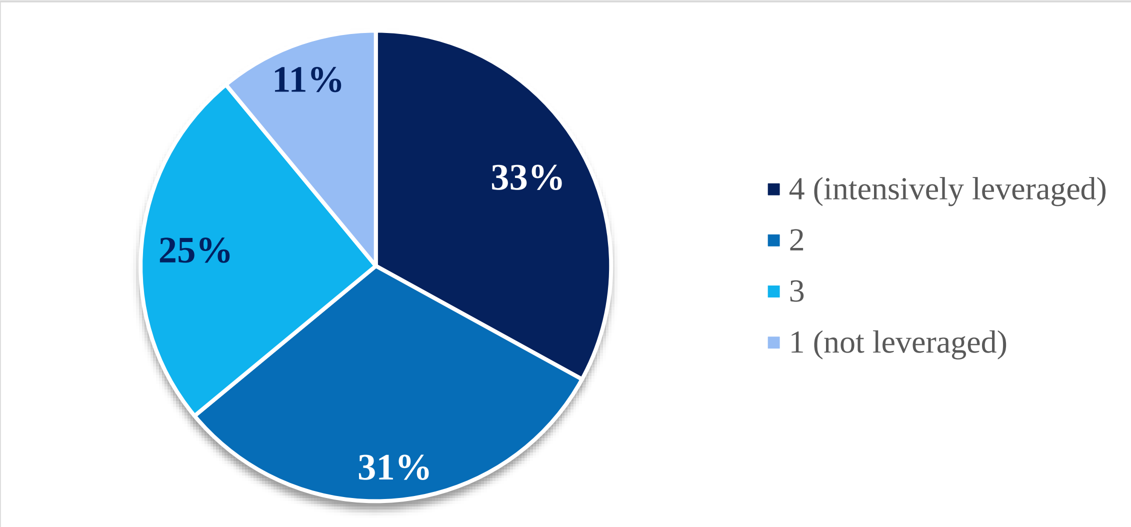

Fig. 15. Level of use of the collected data *(sample: 83 companies)*

3.1.8 ACTIVATION OF ADDITIONAL SERVICES

Further considerations can be raised starting from the results obtained to the question about the activation of services additional to the ones provided by the implemented Industry 4.0 IoT-enabled solution. The activation of push notification services in order to be informed in case of occurrence of specific events (plant or machine downtime, critical temperature or pressure conditions, gas leakage, etc.) turned out to be the additional service preferred by participants. The addition of ‘Predictive maintenance’ and ‘Energy management’ services, instead, obtained similar results, respectively registering 21% and 20% of the total answers. Although experts consider them the additional service that will be activated the most in the next future, pay-per-use resulted is still not widespread among manufacturers (Fig. 16).

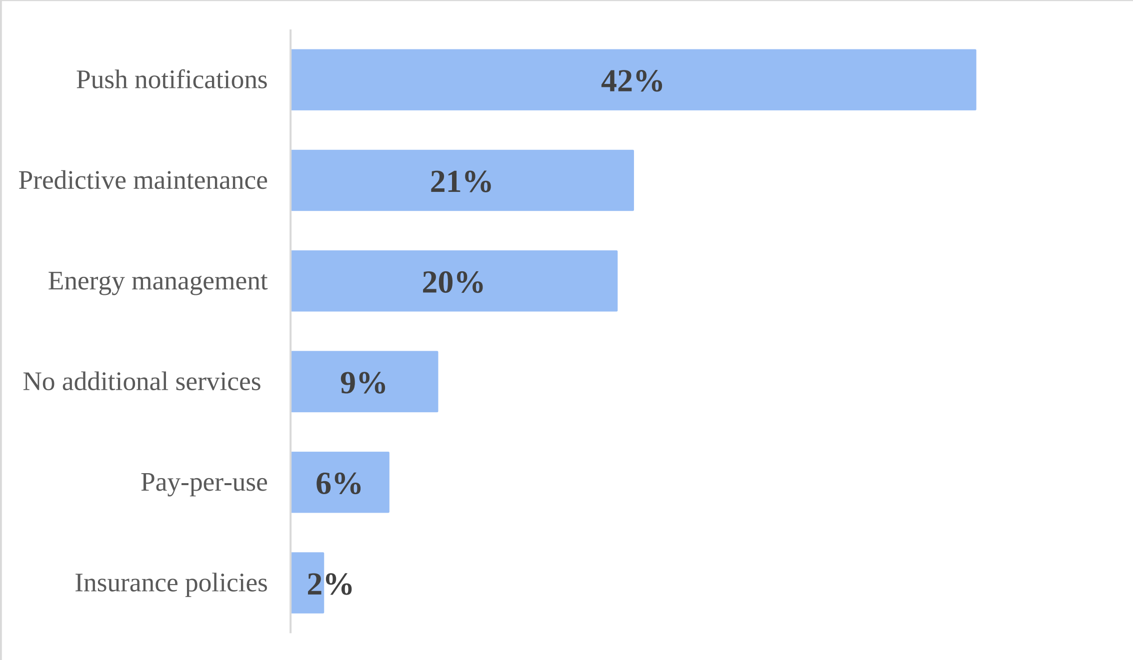

Fig. 16. Activation of additional services *(sample: 114 companies)*

3.1.9 FINANCIAL PERSPECTIVE

In this respect, the launch of the survey allowed the IoT Observatory of Polytechnic University of Milan to examine also the financial perspective of a Smart Factory IoT-enabled project. As previously argued in the introductory chapter, the overall costs that a company must pay to implement an Industrial IoT solution can heavily weight on its financial statements and many times can exceed the budget allocated to IT expenditures, that usually is around 10-15% of the amount of annual income that companies decide to reinvest to keep their businesses competitive. Besides the initial investment to acquire the IoT device from external vendors and upgrade the legacy equipment to facilitate the digital transformation, manufacturers need to sustain different operating costs throughout the entire life cycle of the project to run the service ranging from solving technical problems and repairing faulty devices to paying power and connectivity bills. 32 companies answered the last question of the survey in which the respondents were asked to provide further details (starting date, IoT technologies adopted, incurred costs) of the projects they implemented in their Smart Factory. Concerning the expenditures, a distinction was made between the initial investment to launch the project and the operating costs to run day-to-day activities. The average values of these costs resulted around 447 k€ for the initial investment and around 10,6 k€ for the operating costs.

3.2 TELEPHONE INTERVIEWS

As previously anticipated, 17 companies among those that participated in the survey gave their availability for an individual phone interview during which they deeply detailed their Industry 4.0 projects and provided their expert opinion with regard to further questions of researchers. The questions that were most frequently asked concerned:

- the role played by the Internet of Things (IoT) in the launched project;
- the major barriers faced during the implementation phase;
- the current stage of the project in its lifecycle (preliminary analysis, pilot or executive);
- the difficulties in accessing the Industry 4.0 National Plan fiscal incentives and the role of this latter in stimulating the company to start the digital transformation;
- the maturity of the technologies currently available on the market and the overall ability of suppliers to satisfy the manufacturers' requests;
- the willingness to launch other Industry 4.0 projects in which the Internet of Things (IoT) is the key enabling technology;
- the level of use and processing of the data gathered thanks to the implemented project.

The realized interviewed enabled to examine some relevant aspects related to the launch of IoT-enabled Industry 4.0 projects, some of which already emerged from the survey and discussed in the previous chapter.

About the barriers that a company can face during the development of this kind of projects, the insights obtained thanks to the individual interviews are consistent with the results achieved during the survey. In addition to the economic efforts that an Industry 4.0 requires, the interviewed companies agree that another great obstacle to face is represented by the human resources. Almost all the interviewed companies believe that the cultural barriers constitute a great hurdle to the success of the project. With the digitalization of the manufacturing activities, the employees working in the technical and productive area must necessarily interact and collaborate with the IT department. The transition from a system in which there were departments that worked independently and provided sequential services to one that implies interconnected activities and demands a continuous information sharing, necessarily causes organizational frictions. Moreover, Industry 4.0 requires internal competences able to manage these complex projects, but manufacturers encounters difficulties in finding qualified and skilled workforce already prepared to face the challenges that the digital transformation presents. An additional element of challenge is represented by the necessity of introducing changes of this magnitude in working contexts already under pressure that demand the achievement of high-performance targets. The solution to this issue is to proper manage the process of change establishing specific roles (project champions, sponsors, change agents, etc.) responsible to effectively communicate the objectives that the organization aims at achieving by means of the underlying project and stimulate the commitment by the people. In order to overcome the internal resistances to change, several actions can be undertaken: training, communication, evaluation and encouragement systems or command, if strictly necessary.

Concerning the role played by the Industry 4.0 National Plan as driving force, in the majority of the cases interviewees affirmed that it was certainly a great opportunity to save money and broaden the scope of the project, but the desire to innovate existed also before the approval of the Plan. A successful innovative project, in fact, can not abstain from a structured and strategic motivation from the management and launching a project of such magnitude without an executive control necessarily leads to failure. Therefore, the fiscal incentives provided by the Plan, above all the super and hyper depreciation, certainly constitute an element of high attractiveness and many firms adjusted some aspects of their projects to meet the established requirements and gain access to them, but they do not represent the

only reason to launch such projects. Many firms devoted the financial resources obtained thanks to the Plan to further extend the investments they already sustained to other machines and equipment located in the Smart Factory.
Another topic that caused not a few complaints by manufacturers is the inadequate offer of solutions currently available on the market. Usually manufacturers do not develop internally Industry 4.0 solutions and are forced to rely on third parties to start a project of this genre. Nevertheless, interviewed companies affirm that, at a technological standpoint, the solutions available on the market are not standardized and the providers often are not able to supply what manufacturers require. Although an increasing number of manufacturing firms are making their move towards the fourth industrial revolution, the level of readiness of providers is inadequate. To make an Industry 4.0 project succeed, companies have to build collaborative partnerships with system integrators and consultancy firms and develop the solution that mostly suits their needs.

To summarize, the major topics that emerged from the individual interviews are the following:

- the need to rearrange the organizational structure and integrate departments (IT and OT) that previously worked independently and the lack of workforce properly skilled for the Industry 4.0 constitute the main obstacles to the success of an IoT-enabled project that aims at transforming the manufacturing processes of a company;
- the fiscal incentives provided by the Industry 4.0 National Plan represent an attractive opportunity to save money and, therefore, enlarge the scope of the project;
- the solutions currently available on the marketplace are inadequate to satisfy the increasingly complex requirements of the manufacturers.

In the boxes provided below, the interviews related to the most interesting projects are briefly described.

Box. 1: Adige Spa - Material handling

Adige Spa has recently launched a pilot project through which it intends to create a Digital Twin of the materials being processed within the plant and trace their logical flow across the entire production line. The purpose of the project is to reduce the amount of material circulating in the production site and avoid losing products. During the interview the company stated that the main factor that causes efficiency loss is the amount of time that is employed to manage the logical flow of materials, in addition to the set-up time needed to prepare the machine. Adige Spa recognizes the potential of the IoT to create a new source of value and strengthen the experience of its customers along their purchasing process. The company plans to make the information gathered available and transparent to its clients in a 'Servitization' perspective in order to keep them constantly informed about the progress status of their order.

Box. 2: Bosch - Material handling

With the purpose of automating the material handling process, the company decided to embrace the Industry 4.0 paradigm. To achieve this aim, it launched a project intended to interconnect the different assembly lines and collect all the necessary information related to the movements of the processing units across the line. Moreover, the new system adopted enables the company to monitor across time some physical parameters (the pressure, the torque, etc.) of the process and evaluate if it is stable or it is experiencing changes or, even, deteriorating. The company is now seeking to develop a predictive model to early detect production issues and prevent downtimes.

Box. 3: Bayer - Production management

In the production facility located in Garbagnate, the company has recently launched a pilot project through which it aims at introducing the IoT in the processes related to the production. To reach this goal, Bayer connected the Information Systems, the machineries and everything that generates data in a unique, large database fuelled by powerful algorithms. A particular attention was deserved to the packaging line that was equipped with a large number of sensors, thanks to which production supervisors can monitor the functioning of the shop floor machines. The project was further extended also to the concept of predictive maintenance, aiming at managing the deterioration of the machines in an efficient manner. By means of this project the company envisions to support the decision-making process and predictively identify the root causes of any issue occurring at the production line level.

Box. 4: Forge Monchieri - Predictive maintenance

The company developed a system able to gather data from sensors embedded sensors placed on the industrial ovens, more in detail on the thermocouples that measure the temperature parameters in the heating and heat treatment phases and display them with advanced visualization tools. The supervisor, or his subordinate, can access this data and monitor in real-time the functioning of the machine. The real value of the system, however, lies in its ability to autonomously trigger maintenance process anticipating the actual occurrence of failures so that the company can save time and financial resources.

Box. 5: Sew Eurodrive - Material handling

The company internally developed a system for the real time traceability of an assembly order that enables any member of the organization to monitor the progress status of each order and the location of each production unit. The project refers also to the vehicles and machineries that become in practice the actual owners of information. This enables the company to gain a comprehensive understanding in real time of how the vehicles are moving, where they are exactly and what they are carrying. The future ambition of the company, that is currently a testing phase of the project, is to implement a predictive maintenance strategy through which critical process and technical parameters are monitored and remedial actions are autonomously activated in the cases of failure and malfunctioning.

Box. 6: Vitec - Quality assurance

The company is heavily investing in initiatives that can transform its manufacturing process. The projects that leverage the IoT as enabling technology are focused on two aspects: the management of the functioning of the shop floor machines and the quality control of the production units. With regards to the first subject, the aim is to compute the productivity of the machines, the OEE, and allow the production line workers to access the resulting information. To reach this goal, the company substituted a large portion of its compressors with others equipped with advanced sensors that enable to monitor their functioning performance, but also their energy consumption. Then, the company is planning to equip the machines designed to assess the quality of the processing production units with sensors so that they can autonomously evaluate the control charts and deviation events.

Box. 7: Whirlpool - Production management

The company is dealing with the concept of Industry 4.0 with the purpose of gaining a comprehensive view in real time of the operations that are executed in its plants, spread all over the world. To reach this objective, it has recently launched two pilot projects, one in Slovakia and the other in Poland, but in 2019 it is planning to implement similar projects in its Italian production sites. The project consists of interconnecting the shopfloor machines with the ERP in order to optimize the production scheduling. By means of these projects the company can monitor in real time some process parameters in detail and control the efficiency of the shop floor machines, measuring their OEE but also their energy consumption. This last aspect is performed at the machine level, but the company is planning to evolve it at subsystem level, that is the overall factory. Moreover, preliminary studies are carried out with regards to the topic of predictive maintenance.

4 FRAMEWORK

The aim of this work is to depict how companies operating in the industrial sector and embracing the Fourth Industrial Revolution are leveraging the Internet of Things (IoT) in their Smart Factories to gain business benefits and create additional value to their customers. In order to accomplish this purpose, it has been developed a qualitative framework that aims at providing a comprehensive perspective of the different applications of the Industrial IoT within a Smart Factory. The model offers an immediate interpretation and understanding of a phenomenon that is expected to disrupt the overall manufacturing sector.

The proposed diagram (Fig. 17) consists of two dimensions that represent two fundamental aspects of an IIoT system applied in a Smart Factory. On the vertical axis, the 'Network Complexity' variable indicates the amount of end nodes that are connected thanks to the Industrial IoT paradigm. On the horizontal axis, instead, the 'Synergism' variable defines the extent to which the solutions leverages the Industrial IoT, which is the main enabling technology of the solution in question, and the other Industry 4.0 enabling technologies.

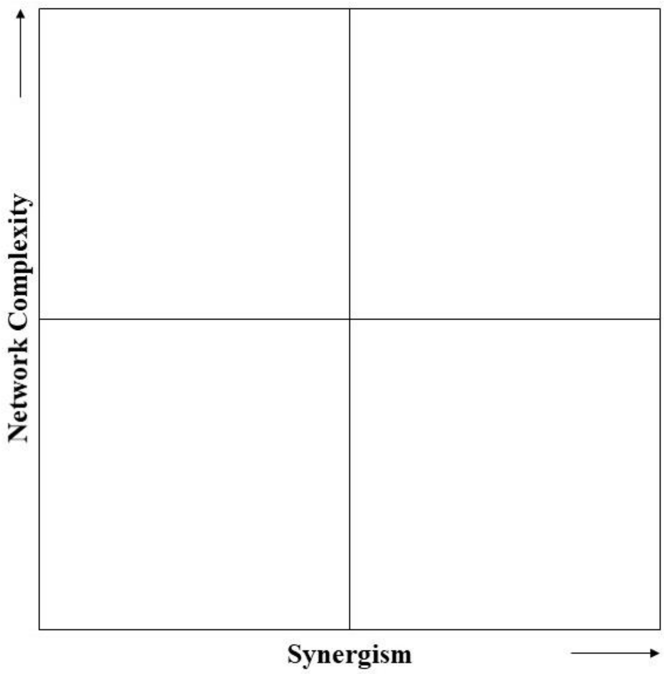

Fig. 17. Framework

The two variables are not necessarily independent: a solution that deploys a large fleet of IoT-connected AGVs to move materials implies a network constituted by a large number of end nodes; the same reasoning stands for a solution that displays an alert on wearable devices. To follow, these two dimensions will be largely discussed. In the next chapter, several stories of manufacturing companies that successfully implemented an Industrial IoT-enabled solution in their Smart Factories will be presented. These best practices, two for each Industrial IoT applications within a Smart Factory, will be then studied with the support of the proposed framework in order to illustrate in detail how the matrix works and assess its robustness by verifying the uniformity of the dispersion of the items within the model. The Industrial IoT real-world applications will refer both to Italian and foreign companies in order to be able to compare the couples of cases and generalize the different applications, fixing a qualitative centroid of them. Finally, the advantages and the limitations of the proposed framework will be considered and areas for further improvement will be identified.

4.1 DESCRIPTION OF THE DIMENSIONS

4.1.1 SYNERGISM

Industry 4.0 is driven by the combination of some major technology innovations, the ‘Smart Technologies’, that contributed to significantly disrupt the landscape of the manufacturing industry. The industrial companies benefit from the resulting inter-connection and cooperation of their resources (physical assets, people and information) to drastically improve their business efficiency and be more competitive. Extending the discussion started in the introductory chapter, the technology trends that facilitated the transformation of the industrial production and, therefore, led to the beginning of the Fourth Industrial Revolution are[26]:

- Industrial IoT;
- Industrial Analytics;
- Cloud Manufacturing;

[26] https://blog.osservatori.net/it_it/industria-4-0-quarta-rivoluzione-industriale#tecnologie

- Advanced Automation;
- Advanced Human-Machine Interface (HMI);
- Additive Manufacturing.

In order to reap the greatest return from the Industry 4.0 paradigm, these technologies might be integrated into interconnected and autonomous systems so that they can freely cooperate and communicate amongst and across each other. The future of manufacturing, in fact, is in finding the most suitable junction between these high-tech tools and learning how to tie them together as a whole system. The full potential of the 'industrial Internet' will be reached when these ‘Smart Technologies’ fully merge with the physical assets[27].

On the horizonal axis of the proposed framework, the ‘Synergism’ dimension indicates the level of cooperation and interaction that occurs in the solution in question between the Industrial IoT and the other Industry 4.0 enabling technologies. In this way, solutions and applications in which the IoT works together with other ‘Smart technologies’ of the Industry 4.0 and whose outcome strongly depends by the proper functioning of this junction will be assigned with high values of ‘Synergism’. On the contrary, solutions and applications that leverage the IoT without the support of other Industry 4.0 enabling technologies will be associated with low values of ‘Synergism’. This dimension does not consider the number of technologies that work together but, rather, the synergism of them in their practical use.

The binomial Industrial IoT and Industrial Analytics immediately comes to mind. The increasing use in the industrial sector of devices equipped with sensors and connected each other led to the creation of massive amounts of data that forced manufacturers to adopt advanced tools to extract valuable information and support decision-makers. The use of the IIoT technology in the manufacturing floor, in fact, is not limited to the remote control of some specific industrial parameters or the tracking of products and handling systems within the production line, but it

[27] https://www.industryweek.com/systems-integration/ge-says-industrial-internet-could-be-worth-trillions

evolved, and the connected sensors attached to the physical assets use machine learning and artificial intelligence to predict occurring scenarios and autonomously take corrective actions. Through predictive maintenance, for example, connected sensors can early detect if the machine is likely to breakdown or enter a dangerous operating condition and proactively trigger a maintenance request.

IIoT-enabled solutions also leverage the Cloud paradigm and Edge Computing to analyse data in external servers and access various resources on-demand. Cloud Manufacturing enables spread, agile and on-demand access to a collection of resources that support the production processes and the Supply Chain management. Cloud Manufacturing solutions integrate multiple cloud resources to provide users with a one-stop platform for building industrial IoT applications. They enable the existing or newly developed industrial devices to quickly access the cloud platform and synchronize the collected information to realize data interworking between devices and between devices and systems helping enterprises to quickly learn the running status and real-time production capacity of devices[28]. Moreover, these solutions provide the software platform of the edge computing gateway that obtains the device information and offers powerful capabilities such as real-time computing and instant parameter optimization.

The IoT also impacted on Industrial Automation in the measure that manufacturing companies are connecting to the Internet an increasing portion of their factory robots in the prospect, for example, of implementing preventive maintenance and inhibit assembly line interruptions and downtimes. Within a manufacturing facility, material handling and transportation represent major activities in the production process and Automated Guided Vehicles, or AGVs, are increasingly demanded on the marketplace because they prevent manufactured product or raw materials from being damaged and increase workplace safety avoiding accidents that may cause harm to the workers. IoT-based AGVs communicate all the information regarding transporting material [54] (description, batch, quantity, etc.)

[28] https://medium.com/@Alibaba_Cloud/alibaba-cloud-industrial-iot-platform-for-industrial-manufacturing-d442aa7c941

and allow manufacturers to monitor in real-time all the operations being performed in the production system effectively reporting bottlenecks.

The world of connected devices in the Industrial Internet of Things (IoT) is hugely related also to the Human Machine Interface (HMI) tools. User interfaces in industrial controls evolved significantly in recent years, moving from dumb terminals and simple LED indicators to graphical touchscreen displays, phone and tablet apps and wearable devices. Therefore, a key element of an IIoT-enabled projects becomes data visualization: operators and supervisors have the possibility to rapidly access all the necessary information about the state of the equipment and the progress of the production directly from their workstation through touchscreen totems installed on-board machine in the workstation or from anywhere they find through wearable devices and mobile apps. With the proliferation of connected devices, control engineers persistently demand to access plant processes and equipment conditions from any location on any device. They expect the HMI to go beyond read-only capabilities and information visualization to become a control panel in their pocket that offers them the possibility to interact and communicate with the plant equipment directly from their handheld devices[29].

The combination of the IoT with the Additive Manufacturing (3D printing) in the context of Smart Factory is quite an unexplored issue but it is attracting the attention of an increasing number of researchers. The major advantage of adopting 3D printing in manufacturing is that it uses only the material that is strictly necessary to build a product making possible to design lower cost, but also more complex, products while obtaining a substantial reduction in the industry's ecological footprint. At the moment, the meeting point between the IoT and the Additive Manufacturing lies outside the production facility perimeter. The information gathered from sensor-embedded products along its lifecycle provide manufacturers a design feedback and a better understanding of product performance enabling them to use these data to create custom-made products, even more accurate if printed thanks to Additive Manufacturing. In the context of Smart

[29] https://www.designnews.com/automation-motion-control/hmi-challenges-industrial-iot-world/213642922259598

Factory, manufacturers are embedding the milling machines, as well as similar arrays of injection molding presses and 3D printers, with connected sensors to use the data collected to track the progress of orders and help optimize scheduling[30].

4.1.2 NETWORK COMPLEXITY

The second dimension proposed by the framework is called 'Network Complexity' and it is measured by the number of end nodes that constitute the IIoT-enabled solution. This variable aims at evaluating the grade of geographical dispersion of sensing devices within the production facility. In this way, solutions and application whose architecture consists of a considerable number of end nodes will be classified with high values of 'Network Complexity'. On the contrary, solutions and application whose network is composed of few end nodes will be classified with low values of 'Network Complexity'.

The Industrial IoT allows manufacturers to create an intelligent networking of manufacturing devices ranging from individual shop floor machines to entire production facilities. From an architectural perspective, an Industrial IoT environment is a complex system formed by several types of nodes: sensing, local and remote embedded processing nodes, connectivity, edge, etc. For the sake of simplicity, this dimension refers only to the number of physical IoT-connected devices belonging to the network and interacting each other over the Internet. They include sensors attached to the physical assets, human machine interfaces (HMIs), smart meters, actuators, security equipment, wearable and mobile devices, controllers, etc. At the core of any IoT environment there are sensors, whose relevance has been already discussed in the Introductory chapter, that collect data and transmit them across the network. This data then gets interpreted by dedicated software and enables the solution to perform the task for which it was designed. The system that originates is the combination of cyber and physical systems and enhances the interaction among machines, devices, products, sensors, processes and people.

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[30] https://www.sculpteo.com/blog/2018/07/25/iot-and-3d-printing-how-to-combine-these-two-technologies-to-build-better-products/

As already explained at the beginning of this chapter, the two variables that constitute the framework can somehow relate each other. Specifically, high values of ‘Network Complexity’ are registered when the solution leverages Advanced HMI (e.g. wearable devices) or Advanced Automation (e.g. Automated Guided Vehicles, or AGVs) technologies.

4.2 DEVELOPMENT OF THE FRAMEWORK

With the purpose of illustrating how the framework works, twelve exemplary application of the Industrial IoT in a context of a Smart Factory will be studied in relation to it. Specifically, each best practice will be discussed and the relative position within the proposed framework will be properly justified. The selected best practices were obtained by secondary sources. For each IIoT application in the context of a Smart Factory, a couple of model case studies are discussed. It has been decided to present one half of the best practices belonging to Italian companies and the other half belonging to foreign companies in order to offer a wider perspective of the discussing topic.

Below it is presented a table (Table 2) containing the list of the selected companies that successfully implemented an IoT-enabled project in their Smart Factories.

	ITALY	**FOREIGN**
Production management	Valmex	Hirotech
Predictive maintenance	Paglieri	Fanuc
Quality assurance	Brovedani	General Electric
Material handling	Marcegaglia Group	Saint-Gobain
Workplace safety	TWL	North Star
Energy management	Patheon	Festo

Table 3. List of companies that successfully implemented IoT-enabled projects in their Smart Factories

4.2.1 PRODUCTION MANAGEMENT

ITALIAN SCENARIO: THE EXPERIENCE OF VALMEX

Company profile			**Project**		
Country	*Sector*	*Size*	*Year*	*Stage*	*Facility*
Italy	Manufacturing	Medium	2017	Executive	Cartonceto, Italy

Valmex is one of the main producers of copper, aluminium and stainless-steel heat exchangers for gas boilers and is present with its heat exchangers in the industrial refrigeration for several applications. The company employs 350 workers and its revenue reaches € 70 mln.

In 2017 they opened a new production site, completely devoted to the production of CIRCOND, a single stainless-steel coil heat exchanger with a high technological value. The plant was designed to meet the requirements of Industry 4.0 and robotics, automation and data analysis work together to ensure the maximum visibility of the operations[31]. Thanks to this 'iperconnected' factory, Valmex is able to monitor in real time each stage of the production process assessing the performances of the machineries located in the shop floor, monitoring, for example, the temperature of the industrial ovens used to produce the heat exchangers and receiving alerts in case of malfunction. In this way, the company acquired a great visibility of the process and is able to track the product flow in real-time. Moreover, the company can certify the origin of each component of the heat exchangers realized in the new plant by means of state-of-the-art sensors and an extremely flexible software able to storage and handle massive amounts of data. Initially, the company launched a pilot project in a single production facility and, thanks to the benefits reaped, especially in terms of efficiency, it extended it to the its other plant located on the National territory.

[31] http://www.ansa.it/industry_4_0/notizie/storie_impresa/2018/08/08/valmex-uno-stabilimento-iperconnesso_377c4c70-1623-4f41-be3f-4e22485d4ff1.html

In the description of the case, all the elements necessary to position the adopted solution in the qualitative framework proposes in this work are well highlighted.

With the purpose of ensuring the greatest visibility of the operations that occur in the production line, the solution leverages the Industrial Internet of Things (IIoT) in cooperation with two other Industry 4.0 enabling technologies: the Industrial Automation and the Industrial Analytics. The project, however, does not contemplate elements of artificial intelligence and does not use Advanced HMI, such as wearable devices or mobile apps, that is the reason for which it does not achieve the highest values of 'Synergism'.

In relation to the number of nodes included, the resulting network of the studied solution can be considered rather complex. The solution, in fact, allows Heads of Production to monitor the critical parameters of the shop floor equipment and enables a full traceability of the components being processed. In conclusion, also the 'Network Complexity' axis registers rather high values.

FOREIGN SCENARIO: THE EXPERIENCE OF HIROTEC

Company profile			**Project**		
Country	*Sector*	*Size*	*Year*	*Stage*	*Facility*
Japan	Automotive	Large	2017	Executive	Detroit, USA

Hirotec Group is a Japanese corporation, leading the global automotive market by providing high quality doors and exhaust systems. It owns 26 facilities spread in nine countries around the world.

With the advent of Industry 4.0 models, the company realized that the implementation of Smart Factory innovations would have ensured the continuity of its manufacturing operations and minimized unplanned downtime in its production facilities. So, in partnership with Hewlett Packard Enterprise (HPE) and PTC, the company integrated its manufacturing systems with an IoT platform[32].

In order to successfully implement this solution, Hirotec completed three pilots. The first enabled the company to capture and analyse data from eight computer numerical control (CNC) machines in its production plant located in Detroit. The following pilot made Hirotec able to perform remote visualization of an automated exhaust system inspection line collecting data from inspection robots, force sensors, laser measurement devices and cameras. Thanks to the third pilot, finally, the system performs real-time visualization and automatic report generation for the entire production line of an automobile door production facility.

Through the pilots, Hirotec gained real-time visibility into its business operations, which allows the company to rapidly detect issues that impact its efficiency and throughput. Moreover, the solution also equips critical systems, like its exhaust system inspection lines, with machine learning and predictive analytics to predict and prevent failures and tackle unplanned downtime.

From the perspective of the Industry 4.0 enabling technologies that the IoT-enabled solution leverages, the one that collaborates the most with the Industrial IoT is, without any doubt, Industrial Analytics. The solution, in fact, in addition to processing data to provide predictive and preventive indications, performs also analyses of historical data with the purpose of monitor production facility performance and identify new ways to drive improvements. Moreover, the solution takes advantages also of Industrial Automation as IoT-connected sensors are embedded in inspection robots operating in the automated exhaust system inspection line.

With regard to the complexity of the network that is generated, in addition to place smart sensors on the inspection robots located in the automated exhaust system inspection line, the solution aims at connecting the entire production line of a

[32] https://enterpriseiotinsights.com/20171106/smart-factory/hirotec-adopts-smart-factory-concept-eliminate-unplanned-downtime-tag23-tag99

production facility. The result of this operation will be that of making the network of things extremely complex.

In the diagram below (Fig. 18), the two experiences are examined in relation to the diagram proposed in this work.

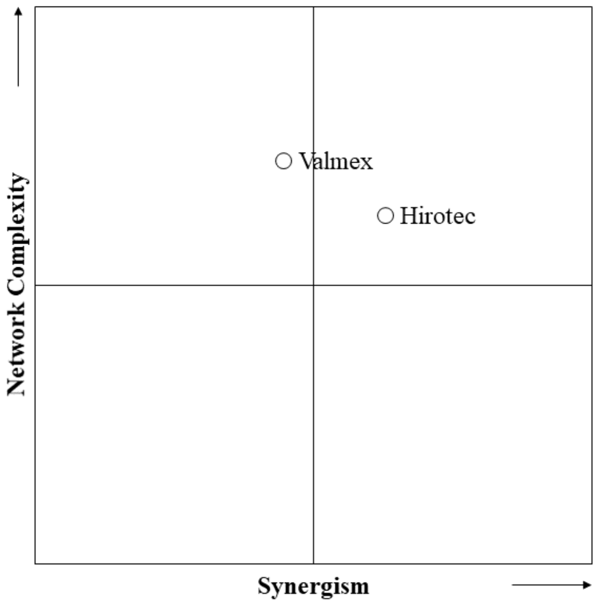

Fig. 18. Analysis of the 'Production management' IIoT applications in relation to the proposed framework

4.2.2 PREDICTIVE MAINTENANCE

ITALIAN SCENARIO: THE EXPERIENCE OF PAGLIERI

Company profile			**Project**		
Country	*Sector*	*Size*	*Year*	*Stage*	*Facility*
Italy	Chemical	Medium	2018	Executive	Alessandria, Italy

Paglieri is historic Italian company leader in the personal and household care sector and that markets its products, among which stands out the well-known Felce Azzurra brand, in over 50 countries.

Last year the company began a digital transformation path launching a project aimed at interconnecting the cosmetic packaging plant on the basis of the ‘Connected Manufacturing’ paradigm. In order to accomplish this purpose Paglieri realized the revamping of the line focused on the production of the bath foam of Felce Azzurra and installed from scratch a production line equipping it with the most innovative solutions in terms of connectivity and data exchange[33]. For its implementation the company entrusted two excellent technology providers such as Cisco and Alleantia adopting the 'Easy Connect Machines' solution designed by Cisco. Thanks to this project the machines interact with the company's systems, exchanging information that allows them to make intelligent decisions and harmonize business processes[34]. In this way the industrial systems of Paglieri are networked allowing the company to collect valuable information to optimize the production process, monitor the performances of the shop floor machineries or remotely manage their functioning. The resulting production system is comprised of machines able to autonomously predict failures and trigger maintenance services when needed.

The solution meets the requirements of the National Industry 4.0 Plan and allowed the company to access to expected fiscal benefits. Moreover, the company increased the visibility of the KPIs pertinent to the production and increased the Overall Equipment Effectiveness (OEE) across its operations.

It is extremely interesting to discuss about the solution adopted by Paglieri in relation to the framework developed in this work. The solution, in fact, leverages the Industrial Internet of Things to monitor the functioning of the machineries located in the new production line, but more importantly, it integrates elements of artificial intelligence (AI) and Industrial Analytics to enable shop floor machines to predict failures and autonomously send a maintenance service request, if critical parameters are met. In the framework proposed, a great relevance is attributed to the solutions that integrate the Internet of Things paradigm with the Artificial Intelligence so that machines can perform actions independently, without the interventions of humans. So, the solution adopted by Paglieri locates itself at high position with respect to the 'Synergism' dimension. With regard to the complexity of the network generated among "things", the number of nodes needed to

[33] https://www.alleantia.com/paglieri/
[34] http://www.italtel.com/success-stories/paglieri-industry-4-0-is-already-a-reality/

successfully implement this solution is extremely high. Even though this project does not integrate the IoT with industrial automation aimed at handle materials, that would have made the resulting network even more branched and dynamic, the connection is established among production line machineries, Head of Production and machines suppliers that can constantly access the functioning parameters of machines and intervene when needed.

FOREIGN SCENARIO: THE EXPERIENCE OF FANUC

Company profile			**Project**		
Country	*Sector*	*Size*	*Year*	*Stage*	*Facility*
India	Robotics	Large	2016	Pilot	USA

Fanuc is a Japan-based manufacturing company engaged in the design and production of factory automation machineries.
The company aggressively embraced the concept of predictive maintenance with the purpose of reducing downtime in its customers' industrial facilities. In partnership with Cisco Systems, the company decided to connect its industrial robots to a system to ensure their proper functioning and know in advance if a failure of a component is going to happen[35]. By means of this solution, that was already tested in a pilot project by a major automotive manufacturer, IoT-connected sensors transmit all the relevant data to the Cisco Cloud, where the Cloud analytics process the information received and predict the need for maintenance. Therefore, in the case that a pending issue is detected, the system promptly notifies the customer and the charged service team, so that replacement parts are ordered, and maintenance service personnel is sent to the site to help the customer prevent an unexpected breakdown event. This project belongs to a wider program initiated by Fanuc that the company calls "Zero Downtime" (ZDT) aimed at minimizing downtime in factories.

[35] https://www.designnews.com/automation-motion-control/predictive-maintenance-hits-robotics-fanuc-and-cisco-team/27855732245861

Considering the placement of the solution described above within the framework proposed in this work, on the horizontal axis it can be said that the solution developed by Fanuc leverages the Industrial Internet of Things in collaboration with other Industry 4.0 enabling technologies. First, the solution considers attaching IoT-connected sensors to robotics that belongs to the category of the Industrial Automation. Moreover, it resorts to the Cloud, where data gathered by embedded sensors are sent and cloud-based analytics are performed to predict failures of robots located in customers' production facilities. Even Advanced HMI are partially leveraged since alert notifications are sent to customer and service providers through specified apps. The resulting network of sensing devices and end nodes is rather wide, as the Industrial IoT technology is in charge of connecting the industrial robots operating at the shop floor level to different actors: the operators responsible for the maintenance service, the supplier of the replacement components and the Head of Production. For this reason, on the vertical axis of the framework the solution obtains high values of 'Network Complexity'.

In the diagram below (Fig. 19), the two experiences are examined in relation to the diagram proposed in this work.

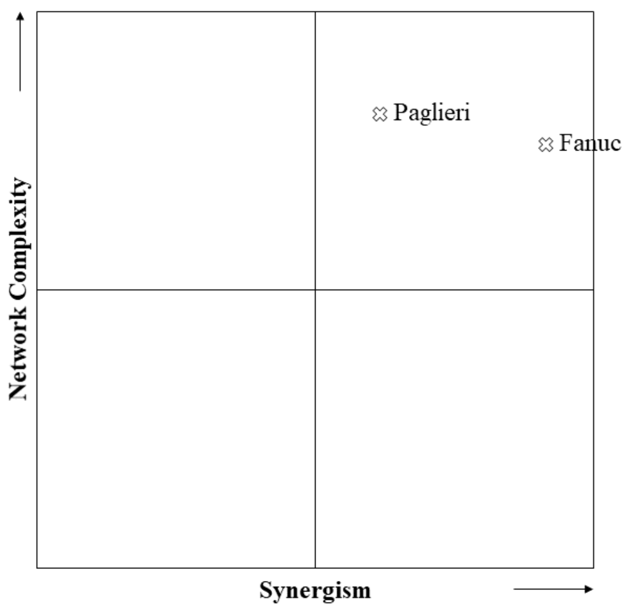

Fig. 19. Analysis of the 'Predictive maintenance' IIoT applications in relation to the proposed framework

4.2.3 QUALITY ASSURANCE

ITALIAN SCENARIO: THE EXPERIENCE OF BROVEDANI

Company profile			**Project**		
Country	*Sector*	*Size*	*Year*	*Stage*	*Facility*
Italy	Manufacturing	Large	2017	Executive	Pordenone, Italy

Brovedani is a manufacturing company dealing with the production of components devoted to the automotive sector, highly specialized in the realization of fuel and diesel common rail injection pumps. The company has 6 production sites distributed among Italy, Mexico and Slovakia and its established competence allowed it becoming the strategic supplier of multinational corporations such as Bosch, Continental, Magneti Marelli.

In 2017, the company relied on beanTech to develop a system able to monitor the superficial and dimensional quality features of the realized units. To respond to the needs of the customer, BeanTech designed a smart and scalable control station that autonomously conducts the dimensional and quality measurements with an accuracy level of the order of micron (μ). The operator can interface with it and configure it according to the specific requirements of the production process and the quality measurement. The software and hardware architecture of the solution[36] is integrated with the automation systems situated within the production plant sharing information with MES and ERP systems and tracking the production flow along all its stages. A type of control feasible thanks to this solution is the visual inspection system that, by the means of the management and the analysis of data gathered during the production process, examines the state and the dimension of the mechanical piece and sorts them in different containers according to the detected faults. In addition to reducing production wastes, the adoption of the solution designed by beanTech allowed Brovedani to continuously monitor in real-

[36] http://www.beantech.it/clienti/industry-brovedani-group/

time the performances of the machineries so as to take immediately corrective actions in the case of necessity.

The solution developed by Brovedani is quite simple in relation to the number of nodes and connections that the resulting network generates. The operators monitor the performance of the quality assurance process exclusively on-board machine and the sensing devices are grouped in a single work station, as embedded sensors refer to the quality measurement machines. The solution, for these reasons, reports low values of ‘Network Complexity’.

In relation to the ‘Synergism’ dimension, instead, the project launched by Brovedani, in addition to the Industrial Internet of Things, leverages also the Industrial Analytics, to gather and analyse the production data and monitor the superficial and dimensional quality features of the realized units, and the Industrial Automation, as it deploys advanced machines to perform quality control and inspection activities. Despite this, it does not include elements of artificial intelligence and use traditional HMI devices to display information.

FOREIGN SCENARIO: THE EXPERIENCE OF GE AVIATION

Company profile			**Project**		
Country	*Sector*	*Size*	*Year*	*Stage*	*Facility*
USA	Automotive	Large	2017	Pilot	Ohio, USA

GE Aviation, a subsidiary of the General Electric conglomerate, is among the top aircraft engine suppliers, and offers engines for the majority of commercial aircraft.

The company, in recent years, has started performing engine mechanic tests with the combined help of IoT-connected torque wrenches and Google Glasses[37]. Each torque wrench in the assembly line is univocally identified by an IP (Internet Protocol). When connected to the Cloud, the IP torque wrench captures the torque

[37] https://www.aviationtoday.com/2017/07/19/ge-aviation-engine-mechanic-tests-iot-connected-torque-wrench/

applied to a specific part, the specific wrench that was used, when that wrench was last calibrated and the employee who used it[38]. In this way, faults can be detected in real time, and, even when they're missed, the Cloud can trace every part affected back to the root cause. The solution supports operators to optimally tighten bolts while performing routine assembly and maintenance tasks. The result is increased mechanic efficiency and reduced errors at key points in the assembly and overhaul of engines, unlocking millions of dollars in savings both for GE and its customers. In general, manufacturers are increasingly integrating smart and connected tools to improve product quality and cutting down errors.

This is an IoT-enabled application that is increasingly gaining ground in the manufacturing facilities. By means of several IoT-connected sensors, GE Aviation's tools can be connected, and operators can perform assembly tasks continuously interacting with engine maintenance technicians through smart glasses. The combined use of wearables and Industrial IoT is a very interesting trend destined to transform the entire business. To this, it is important to highlight the contribution of the Cloud that allows to store relevant information and detect root causes. For this reason, the solution adopted by GE Aviation takes advantage of the collaboration between the Industrial IoT and two other Industry 4.0 enabling technologies, the Advanced HMI and the Cloud Manufacturing, obtaining high values of 'Synergism'.

Regarding the number of end node devices that are included in the IoT-enabled network, the system results averagely branched. In fact, the sensing nodes are located mostly in the work station enabling the dynamic connection among the smart tools and the aircraft engine being processed. In case of need, the operator can also ask for the remote support of expert technicians. The generated system results averagely complex indeed obtaining average values of 'Network Complexity'.

[38] https://www.cio.com/article/2910736/manufacturing/four-ways-the-internet-of-things-will-change-shop-floor-control.html

In the diagram below (Fig. 20), the two experiences are examined in relation to the diagram proposed in this work.

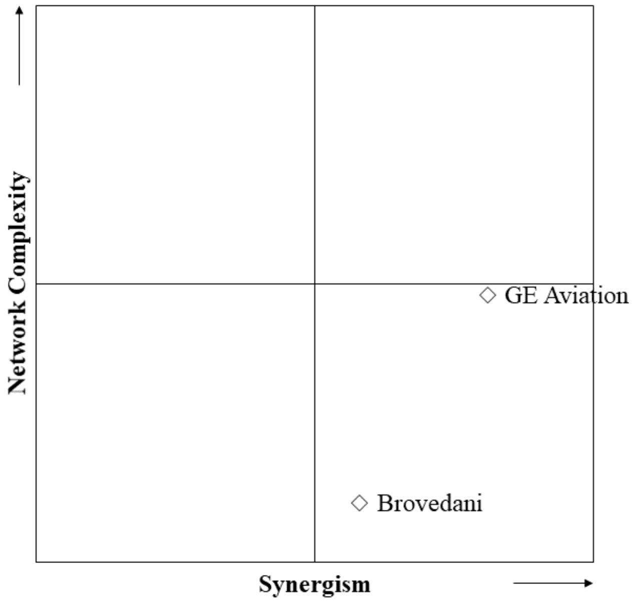

Fig. 20. Analysis of the 'Quality assurance' IIoT applications in relation to the proposed framework

4.2.4 MATERIAL HANDLING

ITALIAN SCENARIO: THE EXPERIENCE OF MARCEGAGLIA

Company profile			**Project**		
Country	*Sector*	*Size*	*Year*	*Stage*	*Facility*
Italy	Manufacturing	Large	2009	Executive	Ravenna, Italy

Marcegaglia is an Italian industrial group operating in the steel processing sector, with operations and production plants spread all over the world.

In 2009, the Group decided to launch two industrial automation projects[39] in its plants located in Ravenna and Casalmaggiore. These projects aimed at introducing automated systems in all the handling operations, referred at moving both raw materials and finished products, along the entire production process. To reach this

[39] https://www.cisco.com/c/it_it/about/news/2017-archive/20170210.html

purpose, the company decided to rely on ‘Cisco Connected Factory’, thanks to which it managed to develop a wired and wireless architecture able to exchange data and information with the new machineries integrated in the production plants. Concerning the plant located in Ravenna, the company introduced a fleet of Automated Guided Vehicle (AGV), in charge of handle the coils across the different work stations and towards the loading points for the final shipment. About the plant located in Casalmaggiore, instead, it was implemented a complex of bridge cranes in charge of stocking the pipes picked directly from the shop floor and loading them into the trucks. Both the AGVs and the bridge cranes receive and transmit data between each other and with the central system that issues missions and manages the fleet of connected machines. In this way, the solution enabled an endless communication between the automated machines, the PLCs and the system and the company benefitted from the improved production processes and enhanced competitiveness.

The generated network of end nodes that results from the adoption of the solution is extremely extended and it includes the fleets of AGVs, the various bridge cranes, the PLCs and the central system. The selected architecture enables the complete integration of the plants to the environment of business network. For this reason, the solution achieves high values of ‘Network Complexity’.
Concerning the ‘Synergism’ dimension on the horizonal axis of the framework, the solution integrates in a model way the Industrial IoT and the Industrial Automation technologies. In both the solutions adopted in the two production plants, in fact, the automated systems are connected to the central system with which they continuously communicate and exchange relevant information. Moreover, the IoT-connected sensors enable to monitor the localization of the AGVs within the manufacturing facility.

FOREIGN SCENARIO: THE EXPERIENCE OF SAINT-GOBAIN

Company profile			**Project**		
Country	*Sector*	*Size*	*Year*	*Stage*	*Facility*
France	Construction	Large	2019	Executive	N/S

Saint-Gobain is a French multinational corporation that designs, produces and distributes materials and solutions for the construction sector. Today, the Group boasts an international presence in 67 countries, employing about 179.000 staff and accounting a total turnover of € 40.8 billion.

In recent years, the Group decided to become active in the Industry 4.0 field, to the extent that all its Business Units defined their implementation strategy, with respect to their global strategies and markets. In this context, it's worth mentioning the project that the Group developed in collaboration with Oppent, an innovative company operating in the advanced motion technology sector. By means of this project[40], Saint-Gobain intends to automate the handling process of the finished abrasive wheels from the robot cell towards the finished products warehouse and, at the same time, the supplying of the cell with the rough wheels coming from the semi-finished products warehouse. The technical solution identified was to provide the plant with an EVO cart system able to handle special racks containing abrasive wheels in a finished or rough state and constantly interact with a robot cell. The robot is equipped with Industrial IoT-enabled sensors that enable it to sense and perceive the surrounding environment, respond to the highest standard of human and machine safety and communicate in real-time to the central system their exact position and route within the production floor. In this way the internal logistic activities managed by humans will be reduced at the minimum, allowing a non-stop activity of the robot cell. The project delivery is planned to be in March 2019.

The solution consists of equipping the AGV (Automated Guided Vehicle) with IoT-connected sensors in order to fully trace the material handing activity and

[40] https://www.oppent-evo.com/en/case_history/production-of-building-materials-for-the-construction-industry/

establish a real-time communication between the robot and the central Information System. In this sense, the solution developed by Saint-Gobain effectively leverages the Industrial IoT with another Industry 4.0 enabling technology, the Industrial Automation. The Industrial IoT paradigm plays a relevant role enabling the system to collect meaningful data and communicate them farther up the automation hierarchy. Therefore, considering the framework proposed in this work, on the horizontal axis the solution obtains high values of ‘Synergism’.

With the regard to the complexity of the resulting system, the solution envisages the connection of a single AGV robot that communicates the data gathered to the central system. In comparison with other similar applications enabled by the Industrial IoT, which envisage the interconnection of entire fleets of automated vehicles aimed at handling raw materials, semi-finished and finished products, the ecosystem generated by the underlying solution results reasonably linear and consisting of few end nodes. For this reason, the solution obtains low values of ‘Network Complexity’.

In the diagram below (Fig. 21), the two experiences are examined in relation to the diagram proposed in this work.

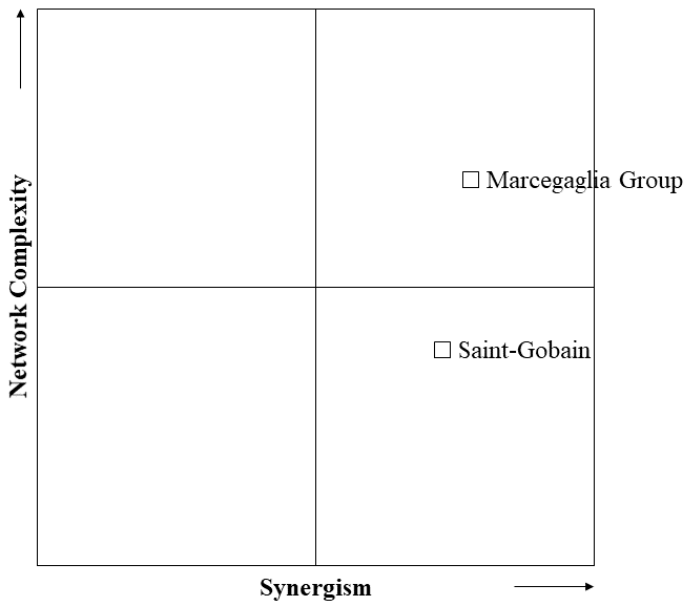

Fig. 21. Analysis of the 'Material handling' IIoT applications in relation to the proposed framework

4.2.5 WORKPLACE SAFETY

ITALIAN SCENARIO: THE EXPERIENCE OF TWL

Company profile			**Project**		
Country	*Sector*	*Size*	*Year*	*Stage*	*Facility*
Italy	ICT	Small	2018	Preliminary analysis	Udine, Italy

TWL System is an innovative start up, founded in October 2015, that offers high-tech products and services aimed at optimizing the industrial processes.

In 2018, the company marketed "Smart Vest", a wearable solution designed to prevent accidents in the manufacturing workplaces[41]. The jacket, in addition to be a traditional safety vest providing for safeguarding the wellbeing of individuals, is equipped with several sensors that enable it to figure out if emergency situations or injuries are happening or are likely to happen. In the case of occurrence of such situations, thanks to a "case" at the level of the pocket, the device autonomously sent warnings and requests for action to established call numbers specifying with precision the exact location of the accident. The data transfer is bi-directional: on the one hand, as already described, the operator can alert the management about hazardous situations and send requests of first aid; on the other, the head of production can warn operators of occurring or potentially dangerous scenarios. Therefore, the operator can communicate its emergency state by simply pushing a button embedded in the "Smart Vest" immediately, without the need to take off the gloves. This exchange of updates occurs in real time and it helps the company to ensure the safety of its employees. In this way, the Industrial IoT is the enabling technology providing for the connection of the solution with the corporate ecosystem.

The major Industry 4.0 enabling technology of the solution described above is certainly the Industrial IoT that connects the sensors embedded into the smart vests

[41] https://barbaraganz.blog.ilsole24ore.com/2018/09/28/il-giubbotto-intelligente-e-connesso-premiato-made-in-udine-che-previene-gli-infortuni-sul-lavoro/

to the central system. However, the solution shows elements of intelligence as, in case of occurrence of dangerous scenarios, it autonomously sent warning signals or activate first aid requests triggering emergency service requests. Despite of this, it is worth to mention that the solution does not provide predictive indications and the service is activated only in case of real need, leveraging a reactive approach, rather than a proactive one. For this reason, it is located in high positions with respect to the ‘Synergism’ axis.

On the other hand, different actors are involved into the generated ecosystem, passing from the production supervisors motoring the conditions of the workplace and the shop floor workers directly experiencing the hazardous environment, until arriving to the emergency and first aid equips called to action in case of necessity. Considering that this solution is designed to safeguard all the employees operating in hazardous environments, the same number of smart vests should be provided and connected to the central system. The number of end nodes devices connected results, for this reason, significant and the solution obtains high values of ‘Network complexity’.

FOREIGN SCENARIO: THE EXPERIENCE OF NORTH STAR

Company profile			**Project**		
Country	*Sector*	*Size*	*Year*	*Stage*	*Facility*
USA	Manufacturing	Large	2016	Executive	Ohio, Italy

North Star Bluescope Steel is a leading company operating in the steel industry located in Delta, United States of America, which supplies various industries including automotive, construction, agriculture and general manufacturing applications.

The 4-step process to turn raw materials into hot rolled bands is extremely dangerous and in 2016 the company decided to adopt a solution conceived by IBM to safeguard the wellbeing and the safety of its workers facing an urgent issue in the industrial environment that is workplace safety. The IBM’s Employee

Wellness and Safety solution integrates data from multiple sensors embedded in the personal protective equipment worn by workers, like smart safety helmets and protective vests, and serves as a real-time warning system alerting employees and officers in the case of situations that require immediate attention or potentially hazardous scenarios[42] such as gas or heat exposure, proximity to heavy machinery or moving vehicles and so on. With the purpose of helping organizations monitor the wellbeing of industrial workers operating in extreme environments and preventing fatal incidents from happening the solution leverages both IoT-connected wearable devices sensing workers' vital signs (body temperature, blood pressure, heart rate and so on) and information from the surroundings and data analytics so as to provide preventive and predictive indications when emergency scenarios are likely to occur.

The solution described above is among the most innovative applications of the Industrial Internet of Things in the context of Industry 4.0. The project is ambitious and aims at connecting the entire facility and the resulting network consists of a large number of sensing devices that interact each other continuously sharing relevant information. Sensors embedded in the protective equipment, wearable devices and industrial machines constitute a unique system that strives to safeguard the wellbeing of the workers operating in hazardous conditions.

Even from the perspective of a collaboration and integration of the Industry 4.0 enabling technologies, the solution registers high values. In fact, even though the solution is mainly enabled by the Internet of Things, it leverages also many other disruptive technologies to successfully reach its objectives. First, it deploys devices of Advanced HMI (e.g. wearable devices) to alert supervisors that line workers are getting closer to a potentially dangerous environment. Moreover, it leverages Industrial Analytics to collect data from sensors and provide preventive and predictive indications to those interested.

[42] https://www.ibm.com/blogs/internet-of-things/ibm-employee-wellness-safety-solution/

In the diagram below (Fig. 22), the two experiences are examined in relation to the diagram proposed in this work.

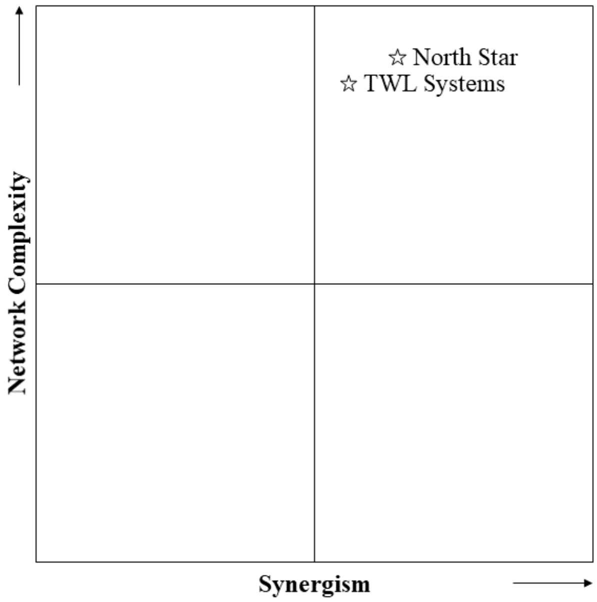

Fig. 22. Analysis of the 'Workplace safety' IIoT applications in relation to the proposed framework

4.2.6 ENERGY MANAGEMENT

ITALIAN SCENARIO: THE EXPERIENCE OF PATHEON

Company profile			**Project**		
Country	*Sector*	*Size*	*Year*	*Stage*	*Facility*
Netherlands	Chemical	Large	2018	Executive	Monza, Italy

Patheon is a multinational leader in the production of drugs and vaccines headquartered in Amsterdam serving the pharmaceutical and the biotechnology sectors and recently acquired by Thermo Fisher Scientific.

In 2018 in the production site located in Monza the company implemented a "Smart Factory" solution designed by AGS aimed at ensuring the correct operating of the plant and protecting the freeze-drying plant and vaccine production from voltage drops that, even if minimal, interrupt the process and irreparably damage

the goods being processed[43]. AGS developed an advanced interconnected system that, in the event of shutdown, automatically provides the power supply required to keep the machineries working until the reactivation of the regular primary energy or the launch of auxiliary power generators[44]. Moreover, the system continuously gather data from the connected sensors on an IoT gateway and, thanks to the adoption of Artificial Intelligence algorithms and machine learning techniques, provides preventive and predictive indications about the electrical load and the performances of the machineries with the purpose of detecting any potential anomalies. The real innovation, however, is the possibility to monitor and "customize" the electrical load of the machineries defining the "behavioural" data and assessing that the critical electrical parameters are compliant with standards.
The solution meets the requirements considered in the National Industry 4.0 Plan and allowed Patheon to gain access to considerable amounts of investment support and take advantage from the expected tax incentives.

The project launched by Patheon can be well represented in the framework that has been developing in the course of this work. Starting the analysis by considering the 'Synergism' dimension, in the description of the case provided above it is highlighted the key role of another Industry 4.0 enabling technology, that is the Industrial Analytics, which process the data gathered from the sensing devices embedded in the shop floor machines and detect dangerous anomalies. By implementing this solution, the Head of Production can predict in advance potential power shutdowns that can negatively impact the productive pace of the facility. The solution, therefore, uses the Internet of Things in cooperation with the Industrial Analytics, obtaining average values of 'Synergism' as the collaboration between the two technologies is the most obvious.
Passing to evaluate the level of complexity of the resulting IoT network, this aspect is very simple to analyse. In fact, the only IoT devices considered in this solution are the production machines that are connected to a central processing node to which they communicate their status of electrical load. In this sense, the resulting

[43] https://www.ags-it.com/progetto-patheon-frs/
[44] http://www.industriequattropuntozero.it/2018/05/07/smart-factory-patheon-si-affida-ad-ags/

network is relatively simple, and the solution comes up with low values of 'Network Complexity'.

FOREIGN SCENARIO: THE EXPERIENCE OF FESTO

Company profile			**Project**		
Country	*Sector*	*Size*	*Year*	*Stage*	*Facility*
Germany	Robotics	Large	2018	Executive	Scharnhausen, Germany

Festo is a German company at the forefront of automation technology sector which, in recent years, is quietly moving to become a market leader in its operating field.

The company announced its entrance into the field of IoT with a product, the energy efficiency module MSE6-E2M[45], that promises a 30 percent reduction in energy costs in manufacturing. Properly designed to monitor loss of hydraulic pressure in factory machines, this IoT-enabled device allows manufacturing companies to measure and reduce energy wastes, leading to lower costs and environmentally sustainable operations. The E2M is the first intelligent energy efficiency module able to monitor and automatically regulate the compressed air supply. If the E2M detects a standby status of the system, the compressed air supply is automatically shut down and the relative consumption drops to zero. Moreover, when the compressed air supply is shut down, the intelligent service module monitors the system for leaks. If anomalies are identified, the entire production line can be slowed down to account for the bottleneck, which can then be repaired on the fly without the need to halt production completely. Finally, operators are equipped with tablet or PCs so that they can autonomously monitor the status of production machines or use automated monitoring systems to check for leakage. By adding artificial intelligence over time, Festo expects to become a major provider of predictive maintenance.

[45] https://www.festo.com/net/SupportPortal/Files/427347/PSI_407_8_MSE6_E2M.pdf

In this application, the Industrial Internet of Things is supported by the Artificial Intelligence since the module, when necessary, is able to automatically regulate the compressed air supply or trigger maintenance service requests. Even though the solution was mainly designed to help manufacturers monitor energy consumption and minimize the relative costs, it is going to extend itself to the predictive maintenance application boosting even more the synergism among the two technologies. However, limiting its use for energy management, the application does not leverage the collaboration of the Industrial IoT with other Industry 4.0 enabling technologies but, in reverse, it uses the connected sensors only for monitoring purposes. For this reason, it was positioned with low values of 'Synergism'. Moreover, the system connects the industrial machine to different actors, alerting operators and supervisors in case of excessive leaks and autonomously activating repair services, if needed. The resulting network of end nodes is averagely complex, if the analysis is limited at considering the energy management application only. The solution, in this sense, obtains average values of 'Network Complexity'.

In the diagram below (Fig. 23), the two experiences are examined in relation to the diagram proposed in this work.

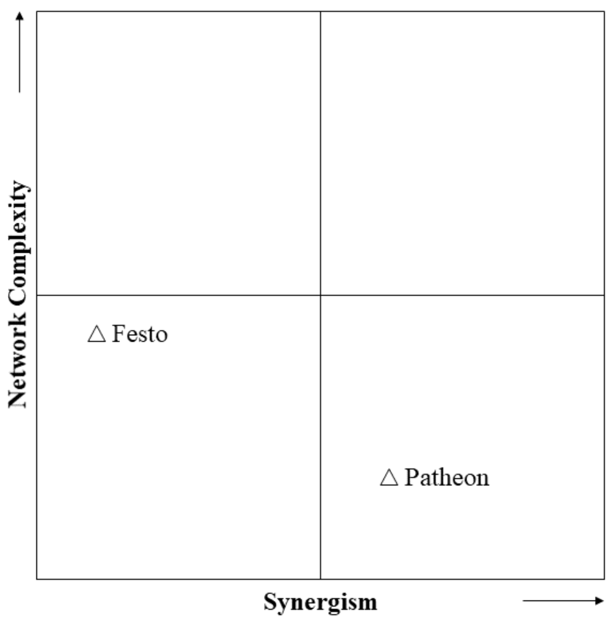

Fig. 23. Analysis of the 'Energy management' IIoT applications in comparison to the proposed framework

4.3 DISCUSSION OF THE RESULTS

At this point, the set of data items representing the twelve best practices has been grouped by the belonging Industrial IoT application and, for each cluster of observations, the corresponding centroid has been qualitatively fixed. This passage enables to examine the different Industrial IoT applications under a new perspective, that is the one offered by the two dimensions composing the framework, providing some interesting insights to integrate the analysis carried out so far. The resulting diagram is shown in the picture below (Fig. 24).

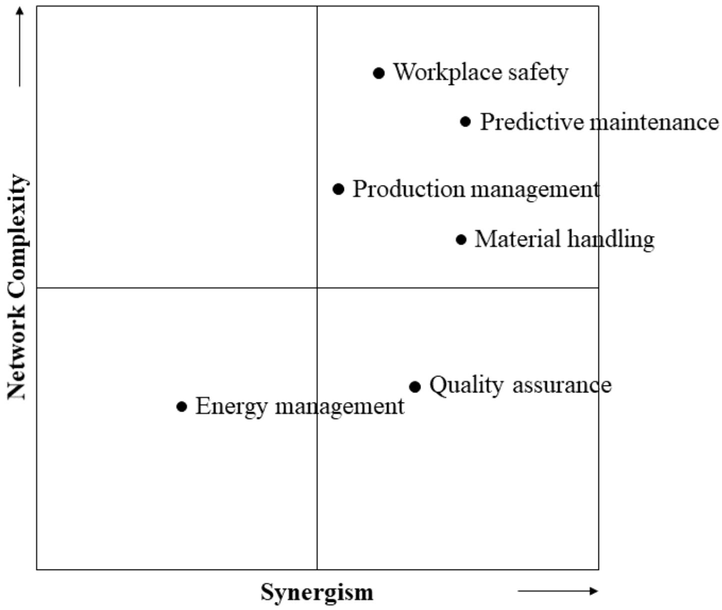

Fig. 24. Analysis of the IIoT applications in comparison to the proposed framework

At first glance, observing the matrix exhibited above, the Industrial IoT applications which are worth being discussed turn out to be 'Workplace safety' and 'Predictive maintenance'. The first resulted the Industrial IoT application with the highest values of 'Network Complexity' since it employs a large number of connected devices involving different actors into the system, passing from the production supervisors constantly up-to-date on the state of health of the shop floor workers, until arriving to the emergency and first aid equips called to action in case of necessity. Moreover, these kinds of solutions leverage the Industrial IoT together with two other Industry 4.0 enabling technologies: the Industrial

Analytics, providing both preventive and predictive indications concerning the occurrence of hazardous scenarios, and the Advanced HMI, displaying on wearable devices the potential warning signals. As regard the ‘Predictive maintenance’ application, similar observations can be made. An increasing number of manufacturers, in fact, decided to add intelligence capabilities to shop floor equipment, thus establishing an extended network that connects production line machines to facility supervisors and maintenance service providers. The resulting production system consists of smart machines able to autonomously predict breakdowns or dangerous operating conditions and proactively trigger maintenance service requests when needed. In addition to the Industrial Analytics, it is increasingly common to find manufacturers that attach IoT-enabled sensors to production robotics, thus taking advantages of the resulting synergies between the Industrial IoT and the Industrial Automation technologies.

Among the Industrial IoT applications located in the “High-High” quadrant, few words must be devoted also to the ‘Material handling’ application. In fact, thanks to the introduction in the Smart Factories of IoT-connected automated guided vehicles (AGVs) designed to handle materials and processing products across the line, major advancements in this field are expected. Although current solutions consider the interconnection of a limited number of AGV robots, manufacturers already envisage to network entire fleets of AGVs to the central system. Thanks to the variety of data gathered, industrial enterprises could prevent manufactured products from being damaged during the handling phase and increase workplace safety avoiding dangerous accidents from occurring. Moreover, IoT-based AGVs could communicate all the information regarding transporting material enabling manufacturers to promptly detect bottlenecks and dynamically schedule activities to be performed.

The adoption of the Industrial IoT to support the quality assurance process and ensure conformance with the contracted quality specifications is another representative case to discuss. The position of the ‘Quality assurance’ application within the framework proposed in this work enables to raise some considerations. The first consideration refers to its high level of ‘Synergism’, due to the fact that these solutions make an intensive use of the Industrial IoT in combination with other Industry 4.0 enabling technologies. In the two real-world experiences presented in the previous paragraph, in fact, the Industrial IoT technologies was adopted in cooperation with the Industrial Automation first and with the Advanced HMI and the Cloud Manufacturing then, proving the high degree of scalability of this application. Concerning the 'Network Complexity' dimension, instead, the extent and the complexity of the resulting network varies according to the individual use case. While in the first application the IoT-connected control station reported the processed data on displays located on-board machine, in the second experience line operators, quality specialists and product managers could remotely access the stream of quality metrics.

A completely different reasoning, instead, must be carried out with regards to the 'Energy management' application. In fact, in the vast majority of the cases, industrial enterprises embed line machineries with IoT-enabled sensors to collect data about their energy consumption so as to immediately detect the sources of energy waste and take more energy-aware decisions. Even though this adoption could lead to significant economic benefits, currently manufacturing companies leverage the Industrial IoT as a stand-alone technology restricting its scope of uses. On the contrary, only a limited number of manufacturing companies leverages the Industrial IoT in cooperation with other Industry 4.0 enabling technologies, in particular integrating computational capabilities to the generated system to prevent power outage or, even, energy consumptions of smaller entity from happening.

4.4 FURTHER EXTENSION OF THE FRAMEWORK

With the aim of providing a wider perspective of the underlying topic in a unique chart, a third variable can be added to the framework. In addition to the 'Synergism' and 'Network Complexity' dimensions, in fact, the proposed framework can be analysed considering also the current rate of diffusion of the different Industrial IoT applications in a Smart Factory environment.

This third dimension will be named 'Diffusion' and it will be measured using the results obtained thanks to the survey launched by the Internet of Things and the Industry 4.0 Observatories of the Polytechnic University of Milan, largely discussed in the third chapter of this work. In this regard, the 'Diffusion' dimension can be numerically expressed and quantified, considering the results emerged from the question of the survey investigating the popularity of the different Industrial IoT applications in a Smart Factory. From the survey, in fact, 'Production Management' turned out to be the most used application being pursued by 22% of the 94 sampled projects. To follow, 'Preventive/Predictive Maintenance' and 'Energy Management' resulted the Industrial IoT applications of, respectively, 19% and 18% of the sampled projects. In conclusion, the Industrial IoT was adopted with purposes of 'Quality Assurance', 'Material Handling' and 'Workplace Safety', respectively, in 16%, 14% and 11% of the cases. From a graphical standpoint, the data will be presented in a bubble chart, in which the size of the bubble represents the rate the diffusion of the various Industrial IoT applications in a Smart Factory.

The choice of using the data obtained from the 'Smart Factory Survey 2018-19' can result simplifying and restricted but it helps the research to provide a broader picture and an original analysis of the Industrial IoT topic. To this end, the proposed model can be absolutely rethought and improved by following studies. In this regard, in the following chapter, the framework will be submitted to criticism and the limitations of its three dimensions will be analysed.

Below (Fig. 25), it is shown the proposed framework resulting from the addition of the ‘Diffusion’ dimension.

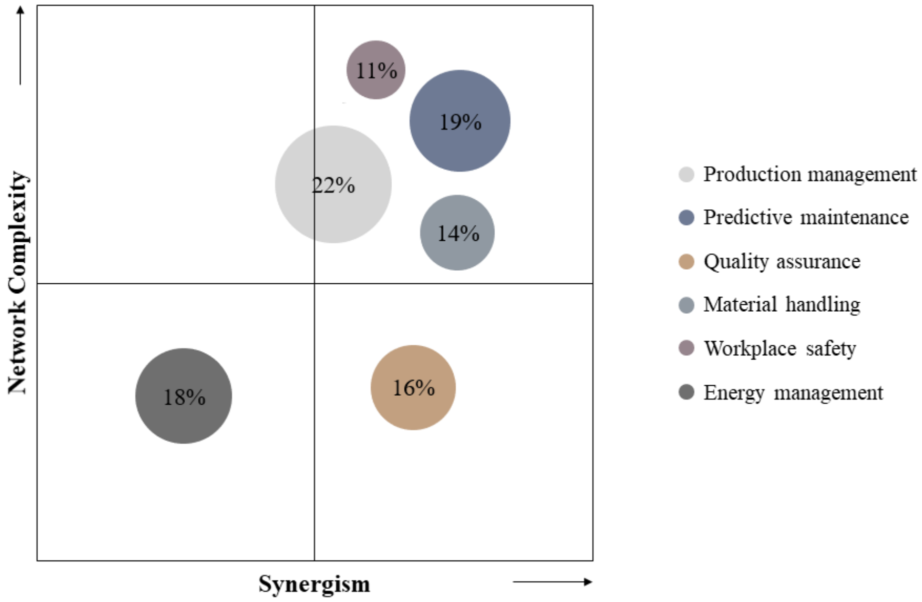

Fig. 25. Further extension of the proposed framework

5 CONCLUSIONS

The research activity conducted in this work can be ultimately summarized in three extended parts: the analysis of the major applications of the Industrial Internet of Things (IIoT) in a Smart Factory environment; the discussion of the results of the ‘Smart Factory 2018-19’ survey launched by the Internet of Things Observatory of Polytechnic University of Milan; the development of the qualitative framework to further examine the Industry 4.0 IoT-enabled solutions currently adopted by manufacturing companies.

Thanks to the initial activities of review of the existing academic literature and analysis of secondary sources concerning the adoption of the Industrial IoT in the production facilities, some major aspects of this topic have been argued. First, the rise of the Industrial IoT and the Industry 4.0 accelerated the process of convergence of the IT (Information Technology) and the OT (Operations Technology) environments driving significant transformations within manufacturing organizations. Second, the Industrial IoT, together with the Edge Computing and the Cyber-Physical Systems technologies, led to the dissolution of the hierarchical levels defined by the ISA-95 Standard Automation Pyramid in favour of more collaborative, interconnected and distributed ecosystems. Finally, the Industrial IoT boosted the growth of the concept of ‘Servitization’ in the industrial sector, driving companies to create associated services around their offerings and build new revenue streams.

The analysis of the ‘Smart Factory Survey 2018-19’ launched by the IoT and the Industry 4.0 Observatories of the Polytechnic University of Milan to investigate the current state of adoption of Industry 4.0 IoT-enabled projects by manufacturing companies generated some interesting results. First of all, with a reference sample of 127 IoT-enabled projects, the vast majority of them (62%) was implemented to bring benefits in a Smart Factory, proving the great willingness by manufacturers to sustain this kind of investment. As regards the Industrial IoT applications within a Smart Factory environment, with a reference sample of 94 projects, ‘Production management’ turned out to be the most adopted one, having resulted the desired benefit of 22% of the implemented projects. Great results were obtained also by

‘Preventive/Predictive maintenance’ and ‘Energy management’ applications, respectively related to 19% and 18% of the sampled projects. To follow, the remained projects were implemented for ‘Quality assurance’ (16% of the sampled projects), ‘Material handling’ (14%) and ‘Workplace safety’ (11%) purposes. The results achieved with respect to the major drivers, instead, showed that, generally, companies decide to launch a project of this genre to increase efficiency (75% of the companies) and effectiveness (58%). Interesting results were obtained also with regards to the use of the collected data as 33% of the responding companies stated to have intensively and profitably leveraged the data made available thanks to the implementation of the IoT-enabled project. In relation to the activation of additional services, instead, the majority of the companies (42% of the sample) stated to have applied push notification services, whereas only 6% of the companies declared to have implemented pay-per-use additional services that, according to experts, will heavily impact the manufacturing sector.

During the individual telephone interviews, instead, companies stated that the necessity to rethink the organizational structure and the lack of skilled workforce represent the major barriers to the implementation of Industry 4.0 IoT-enabled projects. Moreover, interviewed enterprises complained the inability of vendors to provide customized solutions able to properly fit their individual requirements.

Finally, the development of the qualitative framework and the examination of the Industrial IoT applications in a Smart Factory environment in relation to its two dimensions enabled to raise some original considerations. The draft of the ‘Network Complexity’ dimension allowed to examine the amount of end nodes included in the network of IoT-embedded devices, whereas the definition of the ‘Synergism’ dimension enabled to stress the fact that the Industrial IoT increasingly applies in Smart Factories in tandem with other Industry 4.0 enabling technologies. ‘Workplace safety’ and ‘Predictive maintenance’ resulted the IoT applications to have obtained the best placements within the proposed framework. Both the applications, in fact, employ a large number of end node devices and involve different actors into the generated network, connecting the operators and the machineries situated at the shop-floor level to the production supervisors and external individuals, that is the emergency and first aid equips in the case of the ‘Workplace safety’ application or the maintenance service providers in the case of the ‘Predictive maintenance’ application. Moreover, they both rely on the unique synergies deriving from the collaborative implementation of the Industrial IoT and the other Industry 4.0 technologies. In the case of the ‘Workplace safety’ application, the Industrial IoT applies together with the Industrial Analytics to predict the occurrence of hazardous scenarios and the Advanced HMI to display the potential waring signals to the involved actors. Interesting reflections emerged also from the analysis of the ‘Material handling’ and the ‘Quality assurance’ applications within the proposed framework. With the growing trend in manufacturing of equipping AGVs with IoT-connected sensors, significant advancements for the ‘Material handling’ application are expected, also in relation to the framework discussed in this work. The solutions currently adopted by manufacturers consist of connecting only a limited number of AGVs to the central system, making a partial use of the gathered data. But, in the next future, industrial enterprises are planning to interconnect entire fleets of AGVs, fully leveraging the potential offered by the variety of the data that can be collected. Ultimately, the adoption of the Industrial IoT to support the quality assurance process proved to be the application with the highest grade of scalability, as certified by the different scope of use that studied companies decided to make. In fact, if in the first case study the Industrial IoT was adopted in tandem with the Industrial Automation and the information were displayed on-board machine, in the second practice the synergies between the Industrial IoT and the Advanced HMI were leveraged, and the network of IoT-connected devices included also quality specialists and product managers that could remotely access the stream of quality metrics.

5.1 LIMITATIONS AND FURTHER DEVELOPMENT

The framework proposed in this work considers two fundamental aspects of the application of the Industrial IoT in a Smart Factory context, properly summarised by its two dimensions. Thanks to the ‘Synergism’ dimension, the framework intends to investigate the level of collaboration that exists among the Industrial IoT technology, subject of analysis of this research, and the other Industry 4.0 enabling technologies, namely the Industrial Analytics, the Cloud Manufacturing, the Advanced Automation, the Advanced Human-Machine Interface (HMI) and the Additive Manufacturing. On the other hand, by means of the 'Network Complexity' axis the framework aims at analysing the numerousness of end nodes devices within the generated system and the level of interaction occurring with each other. However, even though the framework enables to examine the Industrial IoT-connected solutions under the perspective provided by these two significant aspects, it inevitably suffers from some limitations. Below, three major limitations of this framework are discussed: the qualitative nature of the defined dimension, the statistical inconsistency of the sample of examined best practices and the sources of information selected to find and analyse the twelve real-world experiences.

Because of its qualitative nature, the framework founds its results on the individual judgement and sensitivity of the researcher and the raised considerations can constitute ground of disputes and opposite views. Moreover, a qualitative methodology implies that there are no standard rules to follow for the generation of results. However, in contrast with other qualitative models that assume the impossibility of defining the exact measure of their dimensions, the framework proposed in this work can be smoothly translated and evolved into a more scientific model. Both the 'Network Complexity' and the 'Synergism' dimensions, in fact, could be measured using proper indicators in order to minimize any potential ambiguity.

The second major limitation of the proposed framework resides in its statistical inconsistency. The robustness of the discussed framework has been evaluated on the basis of the uniform scattering within the matrix of the twelve items, consisting in manufacturing companies that successfully implemented Industrial IoT-enabled solutions. With the purpose of accurately assessing the goodness of the proposed framework, this latter could be populated with a more significant number of items. By integrating the framework with more observations, in fact, more advanced techniques for statistical data analysis could be performed spotting hidden patterns in the generated collection of data.

Finally, as stated in the 'Objectives and Methodology' chapter, the information about the twelve real-world experiences examined to develop the core findings of this work have been found from online articles published by specialized sites and blogs. As extracted from secondary sources, this information was quick to collect and easy to find, but it suffers from low accuracy and adaptability. An alternative approach that could be undertaken by following studies is to investigate each of the examined best practice by means of focus groups and individual interviews in order to extract peculiar knowledge and validate the necessary assumptions to conduct the research.

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Annex

Title	Document Type	Publication Year
“Industrie 4.0” and Smart Manufacturing – A Review of Research Issues and Application Examples	Review	2017
A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems	Article	2015
A Distributed Systems Perspective on Industrial IoT	Conference paper	2018
A Maturity Model for Assessing Industry 4.0 Readiness and Maturity of Manufacturing Enterprises	Conference paper	2016
A review of industrial wireless networks in the context of Industry 4.0	Article	2017
A Review of the Roles of Digital Twin in CPS-based Production Systems	Article	2017
Cloud-assisted industrial cyber-physical systems: An insight	Article	2015
Cloud-based design and manufacturing: A new paradigm in digital manufacturing and design innovation	Article	2016
Data driven management in Industry 4.0: a method to measure Data Productivity	Article	2018
Design Principles for Industrie 4.0 Scenarios	Conference paper	2016
Energy management based on Internet of Things: practices and framework for adoption in production management	Article	2015
Industrial Big Data as a Result of IoT Adoption in Manufacturing	Conference paper	2016
Industrial Internet of Things-Based Collaborative Sensing Intelligence: Framework and Research Challenges	Article	2016
Industry 4.0: A survey on technologies, applications and open research issues	Review	2017
Integration of Digital Factory with Smart Factory Based on Internet of Things	Conference paper	2016
Intelligent Manufacturing in the Context of Industry 4.0: A Review	Article	2017
Internet of Things (IoT) and its impact on supply chain: A framework for building smart, secure and efficient systems	Article	2018
Internet of Things (IoT) in high-risk Environment, Health and Safety (EHS) industries: A comprehensive review	Article	2018
Internet of Things for Industrial Automation – Challenges and Technical Solutions	Conference paper	2015
Internet of Things in Industries: A Survey	Review	2014
Internet of things: Vision, applications and research challenges	Short survey	2012
Internet-of-things Paradigm in Food Supply Chains Control and Management	Article	2017
Introduction to cyber manufacturing	Article	2016
IOT BASED AUTOMATED GUIDE VEHICLE	Article	2018
IoT powered servitization of manufacturing – an exploratory case study	Article	2017
IoT-based real-time production logistics synchronization system under smart cloud manufacturing	Article	2016
Migration towards digital manufacturing automation — An assessment approach	Conference paper	2018
Security and privacy challenges in industrial Internet of Things	Conference paper	2015
Service Innovation and Smart Analytics for Industry 4.0 and Big Data Environment	Conference paper	2014

Smart factories in Industry 4.0: A review of the concept and of energy management approached in production based on the Internet of Things paradigm	Conference paper	2014
Smart manufacturing, manufacturing intelligence and demand-dynamic performance	Article	2012
SmartFactory—Towards a factory-of-things	Conference paper	2010
The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0	Article	2017
The impact of digitalization on the future of control and operations	Article	2018
The industrial internet of things (IIoT): An analysis framework	Article	2018
The Internet of Things (IoT): Applications, investments, and challenges for enterprises	Article	2015
The Internet of Things: A survey	Article	2010
The Smart Factory: Exploring Adaptive and Flexible Manufacturing Solutions	Conference paper	2014
The value of Big Data in servitization	Article	2015
Towards a theoretical framework of strategic decision, supporting capability and information sharing under the context of Internet of Things	Article	2012
Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination	Article	2016
Understanding the Internet of Things: definition, potentials, and societal role of a fast evolving paradigm	Article	2017
Use of IoT Technology to Drive the Automotive Industry from Connected to Full Autonomous Vehicles	Article	2016
Using Internet of Things to Improve Eco-efficiency in Manufacturing: A Review on Available Knowledge and a Framework for IoT Adoption	Conference paper	2013