When Industry 4.0 meets World Class Manufacturing: Developing a Smart Digital Retrofitting strategy for sustainable manufacturing operations

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ABSTRACT

This paper develops an Industry 4.0 step-by-step implementation strategy drawing from the World Class Manufacturing methodology to achieve sustainable value creation in manufacturing operations. In particular, we focus on the first step of such a strategy – namely Smart Digital Retrofitting – a brownfield approach that integrates new technologies and sensors into legacy systems to achieve Industry 4.0 basic requirements of seamless communication, interoperability among machines, and real-time capability. We characterize this step with the socio-technical system factors, describe its positive outcomes in terms of productivity gains and waste and losses reduction, and discuss its theoretical and practical contributions.

KEYWORDS: Industry 4.0, World Class Manufacturing, Smart digital retrofitting, Operations, Strategy

INTRODUCTION

Industry 4.0 (I4.0) represents a critical paradigm shift for most companies in our world of emergent and continuous changes. Although it has been extensively researched and demonstrated that I4.0 is feasible from a technological point of view, the economic and management considerations still need to be clarified in light of its implementation in terms of continuous improvement to undertake sustainable development (Ghobakhloo et al., 2021b). The existing literature demonstrates a strong research interest in this area, however, the need for a clear implementation strategy remains a challenge, especially for brownfield sites, which are predominant in the industry. Such a strategy can provide sustainable value creation in manufacturing operations, as decommissioned industrial facilities include assets, machinery, and facilities not designed to be I4.0 compliant (Guerreiro et al., 2018). Specifically, firms need to manage legacy and new technological infrastructures and operations simultaneously to enable an uninterrupted transition toward I4.0 technological solutions; they also need to gradually substitute legacy systems and analog procedures while preventing customer downtime and business disruptions (Cenamor et al., 2019; Park et al., 2020).

Nonetheless the confrontation between legacy arrangements and novel practices can be far from a linear process (Åkesson et al.,2018), thus requiring an adaptation of corporate strategies and objectives to recent advancements in I4.0 technologies (Kretschmer & Khashabi, 2020; Åkesson et al., 2018). Moreover, as I4.0 and the growing availability of data create the need to adjust processes within and across various business lines (Warner & Wäger, 2019), the literature pointed out that processes need to evolve differently, depending on the types of transformed business operations and value chain stages. In particular, marketing, advertising, and supply chain management are early targets of I4.0, as they can elicit fast and sizable gains for firms, whereas operations result more complex and require deeper considerations (Ghobakhloo, 2020; Guenzi & Habel, 2020; Taylor, 2017).

Therefore, in this article, we investigate the following research question: *how should a company develop and implement a structured I4.0 strategy for a brownfield plant for sustainable digitalization of manufacturing operations?*

This paper aims to bridge this gap by demonstrating that the seven-step approach of World Class Manufacturing (WCM) is a suitable digitalization framework for brownfield plants. First, we analyze Smart Digital Retrofitting (SDR) as a sustainable and cost-effective first step to make manufacturing operations I4.0 compliant. SDR is a brownfield approach that integrates new technologies and sensors into existing systems to achieve the basic requirements of I4.0: continuous communication, interoperability between machines, and real-time capabilities (Jaspert et al., 2021). Secondly, we develop an I4.0 implementation strategy following the seven phases of the WCM and characterize each phase with socio-technical system factors. We then describe its positive results in terms of increased productivity and reduced waste and loss and discuss its theoretical and practical contributions.

THEORETICAL BACKGROUND

Industry 4.0: Technology, Strategy, and People

The paradigm shift of the I4.0 has created disruptions across the economic system, altered the value creation paths of the companies, and sowed profound structural changes (Bharadwaj et al., 2013). I4.0 does not concern a single radical invention but encompasses various *"'tech ingredients' that are still evolving into new enabling technologies by convergence and mutual combination"* (Culot et al., 2020, p.5).

Indeed the acquisition and implementation of more advanced technologies severely rely on integrating various traditional technologies (Ghobakhloo et al., 2021a). Advanced technologies refer to the modern technological innovations that have been under development for the past few decades and have now reached a level of maturity that allows them to be available for commercial use in the last decade (i.e., Big Data and Analytics, Cloud Computing, Cyber-

Physical Systems, Digital Twin, Industrial Internet of Things, Virtual and Augmented Reality). Whereas traditional technologies, which are considered prevailing and mature information and operations technologies, play a crucial role in supporting the advanced technologies of I4.0 to perform their intended functions, they have been commercially available for the past few decades and have been commonly used across various industries (i.e., Computer Numerical Control System, Industrial Actuator and Sensors, Industrial Embedded Systems, Intelligent Enterprise Resource Planning, Machine and Process Controller) (Ghobakhloo et al., 2021).
The confluence of such digital technologies triggers the convergence between physical and digital spaces, enhancing the limited connectivity inside the firm and the widespread connectivity along the supply chain (Culot et al., 2020). Given the well-known benefits of such technologies – e.g., productivity and efficiency improvements in the value creation process, advances in flexibility and agility, quality enhancements of value offerings, and cost reductions – companies that have been able to integrate them successfully into their existing business strategies, could stay competitive and promote new growth potentials (Kane et al., 2015; Stief et al., 2016; Hess et al., 2016).
However, transitioning from the traditional industry, with few or no technologies introduced in its processes, to I4.0 practices requires a complete review of operations (Ghobakhloo, 2018). Despite I4.0 paradigms, design principles, and technologies have been extensively examined, more empirical investigations linked with the industrial world must be carried out (Koh et al., 2019). The isolated adoption of technologies generates high investments and expectations but marginal gains in product and service development, thus frustrating managers. On the one hand, adopting a novel Information and Communications Technology before implementing an adequate level of lean practices results in high capital expenditure on wasteful and poorly designed processes. Many companies are still struggling with implementing I4.0 solutions into their operations, as purely technological adoption does not generate the expected results (Tortorella et al., 2019).
On the other hand, I4.0 has been framed as a socio-technical phenomenon, requiring the alignment of technology, strategy, and people (Beier et al., 2020) and, as such, needs to be complemented with adequate digital skills (Firk et al., 2021). This new industrial paradigm changes the roles of human resources and machines in production processes, restructuring the very essence of the workforce concept (Terziyan et al., 2018). Consequently, companies wanting to start their journey toward I4.0 practices must first consider their strategic objectives before implementing any technology (Dalenogare et al., 2018). Therefore, the effectiveness and feasibility of integrating I4.0 into management systems of existing production require more practical insights.

Smart Digital Retrofitting

Brownfield sites, which predominate in the manufacturing industry, are mainly based on heterogeneous technological structures and architectures due to continuous development processes that occurred over the last decades. Indeed, the migration from traditional industry to the I4.0 paradigm presents several issues, as brownfield sites encompass machines and technologies coming from different vendors that are discontinued or no longer updated and were partially replaced by other technologies. As such, replacing old plants with a new-generation plant designed for I4.0 is economically and timely inconvenient and technically challenging, thus opening the doors to the digital retrofit alternative (Ehrlich et al., 2015).
The digital retrofit process involves the addition of new software, hardware, or protocol-related components to existing equipment to expand and update its capabilities and meet new requirements.

This approach is cost-effective – as it avoids the incurring of significant investments required for redesigning or purchasing new equipment – and enables companies to consider a full or partial migration to new technologies while ensuring the continuity of their traditional methods (García et al., 2020). In the context of I4.0, we talk about SDR, which goes beyond traditional retrofitting methods by incorporating I4.0 tools and technology along with the classical retrofitting features (Al-maeeni et al., 2020).
Previous research mainly investigated the technical aspects of retrofitting (Etz et al., 2020; García et al., 2020; Gualtieri et al., 2019), also concerning the improvement of maintenance operations (Cattaneo & Macchi, 2019; Herwan et al., 2019; Hesser & Markert, 2019; Silva et al., 2020), safety operations and assessment (Kummer & Varga, 2019; Wu et al., 2014) and sustainability (Ayani et al., 2018; Lins & Oliveira, 2020; Stock & Seliger, 2016). While we see a growing number of articles with a strong technological approach to this topic, there is still a lack of a socio-technical perspective where the strategic and social aspects are of critical importance (Jaspert et al., 2021). Although the technical changes allow for more efficient processes, they could also negatively impact if those changes are not adequately implemented along with their systemic complementary factors (Pérez et al., 2018).
According to Jaspert et al. (2021), current research on SDR focuses on new technologies and legacy systems but largely disregards transformational aspects regarding the strategy at the organizational level and the interdisciplinary knowledge and skills required for a successful retrofitting process (Jaspert et al., 2021). In fact, *"the complexity, interdisciplinarity, and integrative nature of digital retrofitting make a structured and selectively guided workflow crucial"* (Tantscher & Mayer, 2022, p. 36).

World Class Manufacturing: Principles and Deployment

WCM is a set of concepts, policies, techniques, and principles for operating and managing manufacturing operations that was conceived to deliver world-class performance (Schonberger, 2007). Its purpose is to systematically eliminate waste and losses in manufacturing operations through the rigorous application of standards, methods, and tools. It is based on ten technical and ten managerial pillars (D'Orazio et al., 2020) that need to be developed in parallel to achieve the desired level of excellence in manufacturing operations. Each pillar is mainly linked to a specific area of the production system (such as safety, workplace organization, maintenance, quality, logistics, people competencies, environment, and energy), and through the use of appropriate methods and tools drives its domain to world-class excellence.
For all pillars, WCM defines seven development steps in three phases: reactive, preventive, and proactive (De Felice et al., 2013). These seven steps are designed to guide the implementation of the pillars' activities in a sustainable and integrated way. During the first reactive steps, the purpose of each pillar is to restore basic conditions and standardize the shopfloor and behaviors to ensure they are maintained. In the preventive steps, each pillar focuses on attacking more challenging losses through the use of intermediate methods and tools. Finally, during the proactive steps, each pillar leverages advanced methods and tools to continuously challenge the remaining losses while striving to pursue world-class performance.
Together with the WCM pillars and their seven steps, another fundamental characteristic of the deployment of WCM in manufacturing operations is its model and expansion area approach. Manufacturing processes and flows are first prioritized for each pillar based on the amount of waste and losses they are embedded with. Each pillar is then first implemented in a model area, which is the most critical for the pillar's domain in terms of waste and losses. As the steps or depth in the model area progress, the organization develops knowledge and skills on the correct application of the pillars' methods and tools while also improving an area that, due to its

criticality, maximizes the effectiveness of its activities. After certain depth milestones are achieved, each pillar then expands to other areas, following the waste and losses prioritization previously described. It is essential to underline that the target level of depth and expansion of a given WCM pillar is defined at a strategic level based on the actual benefits expected from the application of the pillar. Therefore, not all areas are covered by a WCM pillar, and not all covered areas are necessarily required to reach the same level of depth as the model area.

THEORETICAL MODEL

Implementing Industry 4.0 with a World Class Manufacturing Framework

As highlighted by Peças et al. (2021), little research was found regarding a holistic application of I4.0's technological concepts towards continuous improvement, which clarifies the potential for improving its effectiveness (Peças et al., 2021). While WCM is mainly based on continuous improvement and loss elimination, Industry 4.0 is based on using all accessible information and data of systems and making decentralized decisions, both involving a global vision and a systemic approach to global profit optimization (Ebrahimi et al., 2019). In this context, the connection between WCM and Industry 4.0 practices paradigm should transform the factory into a fully interconnected environment where decisions can be quickly made based on reliable, accurate, precise, and real-time data (D'Orazio et al., 2020).

Current continuous improvement practices do not have the speed of this new technological standard (Rossini et al., 2019), and there is not much research regarding the holistic application of Industry 4.0 concepts towards continuous improvement, which clarifies the potential for improving its effectiveness (Peças et al., 2021).

However, it is essential to underline that the purpose of this investigation is not to propose a structured approach to integrate lean manufacturing and continuous improvement systems, such as WCM, with Industry 4.0 solutions. The investigation rather focused on developing an innovative framework, based on WCM's seven-step approach, to guide the implementation of Industry 4.0 solutions within manufacturing operations. Within this topic, the purpose of this article is to present the first step of the newly proposed framework, concentrating on SDR as a sustainable and cost-effective first step to making manufacturing operations of a brownfield plant I4.0 compliant.

METHODS

We conducted an exploratory case study of a global automaker company to investigate how a company can develop and implement a structured I4.0 strategy for a brownfield plant for sustainable digitalization of manufacturing operations (Yin, 2017). Such a company recorded a turnover of $100+ bln in 2020, employing over 200.000 people across its 50+ manufacturing plants. In particular, drawing on the principles of WCM and I4.0, we investigated *whether WCM can provide a suitable framework for a company's I4.0 strategy, integrating its digitalization path to achieve sustainable improvements in performance.*

The timeframe for the case study analysis is 5 years, starting from 2017 when the Italian "National Plan Enterprise 4.0", also known as "Piano Nazionale Calenda" – now "Transition Plan 4.0" ("Piano Transizione 4.0") – named after the Minister of Economic Development, was introduced. This plan aimed to promote and foster the adoption of I4.0 technologies, after many years of very minimal attention in industrial policy. It includes measures like "hyper depreciation" and "tax credit for innovation", incentivising investments in technologies, supporting R&D spending, and encouraging training programs to develop the required competencies. The funds

are allocated to machinery and automation solutions, machine maintenance and installation, electrical and electronic equipment, and other investments (MISE, 2017).
We draw on the WCM methodology for the following reasons: (i) it is a philosophy adopted by the company since the early 2000s, therefore, well established at all company levels and practices, especially from the employees' mindset viewpoint; (ii) although it is not a brand-new methodology, its fundamental concept of continuous improvement is more current than ever, especially in the context of the Fourth Industrial Revolution; (iii) it provides a suitable and a systematized framework for better outline and implement the wide concept of I4.0 starting from a model area (manufacturing operations) considered as a pilot. Since 2015, when the I4.0 topic became highly discussed, the company has been reflecting on how to integrate the WCM methodology with the implementation of I4.0 in its manufacturing sites. More specifically, it recognized the risks coming from the implementation of I4.0 solutions without a clear strategy and began reflecting on how to apply WCM's logic and principles to the digital transformation of its industrial sites.

Data Collection

The data were collected during 2022 through multiple data sources to gain a deeper understanding of the dynamics under examination by increasing the information base and diversifying data to reduce biases and triangulate the data to strengthen the reliability and validity of our findings (Patton, 2014).
The primary data collection involved semi-structured face-to-face interviews conducted in Italian and English by at least two researchers following a predetermined topic list. First, we interviewed 11 WCM top and middle managers of the global automaker company; then we interviewed 6 top managers and scientific researchers working in a northern Germany application-oriented research institute with more than 250 employees to ensure a variety of points of view on the same phenomenon under investigation, as well as the granularity necessary for its analysis.
To ensure that experts were knowledgeable and had global visibility on the phenomenon, the expert panel was chosen according to expertise and long-time practical experience on both the topic of WCM and I4.0. Moreover, their heterogeneous background provides an informed opinion on the issues in its different facets.
The interview method was chosen to gather both retrospective and real-time narratives from individuals who have experienced the phenomenon of theoretical interest (Gioia et al., 2013). The interviews lasted from 1 to 3 hours each, were tape-recorded integrally for an overall total of 48,5 hours of interviews, transcribed verbatim, and then translated into English with the help of an independent native speaker, for a total of 330 pages of transcript. An overview of the interviews is shown in Table 1 and Table 2

Table 1: Interviewees of the global automaker company

Interviewees	*In the company since*	*Number*	*Duration (h)*	*Period*
WCM Director Europe and WCM Master Auditor	30+ years	2	2h 2h	15.03.22 29.03.22
WCM Global Autonomous and Professional Maintenance Leader	15+	4	2h 2h 1.5h 1h	11.04.22 15.04.22 27.04.22 04.05.22

WCM Global Cost Deployment Leader	20+	2	1.5h 1.5h	22.04.22 27.04.22
WCM Senior Specialist	20+	2	2h 2h	04.05.22 01.06.22
WCM Global Audit System	20+	1	0.5	01.06.22
International Manufacturing Engineering Leader	30+	3	3h 3h 3h	06.06.22 13.06.22 14.06.22
Global Head of WCM Academy	20+	1	3h	13.07.22
WCM Logistics Pillar Leader	20+	1	3h	14.07.22
WCM Senior Specialist	20+	1	3h	14.07.22
ICT and WCM Manager	20+	1	2h	15.07.22
WCM Innovation and Industry 4.0 Leader	20+	3	3h 3h 3h	16.03.22 26.04.22 19.07.22
WCM Powertrain Maintenance Specialist	30+	1	2h	15.07.22

Table 2: Interviewees of the research institute

Interviewees	*In the research institute since*	*Number*	*Duration (h)*	*Period*
Director R&D Division Manufacturing	25+	1	1h	10.10.22
Group Manager - Distributed Computing and Communication	10+	3	2h 1h 2h	10.10.22 18.10.22 16.11.22
Scientific researcher - Distributed Computing and Communication	5+	2	2h 1h	19.10.22 6.12.22
Scientific Researcher - Manufacturing Operations Management	5+	1	1h	5.10.22
Scientific Researcher - Sustainable manufacturing systems	5+	2	2h	19.10.22
Group Manager – Manufacturing Operations Management	10+	1	1h	18.10.22

We also gathered qualitative and quantitative data from secondary sources, that is, from publicly available information and internal documents, for a total of 350 pages to complement primary data from interviews (Eisenhardt & Graebner, 2007; Yin, 2017). Table 3 describes the secondary data sources.

Table 3: Secondary data collection	
Description of the data source and year	*Evidence (n. of pages)*
Publicly available information	
White papers	40
Archival documents	90
Reports	55
Databases	-
Website	-
Internal documents	
Financial statements of the global automaker company from 2014 to 2021	75
Company WCM Audits	55
Other technical documents and material provided by the informants	35
Total number of evidence	*350*

Data Analysis

We assessed secondary data sources to ensure their overall suitability for our research questions and objectives. We paid particular attention to the measurement validity and coverage of the data. Then we evaluated their particular suitability, including reliability for our research (Saunders et al., 2012). The analysis of secondary data was the starting point for creating a first understanding of the case company to identify and aggregate an initial I4.0 implementation pattern. Secondary data was then triangulated with other sources to help us refine and strengthen our emerging interpretations (Yin, 2016).

Quantitative secondary data were useful for tracing the company's growth path in terms of size and turnover, considering the investments made in digitalization. Following the prescriptions for case studies, we analyzed our data through multiple rounds of coding (Gioia et al., 2013).

Coding and measurements were implemented to reduce the potential of confirmation bias affecting the results and growing descriptive and theoretical validity (Strauss & Corbin, 2014).

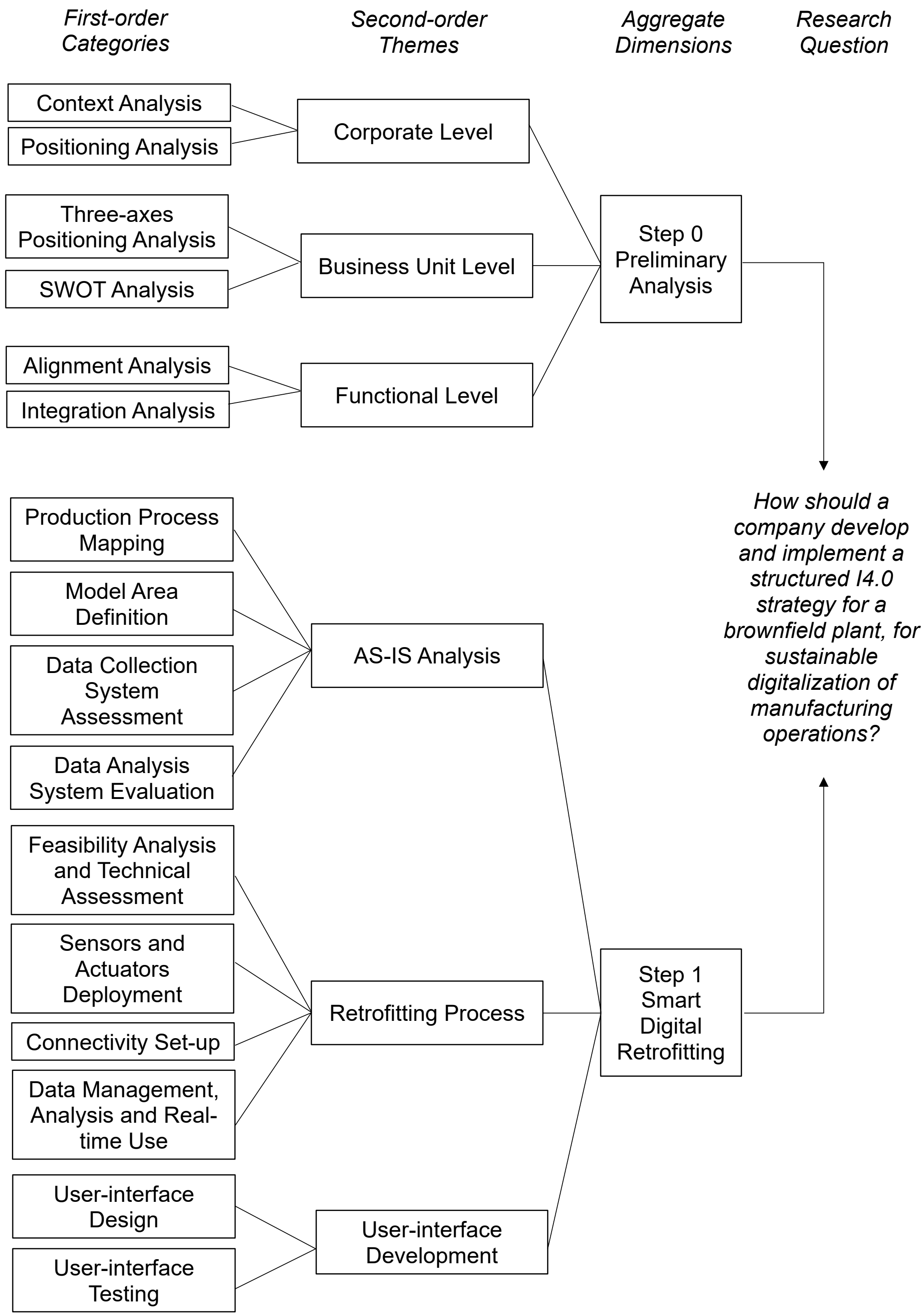
We coded the SDR implementation process of the company according to the WCM principles and practices and searched the data for references to the technological, strategic, and social SDR complementary factors. To verify the reliability of our coding, we individually checked the previously coded text to ensure the internal consistency of the emerging coding structure (Miles & Huberman, 1994), and we performed periodic comparisons between us (Locke, 2001). Through iterations of feedback we have been able to reach a convergence of the experts' opinions.

The inductive analysis of the primary and secondary sources allows concepts and relationships to emerge from the data to identify how a company can develop and implement a structured I4.0 strategy for a brownfield plant for sustainable digitalization of manufacturing operations. We iterated back and forth between the empirical data and emergent theory to identify themes and overarching dimensions to develop an empirically grounded framework.

Then, we disentangled the I4.0 implementation according to the seven steps of WCM, and we characterized each step with the socio-technical system factors. Data were coded into first-order categories, and these were then clustered into second-order themes, which converged into aggregate dimensions (Gioia et al., 2013). We constantly updated and refined our emerging framework based on evidence gathered in subsequent interviews (Burawoy et al., 1991).

The results of the coding procedure are presented in Figure 1 and will be described more extensively in the Results section.

Figure 1: Results of the coding procedure



In the final step of our analysis, a pattern-matching technique was used to compare the predicted theoretical pattern with the observed empirical pattern (Yin, 2017).

RESULTS

Drawing from the WCM methodology and our data analysis, we derived an I4.0 step-by-step implementation strategy. We focus particularly on the first step, identifying SDR as a suitable approach to make manufacturing operations I4.0 compliant and characterizing it with the socio-technical system factors – (i) a sequence of strategic and technical activities required to move to the next step; (ii) the main criticalities to be solved to build a solid foundation/path; (iii) the specific skills required by the company's roles.

Step 0: Preliminary Analysis

It is essential to lay the foundations for an informed and successful long-term strategy.
Its (i) strategic and technical activities are carried out at three different organizational levels: corporate, business unit, and functional.
At the corporate level, the goal is to achieve an overall excellent condition to maximize the profits obtained globally from all the different business units and functions of the company. Two types of analysis should be carried out: context and positioning analysis. For the context analysis, a useful tool is represented by the PESTEL analysis of the surrounding world's Political, Economic, Social, Technological, Environmental, and Legal situation. It is used to determine the external factors and understand the context in which the company operates to properly define goals, priorities, and constraints from the external context. For the positioning analysis, a three-axis tool (level of service, inventory level, operative expenses) is suitable for developing the business strategy that is intended to be adopted. Such a strategy is driven by factors such as market competitiveness and customer response to the company's choices. Each company can choose its positioning independently, considering the type of product or service it offers, usually through a benchmark with other competitors.
The three-axis tool can also be used in the business unit level analysis. In this case, every business unit refers to different targets and has different needs and goals, mainly in terms of level of service. This positioning is not independent from the corporate one since the board defines the company's overall objectives, which are reached through the results of each unit. Then a SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis aims to determine the business unit's competitive positioning by considering and evaluating internal and external elements.
At the functional level – in this case, the manufacturing function is considered – the proposed I4.0 step-by-step implementation strategy can be applied. It is necessary to keep in mind that Manufacturing itself is one of the business functions, so superimposed inputs and constraints must be respected (alignment analysis). Coordination between this function and all the other company functions or departments is fundamental to reaching the global excellence of the company (integration analysis). This means that some specific solutions designed to solve highly specialized aspects of production cannot be implemented at the corporate level because the optimal situation for the company – which is achieved by harmonizing and managing all functions as a whole – does not always correspond to the optimal situation in a single department.
The (ii) criticalities to be solved in this Step 0 are mainly to identify the strategic goals of the retrofitting in terms of I4.0 targets, such as improving working conditions, better quality processes, better communication, collaboration, improved productivity, improved efficiency,

flexibility, agility, or reduced costs. The scope is to evaluate the current status of digitalization through an assessment of the company, an evaluation of current and future resources, and a study of the possible incentives. The outcomes are an Assessment Score and Competence Map, a Benefits and Costs estimation, and a Digital Strategic Plan (including objectives, KPIs, schedule and milestones, and incentives plan).
Finally, the (iii) skills required for top and middle management are mainly analytical, managerial, strategic, and technical.

Step 1: Smart Digital Retrofitting

This step concerns the following three phases: (1) as-is analysis, (2) retrofitting process, and (3) user-interface development.
In the as-is analysis phase (1), a maturity assessment of the industrial process in terms of data collection and management is carried out.
First, the production process needs to be mapped by developing an accurate description of the plant and process to analyze the plant's main functions and identify bottlenecks and critical areas to assess how lean the process is. Then the variables (e.g., temperature, pressure, flow rate) that come into play in the process, the variables already monitored, and those that must be controlled are identified. Significant issues in the process must be solved within this step since moving to the next phase will only be possible if the production system is lean. Therefore, tools from the existing pillars of WCM can be applied to determine how to reduce waste and losses in the process. For instance, valuable tools from the Cost Deployment pillar are Matrix A – which shows where the inefficiencies are in the process and their entity - and Matrix B - which correlates the losses and their root causes in order to act on them directly.
Second, a model area should be defined. Following the WCM approach, the improvement actions are first taken within a Model Area – that generally is the most critical one (e.g., the machine with the highest number of failures) – and then the measures are brought to an Expansion Area, up to be implemented in the whole plant. Therefore, the definition of the Model Area is crucial to get results quickly and develop the experience and know-how necessary to expand the improvement actions throughout the process.
Third, the data collection system should be assessed by investigating which and how the data is collected and distinguishing between basic and advanced data. Basic data focuses on high-level production performance, such as production, quality, and costs/resource consumption. This data must be collected at the end of the production process and specific critical points (bottlenecks), as they are always necessary for an overview of the production. Activities auxiliary to production can also be highlighted when determining critical data to control the operations. Advanced data is more detailed data (e.g., OEE, MTBF, MTTR) for in-depth monitoring and analysis of the performance of a specific and critical portion of the process. It is unnecessary to have them run the process in a traditional way. As the lean manufacturing system is implemented, these data become an essential source of information to make improvements and to take the production system and all the auxiliary activities under control. Identifying which type of data is necessary is a critical step that will affect the goal definition and the future benefits of SDR.
Finally, the data analysis system should be evaluated. Since the data collection system has been analyzed, it is necessary to investigate how data are exploited. If they are used to monitor and improve the production system, then the system that the company is already using to manage data can be enhanced such that the digitalization process can start. On the contrary, if the company uses no data or the system is not mature enough, a data management system

must be implemented to exploit data coming from production to make the system lean and reduce wastes and losses with the already available data.
In summary, what is required by this step in digital terms is to understand if there are sensors along the line, if they are working and collecting data, and if there is a usage of the collected data. The output of this analysis provides essential information about the process and the capabilities of the company to use and manage data properly.
Two restrictions must be observed to move on to the next step. If the system is not lean, the company cannot move to the next step to avoid the digitalization of waste and losses, which would lead to inefficient use of the resources. Whereas, if the company does not have a system made by software and good practices to manage data, the next step cannot be undertaken because the company is not mature enough to move to the digital approach.
These constraints aim to avoid the arise of digital wastes or inefficiencies in the data management system, which would make the effort in digitalization vain and the investment unprofitable. Moreover, the foundations for a lean manufacturing system are laid since the prerequisites in terms of data collection and management that are defined in this step are also the basic information required to implement a lean manufacturing system, which is fundamental for a manufacturing company that wants to shift towards the I4.0 paradigm.
The (ii) criticalities of the as-is analysis phase to be solved are mainly the clear distinction between basic data and advanced data since it will affect the Smart Digital Retrofitting goals and future benefits.
The second phase of Step 1 is the retrofitting process (2), a strategic technical guide for first-time quality implementation and predisposition for I4.0 scalability. As the vision concerns start from a model area towards implementing I4.0 in the whole plant, a future-oriented mindset is necessary. This phase is also based on four (i) strategic and technical activities.
First, feasibility analysis and a technical assessment are carried out to evaluate all the necessary technical interventions at the hardware and software levels and all related costs (design, acquisition, installation, operation, maintenance, and disposal); and development and installation time (machine downtime). The necessity and cost (time and money) of establishing a comprehensive catalog of existing, employed technologies, communication standards, and/or I/O interfaces are functional for the following activities. In fact, SDR is challenging without this information, as it can be astonishingly time-consuming to find out details about a 30-year-old machine, for instance (that otherwise works well). Such information should be collected systematically and in a structured way; otherwise, when collecting it on-demand, the result is an unpredictable critical path. It also might happen that some information is irretrievably lost; thus, it is necessary to know that to plan an alternative better. Afterward, it is essential to find suppliers for Internet of Things (IoT) devices/hardware components that can interface with those technologies/standards. Such a process might be either expensive and/or time-consuming.
Second, sensors and actuators are deployed by defining the strategic points to record further physical values/variables such as vibrations, temperatures, or cycle times. Upgrading the infrastructure of the legacy machines requires retrofitting smart sensors, actuators, and IoT devices in order to establish a starting point for integrating physical and virtual worlds. These strategic points should be made usable to guarantee data extraction from machines. Therefore, controllers such as microcontrollers, PLCs, or computers are introduced in this step and referred to as IoT nodes. The introduction of IoT nodes ensures the data extraction from the sensors and connects the machine to the internet to facilitate the next steps. Then, a secure gateway between the physical and cyber layers should be established by introducing a middle layer called Industrial Internet of Thing (IIoT) gateway, which is further connected to IIoT middleware. For this purpose, a standardized communication protocol is required (OPC UA): this protocol ensures accurate and swift data transfer between the machine and the IIoT middleware. Finally,

each retrofit device itself should be required to support OPC UA to keep the impact (technical risk, efficiency loss, monetary cost) of legacy technology mismatch as localized and independent as possible.
The last activity of the retrofitting process concerns data management, analysis, and real-time use. As basic/advanced data are digitalized for Smart Data Collection, the collected data is stored in databases, sent for analytical purposes using a web-based software or local edge-computing device, and used in real-time.
The (ii) criticalities to be solved are mainly to create a future-oriented mindset, which is necessary to start from the model area and towards the whole plant.
Finally, the third phase of Step 1 is the user-interface development (3) to make the developed applications easy to use for the operators. Although operators should have experienced at least some training and are known, the interface must be designed to operate by very heterogeneous user groups with little to no training in varying contexts and environments and with only a little knowledge about the users themselves. Its (i) strategic and technical activities are only the development of such a user interface. The (ii) criticalities to be solved are mainly the development of a user interface that is easy to use for the operators.
In terms of skills (iii) of the whole SDR step: (a) operational roles no longer manually enter data but read, understand, and verify the correctness of such data. To do so, basic data analytics skills complement their legacy skills; (b) middle management and process technicians can actually exploit the data collected by strong analytical and data-driven decision skills, in fact, digital technologies require employees to depend more heavily on their analytical skills to solve increasingly complex business problems; (c) top management should be aware of the potential of data and lead the employees towards its exploitation.

<u>Preliminary benefits of an Industry 4.0 step-by-step implementation strategy</u>

The following quantitative results have been provided by the company thanks to the processing performed by its customized and proprietary data collection system, which is specific for identifying waste and losses. In addition to gathering a significant amount of data, this system is also capable of integrating various types of data and cleaning them in order to make them usable for analyzing various KPIs.
We found that the I4.0 implementation in a brownfield setting of automotive manufacturing facilities, together with the application of a lean methodology such as WCM, improves manufacturing data collection accuracy (+85%) and speed (+60%). This reduces the time required to complete improvement projects (-20%), and increases the accuracy of the expected savings (+15%), enabling greater productivity (+20%) while lowering maintenance costs (-23%), downtime (-35%) and quality costs (-25%).
We also found on the one hand that the benefits of WCM on I4.0 concern avoiding automation and digitalization of wastes and knowing what to measure and what to control; on the other hand that the benefits of I4.0 on WCM include the elimination of shortcuts wastes and the use of a reliable source of data to measure improvements.

DISCUSSION AND CONCLUSIONS

To investigate how a company can develop and implement a structured I4.0 strategy for a brownfield plant for sustainable digitalization of manufacturing operations, we conducted an exploratory case study of a global automaker company (Yin, 2017) developing an I4.0 implementation strategy drawing on the principles of WCM.

We propose a preliminary analysis step and a smart digital retrofitting step and characterize each step with the socio-technical system factors. I4.0 requires significant investments from companies, and it is, therefore, necessary to make strategic and careful choices to achieve the planned results – thus making the investment profitable and pursuing sustainable value creation as an outcome of the undertaken actions. However, our results highlight the importance of a Lean Manufacturing system, considered a prerequisite for implementing a successful digital production system. We here discuss three main points.

First, the smart digitalization of existing production processes allows identifying waste and losses more quickly and accurately, guiding plant management to understand the improvements which must be implemented from either a technical or social viewpoint to enhance production performance, for example extending the life cycle of machinery and equipment in a way that is feasible, time-saving, and requires comparatively low investments concerning the replacement (García et al., 2020; Jaspert et al., 2021). I4.0 enables novel forms of organization of manufacturing processes. The distributed model of production can help realize I4.0 technologies' sustainability potential by creating favorable conditions for the development of resource-efficient and sustainable manufacturing (Kumar et al., 2020). Distributed manufacturing's contribution to sustainability is realized through shorter lead times; an emphasis on production to order, rather than make-to-stock; and a modular production process (Srai et al., 2020).

Second, we argue that the SDR should be supported, developed, and implemented by a dedicated team led by a Digital Transformation Officer, a hybrid figure with a mix of managerial and technical skills (Firk et al., 2021). In fact, on the one hand, our findings highlight the need for analytical, managerial, strategic, and technical skills, specifically the complementarity between basic data analytics skills and legacy skills, followed by data-driven decision skills. On the other hand, the need for creating a distinct and central role to handle the digital transformation successfully is fundamental as digital transformation is associated with a shift in corporate strategy toward differential value creation based on digital resources and skills, and it transcends functional and divisional boundaries thus requiring central coordination.

Third, as stated by Terra et al. (2021), we are aware of the difficulties in integrating I4.0 and WCM due to the rapid expansion of production systems and the increasingly complex data monitoring (Terra et al., 2021). Despite the positive outcomes of linking a company's strategy to Industry 4.0 practices and the World-Class Manufacturing method, some challenges still remain, such as the costs associated with the use of technologies, the lack of knowledge of the applied methods and tools, the lack of trained and qualified human resources, and the resistance of people to the use and application of the newly adopted practices. All these factors, mainly related to the lack of staff and finance, might led to losing interest into projects in early stage.

Our study contributes to theory as it refines and enhances the WCM approach – by integrating the I4.0 concept – and systematizes the I4.0 concept – by disentangling its implementation into seven incremental steps with a socio-technical system perspective.

The practical contribution for managers is the definition of a model to guide investments in I4.0 technologies for an optimal implementation of the I4.0 socio-technical system. Specifically, smart digitalization of existing production processes allows managers to identify waste and losses more quickly and accurately, helping them understand the improvements which must be implemented from either a technical or social viewpoint to enhance production performance.

The contribution for policymakers is the definition of industrial and labor policies to enable firms to accumulate competencies and achieve competitiveness improvements.

As this study is part of a bigger research project, future research will focus on the other steps of the I4.0 implementation strategy. Simultaneously, further research is needed in the automotive sector by analyzing other companies and with multiple case studies in different industrial sectors to generalize our findings and study the effects at a macroeconomic level.

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