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Industry 4.0 and World Class Manufacturing Integration: 100 Technologies for a WCM-I4.0 Matrix

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Abstract: In the last decade, technological progress has profoundly influenced the industrial world and all industrial sectors have been confronted with a change in technological paradigms. In such a context, this study aims to analyze the synergies between the technological world of Industry 4.0 and the purely organizational and managerial domain of World Class Manufacturing, a model of Operational Excellence. The objective is relating the driving dimensions of the World Class Manufacturing (WCM) system to the technological macrocategories of Industry 4.0: this would allow the identification of which technological solution to leverage on, aiming at optimization in a given World Class Manufacturing pillar. The result is a "WCM-I4.0 matrix": a proposal to reconcile, exploit and trace the relations between the two complex concepts. The WCM-I4.0 matrix includes, by now, 100 Industry 4.0 technologies that best suits with the World Class Manufacturing pillars.

Keywords: Industry 4.0; Operational Excellence; World Class Manufacturing

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1. Introduction

Industry 4.0 (henceforth, simply I4.0) is the discriminating element that since the end of the first decade of the 21st century has been presenting itself as a facilitating agent and an improver of industrial activities, which are made simpler and more effective through heavy exploitation of modern ICT technology. Adopting the I4.0 paradigm means transforming the factory into a fully interconnected environment, where decisions can be quickly made based on reliable, accurate, precise and real-time data. However, the impact of I4.0 is not limited to the shop floor: I4.0 is a digital revolution that is pretended to have a global influence, unraveling the real potential of a circular economy, as well as enabling sustainable manufacturing [1,2].

On the other side, World Class Manufacturing (WCM) is a model of the Operational Excellence approach, worldwide adopted. It is a structured and rigorous methodology that completely envelops the manufacturing sector, whose objectives are the identification and the elimination of waste and losses in manufacturing processes in order to reach, in the end, the targets of zero accidents, zero rejects, zero failures and zero stocks [3].

Currently, I4.0 is in fashion [4], and most companies around the world are considering investing in technology under this large umbrella. These companies often leverage their own countries' regulations that, to defend the competitiveness of their manufacturing sector, do not hesitate to subsidize or finance investments in automation, robotics and electronics. Not a few manufacturing companies are facing the need to identify the synergies between possible investments in these technologies and the applications of Operational Excellence, often based on the WCM pillars.

In this sense, leveraging on the discussions with a panel of experts within the Operations Excellence Think Tank of "Tor Vergata" University of Rome, this study aims to highlight these synergies by connecting the driving dimensions of the WCM system to the technological macro-categories of I4.0

and allowing the identification of new technological solutions in response to a need of improving a WCM pillar.

In order to analyze the interaction between the technological world of I4.0 and the purely organizational and managerial production world of WCM, the genesis of the economic/industrial principles that gave birth to both the concepts are now briefly recalled.

1.1. Brief Introduction to Industry 4.0

The Fourth Industrial Revolution is derived from the increasingly widespread and efficient use of digitization in production environments. The concept was first mentioned in 2011 by the German Government, inside some hi-tech strategic guidelines [5]. I4.0 is defined by a pervasive interconnection between objects that lead to fully automated production, as well as a smarter and networked world [6]. There are many definitions assigned so far, among which the following:

- Flexible production for the entire plant life cycle based on the integration of data-based models and decisions [7];
- The profound transformation of business models enabling the fusion of virtual and real worlds in robotics, the application of digitization, automation and robotics [8];
- Knowledge-based and sensor-based self-regulating production systems [9].

The design principles of I4.0 are agility, decentralization, digitalization/communication/standardization, information transparency, integrated business processes, interoperability, modularity, predictive maintenance, real-time capability, service orientation, self-aware/optimization/configuration, technical assistance and virtualization [10,11].

This leverages on the analysis of a huge amount of data (Big Data), on the interconnection between objects via the Internet (called the Internet of Things, henceforth IoT), using a scalable calculation resource open to all participants in value creation (Cloud). In addition, the relationship between man and machine has undoubtedly improved and, at the same time, the process of exchanging information between machines and their drivers is more collaborative. Predictive and condition-based maintenance will also benefit from the possibilities offered by I4.0 [12].

The topic of the "active" role of the machine is significant: through the implementation of training and telecontrol software in real time, any device in the plant can make its status known, not only at the IT level, but also to all the other members of the shop floor. In such a scenario, elements of novelty regarding advanced robotics and other enabling technologies characteristic of this industrial revolution, such as additive manufacturing, i.e., the application of 3D printing in the production context, overlap.

The technological areas that form the I4.0 universe [13,14] are: Cyber-Physical Systems (CPSs), Cognitive Computing, Cybersecurity, Cloud Computing, Mobile Technologies, Machine-to-Machine, 3D Printing or Additive Manufacturing, Advanced Robotics, Big Data/Analytics, Internet of Things and RFID (Radio-Frequency IDentification) Technologies. These are briefly summarized in Section 4.

1.2. Brief Introduction to World Class Manufacturing

Operational Excellence is the area that includes the set of models, methods, approaches and tools through which each organization sets itself the goal of constantly improving its operations towards excellence. Operational Excellence models differ from traditional models in that they aim at a long-term change in the company's organizational culture. Exactly in this context, World Class Manufacturing, a model of Operational Excellence, has been developed.

The "Lean Production" Japanese production model is an approach to organizational and production management characterized by the continuous effort in the elimination of waste, in order to maximize the relationship between value and cost. It was conceived by Taiichi Ohno and Shingeo Shingo in the 1950s, in the context of the Toyota Production System [15], and celebrated by Krafcic in 1988 [16]; following this approach, Richard Schonberger [17] and Richard Keegan [3] took cues from Lean Production giving rise to the World Class Manufacturing (WCM) concept: in the early 2000s, the expression World

Class Manufacturing was taken up by Hajime Yamashina, with the aim of identifying a new model of Operational Excellence, making improvements from the traditional TPS approach, as well as making a series of adaptations to Western culture, which is profoundly different from the Japanese one [18]. To date, it is adopted on a global scale by most major manufacturing companies.

2. Literature Review on WCM and I4.0 Relations

There are many trends that have driven industries to move towards a new paradigm, including political, economic, social, technological, environmental and legal issues [19]; among the most relevant, the following can be found [19]:

- Reduction of time-to-market to develop, produce and market new products and services, which require increasingly high innovation capacities;
- Increased customization to meet the needs of individual consumers;
- Greater flexibility with faster and more versatile production processes capable of producing in smaller batches while maintaining high levels of quality;
- Decentralization of the decision-making process;
- Increased resource efficiency;
- Technological innovations such as the Internet, apps, social, networks, systems engineering, smartphones, laptops, 3D printers, AI (Artificial Intelligence) and Machine Learning, MES (Manufacturing Execution Systems), etc.

In a similar context, I4.0 proposes new technological solutions whose impacts can now be clearly outlined.

Digitized production has an impact on production processes, performance and business models, defined as a system of interconnected and interdependent activities that determine the way the company operates with its customers, partners and vendors. While there is no consensus among researchers on the definition of a business model, most agree that it includes a comprehensive and systematic approach to explain how companies do business, i.e., how value is generated and delivered. Because of environmental dynamics, even an established and successful business model cannot be assumed to be permanent and "the superior ability to reinvent your business model before circumstances impose" [20] is considered an increasingly vital source of competitive advantage in volatile and complex environments. I4.0, in this sense, proposes itself as a determining agent in the design of these new business models. The implementation of more efficient and faster production systems and innovative technologies enables leaner processes, faster time-to-market for new products and services as well as related delivery times, shortening production phases and increasing product differentiation capabilities. At the same time, it is to be expected that businesses in I4.0 need enhanced social and technical skills; it is also expected to be a shift toward design thinking instead of production thinking [21].

It seems that scientific literature does not include, to date, studies specifically focused on the relationship between I4.0 and WCM. On the contrary, there are already numerous papers and case reports on I4.0 applications in specific industrial contexts, but these are not helpful to analyze possible synergies between I4.0 and WCM. Differently, some recent papers present, indeed, the synergy between Lean Manufacturing and I4.0 [22,23] but since WCM is not considered, and it presents some significant differences from the Lean approach, these papers give a minor contribution to the authors' aim. At the same time, notwithstanding the differences between WCM and Lean, because there are some shared principles between these approaches, literature dealing with the link between Lean and I4.0 has been analyzed: the work of Rosin [24] clarifies the relationship between I4.0 technologies and Lean principles, pointing out which Lean principles are strongly impacted by I4.0 technologies, and which are not. It also resumes the two current visions of researchers about the link between Lean management and I4.0: some state that Lean is a necessary foundation for I4.0 [23,25,26], others that I4.0 improves the effectiveness of Lean [27–31]. These contributions may help understanding where I4.0 may impact on WCM, for those common principles between WCM and Lean philosophy. However, to the best of the knowledge of the authors, there are only two scientific contributions specifically dealing with WCM and I4.0 [32,33]; these papers, however, investigate the relationship and correlation between the I4.0 principles and the technical pillars of WCM, to guide a transition phase in which WCM could adopt some of I4.0 principles, with some structural modifications.

In the present work instead, the aim is to identify the I4.0 technology solutions that can contribute to improving a WCM oriented production optimization approach. So, the focus is not on the integration between I4.0 and WCM paradigms, but on the impact of I4.0 on WCM. At the same time, following the cited contribution, an advancement is proposed: for each WCM pillar, the I4.0 technologies that can contribute to its development are analyzed and listed.

A study methodology was conceived ex novo, based on the creation of a matrix (WCM-I4.0 matrix) along with the comparative and critical analysis of individual contributions of I4.0 technologies to WCM pillars.

3. Methodology to Structure the WCM-I4.0 Matrix

The proposed WCM-I4.0 matrix aims to highlight the technologies that can best serve and satisfy the needs of the WCM world. The idea comes from the need to map, in an intuitive and immediate way, the origin of technological opportunities and where they can positively impact on WCM pillars, helping in investment decision-making and allowing to identify the appropriate technological drivers.

The WCM-I4.0 matrix reports the WCM pillars in each row, along with some of their characteristic elements. On the columns, the WCM-I4.0 matrix shows the I4.0 technological areas, rearranged into the following groups:

- Cloud Computing;
- Cognitive Computing;
- Internet of Things;
- Machine-to-Machine (M2M);
- Mobile Technologies;
- Augmented Reality;
- Simulation;
- Additive Manufacturing;
- Advanced Robotics.

As said, also Big Data, Cybersecurity, RFID areas are often cited within the Industry 4.0 universe [13,14,34]. Here, also according to the outcomes of the discussion with the panel of experts, these areas have been excluded from the analysis because:

- Cybersecurity—Intended as the protection of computer systems and networks from the theft of or damage to their hardware, software, or electronic data—is to be considered a prerequisite for Industry 4.0 technologies, not an opportunity area for WCM pillars;
- RFID—Intended as the technology that allows the automatic identification and tracking of objects through radio-frequency tags—was considered as surpassed by, or at least included in, IoT paradigm;
- Big Data—Intended as the area that refers to analyzing and systematically extracting information from data sets that are too large or complex to be dealt with by traditional data-processing application software—can be considered a generic concept and a transversal approach to all the cited areas: for example, Big Data may originate from M2M applications or from mobile technologies, or from IoT. Thus we assumed that the capabilities of performing advanced data analytics methods and extracting value from data can be shared among several cited areas. Analogous consideration can be done for Cyber-Physical Systems, intended as a computer system in which a mechanism is controlled or monitored by computer-based algorithms.

Finally, a set of 100 I4.0 technologies has been identified and represented into the WCM-I4.0 matrix: in each cell, the technologies belonging to a given I4.0 group and providing support to given WCM tools are listed.

In the following paragraphs, the I4.0 groups (elements on the columns) and then the WCM tools (elements on the rows) are briefly recalled, showing the relevant literature that helped the authors in finding the links between the two dimensions.

4. Industry 4.0 Technological Groups

4.1. Cloud Computing

Information and Communication Technology (ICT) has shown constant development over the last thirty years. This, of course, is linked to the recent development of software [35]. In this way, the meaning of Cloud Computing materializes a form of Internet-based computing that allows computerized processes to share resources and data with other devices on demand. This information can also be integrated by all company's facilities. One of the strengths of the Cloud is the possibility of using a shared reserve of technological capabilities, such as applications, software, servers and storage space, without special management efforts. Access is fast and ubiquitous.

4.2. Internet of Things (IoT)

IoT is an extension of Internet use: objects become identifiable and become aware of themselves and their surroundings through the ability to provide, process, receive and exchange data with and other devices.

The IoT enabling requirements are: connectivity of the physical layer (e.g., RFID tags, which carry data and, once recognized, trigger an automatic action); the opportunity to manipulate data; interfaces that are able to interact both at the physical layer and with other systems; standardization of access; solid and robust security, to prevent fraudulent or improper use of knowledge and to ensure the privacy of a company's data. IoT is a funding concept of I4.0, being necessary for many I4.0 technologies, and now easily accessible: the cost of IoT nodes has come down drastically and is expected to fall further [36].

4.3. Machine-To-Machine (M2M)

Machine-to-Machine (M2M) refers to communication between equipment. More precisely, M2M reflects the exchange of information between sensors and actuators in the production environment, enabling unforeseen levels of efficiency to be achieved [37]. "M2M is the communication between two or more entities that do not necessarily require any direct human intervention. M2M services aim to automate decision-making and communication processes" [38]. The shop floor is transformed into an intelligent environment: machines are connected to each other and have full visibility and awareness of the ongoing situation on the shop floor. The results can be translated into significant reductions in stock levels, waiting times and handling activities. Moreover, with the possibility of increasing the integration between the Enterprise Resource Planning (ERP), the Manufacturing Execution System (MES) and the automation layers (SCADAs and PLCs), production orders can be directly transferred to the production line.

4.4. Cognitive Computing

Cognitive Computing is the discipline that attempts to model AI by combining specific human capabilities with machine abilities—such as pattern identification, and the ability to work with massive amounts of data. This system is ideal to interact with those environments, such as the production shop floor, whose complexity is constantly growing.

Cognitive systems also have decision support capabilities: through the processing of millions of data in multiple formats (video, photo, text, web and social pages, etc.) they are able to ask and answer complex human questions, promoting the decentralization of the decision-making process. In this context, machine learning offers solutions to the problem of obtaining useful insights, predictions and decisions from huge data sets [39].

4.5. Mobile Technologies

As already pointed out, the uniform implementation of Industry 4.0 requires a complete and stable interconnection among all its components. Mobile Technologies include all technologies based on wireless communication methods. They enable interconnection between production equipment and operators. Whether mobile phones or tablets, the underlying concept is to achieve faster transmission of information and greater accessibility.

Large amounts of information that were previously only available at a fixed location are now accessible anywhere on the shop floor. In this way, production progress is easily accessible in real time on mobile devices, with which it is possible, among other things, to tag objects and be alerted before a machine stops.

4.6. Augmented Reality

Augmented Reality (AR), or computer-mediated reality, is an interactive graphics system that allows us to intervene on a stream of video images, modifying reality by adding, in real time, virtual contents and animations.

What makes augmented reality different from a video with 3D objects and special effects made with video post-production techniques is that the augmented reality software integrates video footage and virtual objects in real time and in an interactive way: virtual objects that increase the video flow are not static, but can perform movements and animations in response to human actions.

In the industrial environment, this is possible thanks to sensor and actuator systems embedded in the machinery that bidirectionally communicates with the user's virtual glasses. On a practical level, all this can be translated into real-time monitoring of energy parameters, heat, material consumption, wear and tear, stock levels, production efficiency, etc. These functionalities may have a huge impact on the industrial world [40].

4.7. Simulation

Through the integration with the data that the real object can transmit, simulations of real operations are enabled to develop a process of analysis and optimization of the scenarios proposed in the virtual environment. In this way, it is possible to extrapolate new information and forecasts from the virtual world through virtual planning [41]. This allows the reduction of the risk attached to a process, as the latter can be validated in advance. In addition, the integrated modeling of multiple objects that virtually interact (e.g., an entire production line) makes the exchange of information transparent and easy to interpret.

4.8. Additive Manufacturing

The additive manufacturing is 3D printing applied to industry. The ISO/ASTM 52,900 standard [42] defines 3D printing as a process of joining materials to fabricate parts of virtual 3D models generated from data, usually layer upon layer. The main novelty of the process is its difference from the traditional approach, according to which it is a subtractive process that gives shape to the object from an initial shape [43]. There are significant advantages to be found: great ability to customize the product; almost total reduction of material waste, since it can be entirely reworked; objects with a very complex shape can be easily transferred from design to production [44]. These advantages seem to be particularly relevant for medical and aerospace production. At the same time, however, this technology may imply longer manufacturing times, cost and loss of support structures [45], shape distortions and residual stresses in materials due to excessive heat accumulation [46], along with the need of more qualified and, therefore, more expensive personnel.

4.9. Advanced Robotics

One of the most relevant aspects of Industry 4.0 is the achievement of an autonomous production system, powered by robots capable of intelligently completing the tasks, focusing on safety, flexibility, versatility and collaboration [47]. Without the need to isolate its working area thanks to advanced sensor technology, interaction with humans and their working environment becomes more economical and productive, opening many possible applications in industries. Therefore, intelligent robots not only replace humans in workflows within defined areas, but work closely with them, and are able to actively interact with the operator thanks to the interconnection and use of intelligent sensor-based human–machine interfaces.

5. World Class Manufacturing Pillars

World Class Manufacturing (WCM) [48] is a structured production system that promotes systematic, long-term, targeted improvements, with the aim of enhancing and attacking all types of waste and losses, implementing standards and methods, rigorously through the involvement of people. The WCM Manufacturing methodology is structured on 10 so-called "technical pillars", and 10 "managerial pillars", each focusing on specific issues. Since the aim of this work is to analyze the possible benefits of using I4.0 technologies in relation to the technical pillars, the managerial pillars have not been taken into consideration here.

Each pillar, following a logic of seven sequential steps, aims to achieve excellence in the plant by conducting the process of continuous improvement for the specific function of production, transforming a reactive approach to problems into a proactive one, often starting from narrow model areas and then expanding what has been achieved throughout the plant. The following paragraphs analyze each technical pillar detailing the different tools.

5.1. Safety

The goal is to achieve zero injuries. The approach proposed by the WCM is to work on minor injuries, near misses (NM) and insecure actions and conditions to reduce the most serious injuries; attention is, therefore, paid to any event that has the potential to produce an injury.

Therefore, two main activities are carried out:

- Process analysis: for each activity, the presence of risks related to accidents, near misses, conditions (Unsafe Conditions (UC)) or insecure actions (Unsafe Act (UA)) are verified;
- Process monitoring: a matrix is built to track the relevance of injuries and the relationship between them and the UC and AU, the body parts involved, and root causes (S-Matrix);

From this point of view, the seven steps of the Safety pillar encompass the following activities: the analysis of accidents that have occurred with the determination of their causes and countermeasures, the training of operators to avoid insecure behavior, the standardization and systematization of autonomous actions that contribute to the safety of the working environment.

As a consequence the following elements have been reported in WCM-I4.0 matrix for the Safety pillar: S-Matrix (compilation and monitoring), UC, UA, NM and FA (First Aid) register along with injuries recording, risk assessment, autonomous inspection of the operator, control of the use of Personal Protective Equipment (PPE), risk for pedestrians and, finally, countermeasures.

5.2. Cost Deployment

Through a massive data collection phase, Cost Deployment (CD) tracks waste and losses in the plant, defines a relationship between the causal and resulting losses, evaluates their negative impact and defines an improvement plan for priority losses, evaluating their actual benefits. It then monitors the progress of planned activities and sets the activities for the following year. All this is carried out in the seven pillar steps:

- Step 1: Total Transformation Cost (TTC) is calculated, the sum of direct transformation costs, indirect costs (personnel costs, variable costs, fixed costs and personnel costs) and rejects. Top Management defines the TTC Reduction target;
- Step 2: The data coming from the shop floor (Bordereau, Waste collection, production data, HR software, SAP, etc.) are conveyed into Matrix A, obtaining the relationship between the loss or waste tracked and the related process that generates it;
- Step 3: With Matrix B, the relationship between causal losses and resulting losses is identified, in order to reverse the costs of the latter on the former and to evaluate their negative impact;
- Step 4: With Matrix C, a value is given to the losses found in the previous steps;
- Step 5: In Matrix D, through the index ICE (Impact, Cost, Easiness), the priorities of the plant are defined. The losses with a higher ICE value are attacked by the various pillars during the calendar year;
- Step 6: A cost/benefit analysis of the projects defined in the previous step is carried out with the E Matrix;
- Step 7: Starting from the E matrix, an F matrix is built for monitoring and follow-up of improvement projects. The G matrix identifies the projects to be implemented the following year to reach the TTC Reduction foreseen by the management.

The elements of the pillar that can be found in the WCM-I4.0 matrix are: TTC computing, Data Collection, A Matrix, B Matrix, C Matrix, D Matrix, E Matrix, F Matrix, G Matrix.

5.3. Focused Improvement

The Focused Improvement (FI) pillar is closely related to CD, as its main objective is the removal of the most relevant loss items tracked by the CD and which have a significant impact on the budget and plant KPIs [49].

Since in most cases the source of a loss takes the form of a deviation from a process standard, the logic of FI it is not limited to identifying a temporary solution: a cycle—the Deming Plan-Do-Check-Act Cycle (PDCA), whose phases are reflected in the seven steps of the FI—is carried out to find the root causes of the deviation from the standard, in order to implement corrective actions that aim to permanently reduce them to zero, to restore or introduce a new specific standard.

FI also deals with the knowledge management of WCM tools within the plant, trying to increase the level of involvement of operators. In particular, it is responsible for the dissemination of Kaizen methodologies. FI also focuses on the distribution of workloads among WCM actors through the Saturation Matrix.

The FI pillar elements of the WCM-I4.0 matrix are: Operator's tool knowledge, Workload Management—Saturation Matrix, OEE, Minor stoppages, SMED, B/C (Benefit/Cost) Monitoring.

5.4. Autonomous Maintenance

The Autonomous Activities pillar is related to the relationship of the operator with the machine (Autonomous Maintenance) and with the working environment (Workplace Organization). To better highlight the impact of I4.0 technologies on WCM, the Autonomous Maintenance and Workplace Organization have been here divided, despite being part of the same pillar.

Autonomous Maintenance (AM) refers to all first-level preventive maintenance activities: cleaning, checks, inspections, disassemblies, replacements and minor repairs. AM is intended to prevent microstops and failures due to the lack of basic operating conditions of the machinery. The involvement of the operators is crucial, as the following activities must necessarily be carried out at all points of the shop floor without exception.

The activities carried out by the operators range from the restoration of basic conditions to the definition of a fully implemented Autonomous Maintenance program, through the creation and maintenance of the first cleaning and lubrication standards (Cleaning Inspection Refastening Lubrication activities—CIRL, AM Calendar), autonomous inspection and standardization.

Therefore, it is possible to define Autonomous Maintenance as a systematic approach aimed at transferring primary preventive maintenance activities to production operators by implementing well defined and tested standards.

The AM pillar elements included in the WCM-I4.0 matrix are: Machine basic condition, CIRL, anomalies detection, AM calendar.

5.5. Workplace Organization (WO)

The goal of the Workplace Organization (WO) is to increase plant efficiency and productivity by setting and maintaining the appropriate basic conditions, removing non-value-added activities (NVA), involving people and developing process and product expertise. It is, therefore, a set of technical criteria, methods and tools aiming at creating an ideal workplace to ensure the best quality, maximum safety and maximum value.

The objective is the creation of a work area in which the operator has everything he needs to produce; this area, called the golden zone, respects certain ergonomic criteria. For this purpose, the Lean Production 5S approach is applied, the elimination of NVAs is pursued, training is carried out on product characteristics, tools and instruments, along with process standardization.

In the WCM-I4.0 matrix are, therefore, included: 5S, Ergonomics, NVA, Workload balancing, Process Standardization (SOP—Standard Operating Procedures, OPL—One-Point Lessons, etc.).

5.6. Professional Maintenance

The Professional Maintenance (PM) pillar deals with the activities aimed at structuring a maintenance system able to reduce to zero the failures and micro-stops and extend the life cycle of the machinery by increasing the life of individual components, while maintaining an efficient view on processes. Its objective is initially to reduce to zero the stops due to the lack of professional maintenance (Step 1–3), and then to focus on reducing the costs associated with the same activities (Step 4–6).

There are some extra management activities that go beyond the seven pillar steps, like the management of spare parts, lubricants and maintenance box (the WO rules basically apply to the maintenance box). The seven steps are detailed below:

- Step 1: The degradation of the machinery is reduced, and the basic conditions are recovered to avoid accelerated degradation in order to stabilize the MTBF—Mean Time Between Failure (with the support of AM);
- Step 2: A deep analysis of the historical failures is performed to intercept the root causes and eliminate them avoiding their repetition. The so-called EWO (Emergency Work Order) modules are used;
- Step 3: The PM (Machine Ledger) calendar is drawn up, i.e., the calendar of preventive maintenance activities. With this step, we aim at the total zeroing of the stops due to the lack of professional maintenance;
- Step 4: Focus on maintenance costs. The objective at this time is to extend the life of the component, according to techniques of strengthening or reduction of perceived stress;
- Step 5: Reduction of MTTR—Mean Time To Replace or the frequency of planned activities. It is also possible to transfer tasks from PM to AM, reducing the workload of maintenance workers;
- Step 6: Construction of a predictive maintenance system;
- Step 7: Construction of the most advanced maintenance system, such as Improvement Maintenance.

The following elements have been included in the WCM-I4.0 matrix: Maintenance Box Management, Replacement Management, PM calendar, MTTR reduction, Predictive Maintenance.

5.7. Quality Control

The objective of the Quality Control (QC) pillar is to delineate an *a priori* control system: the aim is to identify the root causes of nonconformities, remove them and set the conditions so that they do not recur in the future. QC aims to maximize customer satisfaction by minimizing the costs incurred to achieve it, adapting production systems and improving the skills of employees in solving quality problems [49].

The tools used by QC are various: the Quality Assurance Matrix (QA Matrix) relates each identified defect to the process that generates it, highlighting the frequency with which it occurs, the cost it represents, the severity and the area of detection of noncompliance, allowing to prioritize interventions; the 4M (Machine, Methods, Materials, Man) method allows the analysis of the chronic causes of noncompliance. The losses caused by Machine are attacked with the "seven steps of Quality Maintenance", in which various instruments are used such as PPA (Process Point Analysis), X Matrix (traces the correlation between defect, physical phenomenon, machine component and machine parameter) and QM Matrix (for each defect indicated in the X Matrix, the nominal values are indicated with the respective tolerances, system, frequency and control manager) while those caused by Man Power, Method and Material with the "seven steps of QC Problem Solving".

The following are the QC elements in the WCM-I4.0 matrix: QA Matrix, QA Network, X Matrix, QM Matrix, Defects Monitoring, Statistical Process Control (SPC), Customer Claims Management.

5.8. Logistics

Logistics, also called Logistics and Customer Service, is the pillar responsible for the coordination and management of production, logistics, distribution, purchasing and sales.

The aim is to apply the Just in Time production management model to streamline the internal flow as much as possible by reducing stock, WIP (Work in Progress) and lead time.

The seven pillar steps are concerned with:

- Step 1–3: The re-engineering of the production line, internal logistics and external logistics, takes place. Attempts are made to reduce lead time, batch size by passing through machine set-up times, to reduce material handling and to apply First In First Out (FIFO) logic for material management;
- Step 4–5: The aim is to set up a continuous flow through the leveling of production and of the production mix;
- Step 6–7: The achievement of an accurate and controlled flow, pursuing the objective of fully synchronizing sales, production and procurement activities;

In the WCM-I4.0 matrix, the following Logistics elements are, therefore, included: Line Balancing, Lead Time, JIT Production (Just in Time Production), Stock Management and Picking Activities, Handling.

5.9. Early Equipment Management

The Early Equipment Management pillar, also paired with Early Product Management (EEM/EPM), aims at strengthening the competitiveness of the plant still in its primordial phase, adopting the principle of prevention of problems that may arise during the rough design, basic and detailed design phase, up to the machinery/product start-up phase. The approach takes the form of checklists and Maintenance Prevention Info (MP-Info) sheets, which are modules aimed at creating an information and knowledge base related to the installed systems.

EEM, therefore, consists in the collaboration between designers, production and suppliers of the machinery with the aim of: installing machinery with high-performance indicators; reducing the Life Cycle Cost of the machinery; reducing the number of modifications in the transitory phase (and, therefore, the associated costs); speeding up the start-up of the machinery.

Elements included in the WCM-I4.0 matrix are: Design Process, Number of Modifiers, Technical Database, Performance, Vertical Start-Up, Poka-Yoke.

5.10. People Development

People Development (PD) activities must ensure, through a well-planned training system, that the appropriate skills, technical knowledge and qualifications for each job position are present [49]. The aim of PD is to create a solid system of knowledge expansion in the plant, based on the assessment of skills gaps and the definition of training methods to eliminate these gaps, equally for high- and low-level technical staff. The aim is to empower and, above all, to involve staff in continuous improvement, and to make them versatile in carrying out different tasks.

The main activities, the definition of the training levels, the detection of the necessary and available knowledge, the structuring of the Training Plan, pursue the objective of "zero human error", the reduction of accidents and the improvement of the working climate.

Below are the PD steps:

- Step 1: The priority intervention areas and the model area are defined through interaction with the C matrix of CD;
- Step 2: The map of expected competencies, the CD of human errors and the competence gaps are defined;
- Step 3: Improve team performance, reduce human error and associated losses;
- Step 4: B/C analysis of the training based on the costs associated with lack of knowledge; drafting of a training plan for each resource;
- Step 5: The effectiveness of training processes is improved by focusing on the personal involvement of the operator and identifying the best resources. In general, an attempt is made to establish a system for the development and strengthening of knowledge;
- Step 6: People are trained with more complex tools in order to have specific and elective knowledge, and benchmarking is carried out;
- Step 7: Setting up a system for the continuous evaluation of skills.

Therefore, the elements included in the WCM-I4.0 matrix are: Human Error Management (along with Human Errors Root Cause Analysis—HERCA), Training, Gap Detection, Benchmarking, Absenteeism Management.

5.11. Energy and Environment

The Energy and Environment (EE) pillar defines the management of the environmental programs implemented in the plant. It includes the organizational structure, planning and resources for developing, realizing and maintaining environmental protection. This pillar represents the tool to raise environmental performance, to manage the environmental aspects in the organization, the short and long-term impact of processes, products and services on the environment, focusing on continuous improvement.

Therefore, in the WCM-I4.0 matrix, the following elements were included: Energy, Waste, Water, Pollution monitoring and reduction.

6. Methodology and Results

A qualitative research methodology approach based on focus groups [50] was followed to design the WCM-I4.0 matrix presented in Table 1: the Industry 4.0 technological groups have been shared and discussed with a panel of experts within the Operations Excellence Think Tank (TTOPEX) of "Tor Vergata" University of Rome, along with the WCM pillars. The TTOPEX has been founded in 2019 aiming at providing a platform for information sharing, exchange of ideas, knowledge creation and dissemination of Operations Excellence best practices in industries. Currently, it is composed of 12 experts at managerial or executive positions in various multinational companies operating in different industries: production of robotics and automation technologies, consumer goods, food, beverage, pharmaceutical and textile manufacturing. All the experts have from 10 to 30+ years of proven qualification in Operations Excellence themes, including WCM and technology improvements, given that their roles span from Plant Director to Head of WCM, from Director of Engineering to Director of Operations Excellence, from Operations Manager to Lean Manufacturing Manager, etc. A group discussion has been arranged to brainstorm on the various technologies to be analyzed, according to their potential impact on WCM practice. The focus group was managed as a delayed-response online group [51] with email interaction, due to COVID-19 emergency restrictions limiting face-to-face meetings, and moderated by the Director of the TTOPEX. The discussion ran during March and April 2020. The relative homogeneity of the experts' background combined with the heterogeneity of the represented industries ensured both a competent focus on the topic and a wide range of perspectives.

As a result, 100 I4.0 technology implementations have been selected as those that can contribute to the improvement of WCM, in each specific pillar. These technology implementations are listed in Table 2 while in the next sections the impact of these technologies on each WCM pillar is discussed.

Table 1. World Class Manufacturing (WCM)-Industry 4.0 (I4.0) matrix.

		Cloud	IoT	(M2M) Machine-To-Machine	Cognitive Computing	Mobile Technologies	Augmented Reality	Simulation	Additive Manufacturing	Advanced Robotics
SAFETY	S-Matrix	1, 4				2				
	UA, UC, NM, FA, Injuries Recording	1				3				
	Risk Assessment							68		
	Autonomous Inspection	1, 4					6			
	PPE Check		8		11					
	Risk for Pedestrian		51, 52			53				
	Countermeasures	1, 4	10		59		6, 100			30
COST DEPLOYMENT	TTC Computing	1, 4								
	Data Collection	1, 4				7				
	A-Matrix	1, 4								
	B-Matrix	1, 4								
	C-Matrix	1, 4								
	D-Matrix	1, 4								
	E-Matrix	1, 4								
	F-Matrix	1, 4								
	G-Matrix	1, 4								
FOCUS IMPROVEMENT	Operator's Tool Knowledge		9			5	79	77		
	Workload Management—Saturation Matrix	4, 71, 73	72			74				
	OEE	1, 4	78			78				
	Micro stoppages	1, 4	20, 56	24	58	22	23, 75			
	SMED		34, 67				76	77	40	
AUTONOMOUS MAINTENANCE	B/C Monitoring	1, 4								
	Machine Basic Condition					14, 15	6			
	CIRL		19, 20, 25			16, 18	13, 17, 76	77		
	Anomalies Detection	1	21, 56	24	58	3, 22	23, 75			
	AM Calendar		25			16, 18, 25	13, 76			
WORKPLACE ORGANIZATION	5S		26, 27				28, 29			
	Ergonomics						100	99		30
	NVA									30
	Workload Balancing	1, 4	35	33, 98		39		89		
	Process Standardization (SOP, OPL)		32			16	76	77		
PROFESSIONAL MAINTENANCE	Maintenance Box Management		26, 27				28, 29			
	Replacement Management	41	44		48		50			
	Pm Calendar		25			16, 18, 25	13, 76			
	MTTR Reduction		20, 57		58	22	23, 76	77		
	Predictive Maintenance	1, 62			70	60	55, 63			

Table 1. *Cont.*

		Cloud	IoT	(M2M) Machine-To-Machine	Cognitive Computing	Mobile Technologies	Augmented Reality	Simulation	Additive Manufacturing	Advanced Robotics
QUALITY CONTROL	QA Matrix	1, 4								
	QA Network	1, 4								
	X Matrix	1, 4								
	QM Matrix	1, 4								
	Defects Monitoring	1, 4	84, 90		61	7	88			
	Statistical Process Control	1, 4	85							
	Customer Claims Management	86	87							
LOGISTICS	Line Balancing	1, 4	35	33, 98		39		89		
	Lead Time	1, 41, 54	34, 36, 37	33				45	40	30
	Jit Production	1,4	35, 43, 44	33, 42, 47				45, 46		
	Stock Management and Picking Activities		43, 44, 82	42	48		38, 50	49		31
	Handling		82							30, 31
EARLY EQUIPMENT MANAGEMENT	Design Process	64						65		
	N. of Modifies				69					
	Technical Database	66								
	Performance		67					67	40	30
	Vertical Start-Up				92					
	Poka-Yoke		90		61		97			
PEOPLE DEVELOPMENT	Human Error Management (HERCA)		9			2				
	Training	5	32			5	79	77		
	Gap Detection	1, 4, 93						91		
	Benchmarking	83								
	Tips Management		80			2, 81				
	Absenteeism Management	95, 96	94							
EN&ENV	Energy, Waste, Water, Pollution Monitoring and Reduction	1,4	61	12		60	6			

Table 2. One-hundred I4.0 TECHNOLOGIES.

1	Automatic Real-Time Cloud-based Data Acquisition (Energy Consumption, Efficiency, Wear, Heat, Pollution, Noise, Workload, Product Data, Production Data, Competence)	51	Forklift embedded of sensor mapping the human in the area
2	S-EWO/EWO/HERCA recording with workplace device	52	Automatic braking of forklift sensing a human in a close distance
3	Tag recording with workplace device	53	Pedestrian equipped with map of forklift in movement
4	Real-Time Cloud-based automatic analytics	54	Cloud-based shipping slot booking
5	Cloud Database with WCM tools accessible with workplace device	55	Glass visualization of current component health status
6	Real-Time parameters monitoring with glass visualization	56	HMI panel with procedure to solve anomalies by operator
7	Recording of Bordereau and Scraps with workplace device	57	Automatic call of the machine to maintainer
8	Alert systems for nonuse	58	Machine learning abilities to learn how to solve new anomalies
9	Alarm systems for training needed	59	Machine Learning to prevent unsafe conditions
10	Automatic machine stop due to unsafe conditions	60	Automatic warning with workplace device of abnormal condition of the component
11	PPE check use with Camera	61	Machine learning Quality control for nonlinear defect's pattern
12	Automatic machine stop due to starving situation	62	Real-Time Cloud-based automatic analysis of component remaining life
13	Glass visualization of AM/CIRL/PM Calendar	63	Glass visualization of component remaining life
14	Automatic Warning due to the missing of basic conditions	64	Vertical integration in a shared Digital online CAD Platform
15	Assisted Control of Basic conditions with workplace device	65	Digital Twin plant simulation
16	Guided CIRL/AM(SMP)/PM/Operative Procedure (SOP/OPL) activities step by step	66	Horizontal integration in a shared technical database
17	Glass visualization of dirt source	67	Plug and Play system to create a modular design of the machine
18	CIRL/AM/PM calendar visualization with workplace device	68	Simulation of workplace environment for risk assessment
19	Dirt source monitoring	69	Intelligent Cloud-based Checklist
20	Lubrification Points Monitoring	70	Deep and Reinforcement Learning to predict component remaining life
21	Automatic warning on people on range due to machine anomalies	71	Cloud Database with production engineer's workload linked with Team Project building
22	WhatsApp messages of malfunctioning	72	Alarm System for excessive workload
23	Glass visualization of malfunctioning parts	73	Automatic optimization of workload in a new scenario
24	Automatic Warning on next and previous machines of malfunctioning parts	74	Reminder system for ongoing project
25	Notice of planned CIRL/AM/PM activities	75	Glass visualization for how to solve anomalies
26	RFID objects identification and localization	76	Glass visualization of CIRL/AM/PM/SOP/OPL/SMP SMED procedure
27	RFID tags which store instructions for cleaning tools and objects	77	Virtual Training Simulation (Machine Breakdown, WCM tools, SMED, Procedure)
28	Glass visualization of where replace instruments	78	Efficiency Data on HMI and Workplace device
29	Substitution of physical shadow board with virtual board	79	Tool/utilization glass—guided

Table 2. *Cont.*

30	Robot Collaborative/Exoskeletons support	80	Tips directly sent to Responsible
31	AGV systems for bins and container transportation/picking activities	81	Tips status directly visible by operator with workplace device
32	RFID tag with procedure instructions	82	Automatic Lighting of part to be handled/picked
33	Autonomous workload deployment among the machines	83	Common shared Platform with other company's plant
34	RFID tag embedded in unfinished products to prepare next machine production	84	Automatic Scraps Categorization given by machine sensors
35	Workload shift among stations given by real-time production data analysis	85	Automatic Warning of out of parameters process
36	Automatic Machine configuration	86	Common shared Platform with Customer and Suppliers
37	IT Systems directly connected with MES and PLC	87	Claim directly sent to Line Leader and Quality Manager
38	Glass visualization of unloading procedure goods for suppliers	88	Glass Visualization of Product Defect
39	Automatic request on workplace device of switching workstation	89	Line Process Simulation
40	Operation tuning and better performance with 3D Printing Technology	90	Visual Camera Poka-Yoke and Product's parameters monitoring
41	Digital Platform—opportunity to allocate orders watching at suppliers' capacity	91	Virtual Test to assess competence with automatic gap definition and training needed
42	AGV guided by machines needs indication	92	Machine Learning to prevent reworking and to set correct machine parameters
43	RFID tag on unfinished products to track them in real time	93	Online Test to assess competence with automatic gap definition and training needed
44	Continuous stock monitoring with RFID tag	94	RFID Tag for each employer's badge with his information
45	Virtual CAD model on Kanban loops	95	Automatic data analysis on absenteeism for machine and department
46	Real-Time Kanban optimal size and frequency Simulation	96	Automatic data analysis on absenteeism cause
47	Autonomous Kanban system among stations	97	Glass visualization of defects linear and nonlinear
48	Vocal/Maps interactive guide to find the SKU	98	Production pace tuning according to buffer levels
49	Real-Time Simulation of picking activities path to have the faster one	99	Simulation of workplace environment for ergonomic optimization
50	Glass visualization of stock data	100	Glass visualization of heavy packs

7. Discussion: I4.0 and WCM Synergy

The following paragraphs show how I4.0 technologies can streamline and simplify the processes required by WCM. As shown above, in fact, I4.0 is certainly also a facilitator of the internal dynamics of industrial plants.

The WCM system, for its part, requires great rigidity in terms of information content. It has already been noted that each pillar is structured on seven steps, each of which requires several tasks. Very often, these tasks require a costly collection of information, which is still mostly done on paper. Bordereau, Suggestions, EWO, Tags, HERCA (a simple tool to identify the root cause of human error and set up a countermeasure), Waste Collection, AM/PM/WO Calendars: all these are usually preprinted forms to be filled out by the operator. It is easy to guess how these processes are exposed to frequent errors and inaccuracies. These errors lead to time losses for the compilation and delays in the transmission of the data to the information system. Suffice it to say that each of the above-mentioned tools somehow impact CD, modifying the internal loss items from A Matrix to the allocation of priorities for projects in the D Matrix.

I4.0 can remedy all this, bringing with it a level of accuracy and precision which is essential for WCM. In addition, I4.0 undoubtedly presents itself as a 360-degree quality improvement agent for the working environment: safety and ergonomics levels can be significantly increased with simple (but also complex) technologies. Maintenance performance (professional and autonomous) can improve exponentially, as can Quality Control and Logistics.

These are all pillars of the shop floor, one of the areas with the greatest impact of I4.0 on WCM.

7.1. Industry 4.0 Impact on Safety Pillar

The goal of Safety is zero injuries, zero medication and risk reduction at its root. WCM's approach to safety is based on the principle that any minor or missed injury is a potentially serious injury; serious injuries must also be eliminated. In this sense, I4.0 technologies can offer a significant contribution in several ways:

- Streamlining the main bottom-up processes: the registry of AU, UC and NM can be carried out directly by the operator in the workplace and instantly displayed by safety managers, line managers, supervisors and other operators, ensuring greater transparency of information and shorter response times from management;
- Ensuring the proper use of Personal Protective Equipment (PPE): Visual Camera and nonuse alarm systems can reduce accidents due to the lack of use of PPE;
- Reducing the risks for pedestrians: forklifts and people can be equipped with sensors that signal their presence on interactive maps; a forced braking system can be activated in case the distance between forklift and pedestrian becomes dangerous and the speed does not decrease;
- Introducing new countermeasures: AI allows an automatic stop of the machine as soon as UC occurs, which can also be learned over time thanks to Machine Learning techniques; augmented reality enables the operator to real-time monitoring process parameters in order to recognize UC and prevent UA or, for example, identifying the weight of a load; collaborative robotics and exoskeletons reduce unergonomic operations and help the operator to carry out operations by strongly reducing the associated risk factors.

7.2. Industry 4.0 Impact on Cost Deployment Pillar

CD is the leading pillar of the World Class Manufacturing system and also the one that requires more computing capacity.

The WCM system is based on the possibility of being able to calculate and, therefore, always be able to quantify the losses generated within the plant. To do this, a large amount of information is required. The robustness of this data, in terms of precision, reliability and accuracy, is not always guaranteed, as it comes from sources that are not adequately monitored, whose information pool is limited or entirely entrusted to human monitoring. The risk is significant: the outputs of the A Matrix, and, therefore, the cascade of all the matrices, may not reflect reality. The plant managers assume the risk in taking a direction that may not be appropriate, reacting to a situation that is not real. In the worst case, the expected benefits are not reflected at the end of the year in F Matrix.

The benefit of implementing I4.0 technologies is considerable. Thanks to their use it is in fact possible to automate matrix compilations and TTC calculations: data collection sources can be digitized. Bordereau, Scrap Collection, EWO are directly recorded in a Cloud environment, enabling data computation with the use of appropriate software. The same goes for production and energy data: Cyber-Physical systems constantly monitor the production environment and what is required can be directly entered into the A Matrix.

The I4.0 paradigm, therefore, enables systematization in the collection of data, providing CD with information that helps to faithfully describe the reality of the plant, so as to efficiently direct the use of resources avoiding that they are concentrated where it is not really necessary.

7.3. Industry 4.0 Impact on Focused Improvement Pillar

FI has the task of monitoring the costs and benefits of the active projects in the plant, by suggesting the activities to be carried out and supervising the ongoing activities in accordance with WCM theory. FI is also responsible for the definition of the tools and methodologies to be used in addressing the improvement projects of the other pillars deriving from D Matrix.

I4.0 technologies can offer a contribution to FI on the concepts of continuous monitoring of plant efficiency and other improvement activities of this pillar, such as the reduction of microstops or the execution of SMED (Single Minute Exchange of Die, an improved approach for shortening changeover times) projects. In particular, they can:

- Enable continuous monitoring of efficiency data: Thanks to IoT, it is possible to constantly, reliably and accurately control the Overall Equipment Effectiveness (OEE) of the plant in the Cloud, by performing real-time analysis that can be displayed on the Human–Machine Interface (HMI) or workplace devices;
- Increase MTBMS (Mean Time Between Minor Stoppages) and reduce the duration of the microstops: Machine Learning techniques allow the machine to optimally set working parameters by learning from previous stops, increasing the mean time between two microstops. HMI shows the procedures to solve the most complex anomalies; augmented reality glasses allow the display of malfunctioning components of the machine
- Significantly improve the SMED activities: Augmented reality glasses can show in real time the optimal sequence of activities of a set-up cycle on a machine; virtual training improves the performance of maintenance workers during the production changeover; Plug and Play systems allow a modular design of the machine, aiming to eliminate the set-up activities; in the same way, 3D printing requires almost zero time to set up new production.

7.4. Industry 4.0 Impact on Autonomous Maintenance Pillar

With the AM pillar, the objective is to transform plants and equipment in order to make them safe, clean, reliable, inspectable and maintainable. A calendar of Autonomous Maintenance and CIRL activities is defined and implemented in such a way as to reach the main target of AM (i.e., the complete reduction of faults due to the lack of basic conditions). Moreover, in parallel, AM aims to train the operator in order to make him able to discover anomalies and solve them, to define the correct operating conditions to avoid failures and rejects and to autonomously take care and manage the shop floor.

In this sense, I4.0 technologies can:

- Improve the control and monitoring of basic conditions: Thanks to IoT the machines can autonomously signal the departure from a preset basic condition; with Mobile Technologies

and Augmented Reality it is possible to be guided during the autonomous inspection phase of the machine;
- Improve the time and effectiveness of CIRL and AM activities: Through CPS, HMI allows the monitoring of dirt sources and lubrication points by signaling to the operator the execution of a planned CIRL activity; through the use of on-the-job devices or augmented reality glasses it is possible to view CIRL and AM calendars and be guided during the relevant procedures;
- Improve the phase of detection and resolution of anomalies: Anomalies are automatically signaled by the machine through different types of warnings, directly displayed on the device or to an operator in range; through AR glass visualization, operators can identify the malfunctioning components and be guided during the phase of the resolution of anomalies; Machine Learning techniques enable the machine to "learn" from anomalous events happened in the past and signal the risk of recurrence.

7.5. Industry 4.0 Impact on Workplace Organization Pillar

Workplace Organization deals with the man-workplace relationship while maintaining, however, a constant view of process efficiency. I4.0 technologies in this sense can:

- Significantly improve ergonomics: Collaborative robots and exoskeletons, in addition to reducing the number of NVA operations, replace humans in less ergonomic and more risky operations; the simulation of the work environment and operations can prevent exposure to risk to more or less serious injuries;
- Optimize the use of SOP and OPL: Virtual training instruct operators on the standard procedures to be performed during production cycles; the same procedures can be visualized with augmented reality glasses, by means of a device in the workplace or by reading RFID tags containing this information. This eliminates a large number of paper-based procedures that very often limit the effectiveness of operator training, eventually feeding an effective digitized training system;
- Balance the operators' workload.

7.6. Industry 4.0 Impact on Professional Maintenance Pillars

I4.0 includes the concepts of monitoring, control and implementation, prediction of results, autonomous calculation and classification, concepts that are well suited to the needs of the PM pillar.

In fact, the implementation of I4.0 technologies can bring significant improvements to PM pillar performance:

- MTTR reduction: Machines can autonomously warn the maintainer about the presence of the fault by reporting descriptive information of the faulty component; thanks to Machine Learning techniques, machines can learn from previous faults and remember their precedent behavior; virtual training can reduce MTTR and augmented reality can guide replacement operations;
- PM Calendar execution: The maintenance technician examining the various machines in few seconds can get information on the status of the PM Calendar thanks to augmented reality or to a device connected to the network; the Standard Maintenance Procedures (SMP) can be tested in a virtual environment or can be guided by means of augmented reality glasses;
- Predictive Maintenance: Through suitably positioned CPS and software able to perform computations on complex predictive mathematical models or with the help of Neural Networks and Deep Learning algorithms, it is now possible to have real-time information on the health status of the component, showing the maintainer the estimated residual life via mobile device or through augmented reality glasses; it is possible to receive notifications about the current status of the component, and an alarm before an expected failure.

Summing up, the result is a possible decrease in maintenance costs (in accordance with the logic of the last steps of the pillar) due to the presence of precise and reliable information that guarantees the minimum sum of spare parts and failure costs.

7.7. Industry 4.0 Impact on Quality Control Pillar

The demand for a precise and accurate process monitoring system, together with the opportunity to automate the computation of the pillar's core matrices, makes QC one of the WCM areas that most benefit from the use of I4.0 technologies. In fact, the use of I4.0 technologies makes it possible to:

- Automate the compilation of QA, QA Network, X Matrix, QM Matrix matrices: Cloud services make it possible to take advantage of greater computational power by replacing manual compilation; the necessary condition is also an accurate, precise and reliable system of waste collection that can be ensured through IoT;
- Improve statistical process control: As soon as it is highlighted, the automatic process data analysis can be automated and made available in real-time on any device. The benefits can be seen in the timeliness of the response when a failure occurs, in the reliability of the results, and in the reduction to zero of the expected analysis time;
- Improve quality controls and waste collection systems: Thanks to CPS and learning techniques of recognition and classification, the waste register stays inside the machinery. Machine Learning algorithms enable the machine to recognize nonlinear defect patterns, otherwise untraceable, and advanced cameras allow the prevention (Poka-Yoke) or interception of defects with a maximum degree of reliability.

7.8. Industry 4.0 Impact on the Logistics Pillar

The Logistics pillar foresees strong cooperation with WO to reduce internal handling and to structure the working environment, in accordance with the above paradigms. In this sense, I4.0 technologies can:

- Balance workloads: Interconnected machines are able to autonomously decide how to distribute workloads according to the number of orders required and their available production capacity; they are also able to adapt the production rate to the detected buffer levels, and thanks to real-time simulation a continuous optimization of resources is guaranteed;
- Reduce lead times: The creation of a shared platform with suppliers for order allocation and order management considerably reduces the complexity of relations with suppliers and customers;
- Enabling Just in Time production: In addition to the previously described functionalities, automatic guiding vehicles (AGVs) missions can be directly triggered by machines, and a kanban system can be autonomously managed and implemented through interconnected machines, and/or optimized through real-time simulation.
- Improve warehouse management activities and decrease handling effort: RFID tags continuously track the product and allow continuous monitoring of stock levels, also through augmented reality glasses; picking activities can be optimized through real-time simulation and can be guided by voice and/or interactive map reducing errors and lead times. The use of collaborative and intelligent robots that can move loading units as well as shelving, greatly reduces handling activities.

7.9. Industry 4.0 Impact on Early Equipment Management Pillar

Attention to the transitional phase of the production process is an important component of the WCM system. The EEM pillar is one of the new elements that WCM brings with respect to Lean Manufacturing, and is concretized in the search for high-performance and quality indicators and the reduction of Life Cycle Cost through the efficient design of the machinery. Considering these elements, I4.0 technologies allow to:

- Improve the Design phase of the machinery: A Computer-Aided Design (CAD) platform shared with suppliers allows the faster exchange of information and more efficient cooperation;
- Significantly increase performance: Plug and Play systems generate a modular design of the machine through which set-ups, tooling and cleaning times are reduced: Advanced robotics allow the reduction of the duration of complex operations and additive printing couples many stages of the production process ensuring high product quality most of the time by reducing to zero set-up times;
- Reduce start-up times: Thanks to Machine Learning skills, the machines can quickly learn from previous errors by setting the correct process parameters.

7.10. Industry 4.0 Impact on People Development Pillar

PD has the main objective of aligning the plant on high levels of involvement and competence, to achieve business results and job satisfaction. The pillar inputs do not exclusively come from the analysis of human errors: S-Matrix and QA Matrix, as well as the C Matrix of the CD, are other components on which PD insists to achieve the reduction of wastes and reworks as well as insecure working conditions or actions.

In this case, the I4.0 technologies allow to:

- Speed up the Gap Analysis phases: Online or virtual tests can instantly define the current level of competence and trace the gaps in knowledge, indicating exactly where to intervene by carrying out training activities;
- Improve training activities and the use of tools by limiting human errors: Guides to the use of WCM tools are available directly on the device in the workplace; RFID tags contain specific procedures or instructions for the use of tools that can also be viewed through augmented reality glasses; in the same way, virtual training can be implemented;
- Streamline Bottom-Up flows in suggestion management: Operators can upload suggestions directly to the Cloud, immediately and directly sharing these with the appropriate managers; they can also monitor the status of the suggestion follow-up.

7.11. Industry 4.0 Impact on Energy and Environment Pillar

The EE pillar aims to reduce energy consumption and losses. The I4.0 technologies also in this case are proposed as a facilitating agent for energy control and monitoring operations, considerably simplifying the phases of consumption analysis and research of countermeasures to be applied in relation to the found root causes. They facilitate the monitoring and analysis of pollution and energy parameters: energy, waste, water and pollution can be constantly monitored through CPS; data from multiple plants can be transferred directly to the Cloud and analyzed real-time, extrapolating values in a single environment where homogeneous and heterogeneous data flow together. In addition, energy losses caused by unnecessary consumption can be avoided, as well as out-of-process parameters can be instantly tracked, and can be promptly analyzed and corrected exploiting a warning system. Augmented reality increases these potentialities, enabling the performance of these operations directly on the shop floor.

8. Conclusions

With this work, the authors wanted to highlight the synergy between I4.0 and WCM and the impact of I4.0 technologies on WCM pillars, a subject almost ignored in the literature so far. After outlining the technological panorama of the so-called Fourth Industrial Revolution and recalling the WCM system, a framework to relate the two concepts has been proposed: the WCM-I4.0 matrix aims to track and categorize the technological opportunities that I4.0 can offer to WCM. Each element of the matrix represents a reasonable need for the WCM model, which can be satisfied by an I4.0 technology solution. The WCM-I4.0 matrix has been compiled with 100 I4.0 applications for shop floor management.

Results show that the synergy between the two universes is evident: WCM may benefit greater accuracy, precision and reliability of information gathering thanks to I4.0 potentialities.

What emerges is that a great heterogeneity of technological opportunities can satisfy many of the needs of WCM functions. The totality of the pillars can benefit significantly from an investment in I4.0 technologies.

For each pillar, moreover, some very interesting applications have been found; it is not possible to define with certainty which pillar is the most beneficiary of a hypothetical investment in I4.0, either because it is not possible to fully access the technological panorama (as manufacturers tend to protect their skills and know-how), or because enough technologies have been found to affirm the importance of I4.0 for each component of WCM.

A question may arise on who shall be responsible for the compilation of the WCM-I4.0 matrix inside a WCM organization: The WCM pillar that deals with the modernization of the plant and the implementation of new technologies is the EEM pillar. Consequently, it seems that this analysis shall be performed by the EEM pillar leader. However, the compilation of the WCM-I4.0 matrix shall be done in collaboration with the other pillar leaders who are responsible for identifying and describing their respective improvement drivers and needs.

Thus, the EEM pillar leader, leveraging on his technical knowledge of the I4.0 innovations and applications, may draft a first compilation of the matrix and suggest a set of technologies to be analyzed by the other pillar leaders.

The construction of the WCM-I4.0 matrix is only the first step to effectively align the WCM with I4.0 investments. A further step may focus on the creation of another matrix, to be coupled with the WCM-I4.0 one, which may exploit an ICE index in order to determine the economic impact of each technology implementation inside each pillar, highlighting the associated costs (and aligning these with the Cost Deployment pillar) along with ease and timing of implementation.

In conclusion, this study affirms the importance of Industry 4.0 for World Class Manufacturing. It is important that, with the continuous growth of competitiveness in the markets, could be translated into a necessity.

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