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A framework to design smart manufacturing systems for Industry 5.0 based on the human-automation symbiosis

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ABSTRACT

The concept of Industry 5.0 (I5.0) promotes the human-centricity as the core value behind the evolution of smart manufacturing systems (SMSs), based on a novel use of digital technologies in the design and management of modern industrial systems to take up the socio-technical challenges. In this context, the paper proposes a Smart Manufacturing Systems Design (SMSD) framework enabling I5.0, based on the human-automation symbiosis. Thanks to an 'Augmented Digital Twin' (ADT) able to integrate and digitize all the entities of the factory (i.e. machines, robots, environments, interfaces, people), AI-driven applications can be built to support the user domain and make people and machines co-evolve thanks to a systematic data sharing between physical and digital assets (e.g. digital twin, virtual mock-ups, human-machine interfaces), optimizing factory productivity and workers wellbeing. In this framework, machines and humans can both generate knowledge and learn from each other, generating a virtuous co-evolution, supporting the understanding of the human-machine interplay and the creation of an effective collaboration between people and SMSs. The framework was conceived and validated involving four industrial companies, belonging to diverse sectors, interested in overcoming the current limits of I4.0 lines by including the human factors for future SMS management.

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Industry 5.0; Operator 4.0; Operator 5.0; augmented digital twin; smart manufacturing systems; human-automation symbiosis

1. Introduction

Industry 4.0 (I4.0) indicates a technology-driven strategy to create a significant change in productivity and economic growth, based on real-time data analysis, system intelligence, interoperability, and flexibility (Karnik et al. 2022). Digitization and application of cutting-edge technologies have been fostered by many governments through national programs (e.g. Industrie 4.0, Advanced Manufacturing Partnership, Made in China 2025 and others) as a means to revitalise industry and face the modern societal changes, such as the increasingly aging population (Kuo, Shyu, and Ding 2019). Thanks to a set of enabling technologies, as the nine pillars of I4.0 (i.e. Cyber-Physical Systems, Internet of Things, Big Data, Cyber Security, Cloud Computing, Additive Manufacturing, Advanced Robotics, Modelling and Simulation, Augmented Virtual Reality), all programmes similarly promoted the idea of system adaptation to changing situations and demands, to benefit the overall production. Focusing on humans working in the modern factories, the recently defined concept of Operator 4.0 aims at evolving modern industrial scenarios by defining a knowledge sharing process from/to operators to create a personalized competence development, towards socially sustainable factories (Romero, Stahre, and Taisch 2020). In this context, the modern operator can use different interfaces to make humans part of the intelligent system, overcoming traditional graphical interfaces and pushing the use of novel interfaces (e.g. gesture, touch, voice, biosensors, Augmented Reality (AR)) (Peruzzini, Grandi, and Pellicciari 2020; Khamaisi et al. 2021). Contemporarily, the European Commission has recently defined a new trend called Industry 5.0 (I5.0) to specifically pay attention to the transition towards a human-centric, sustainable, and resilient industry, shifting from smart manufacturing to an effective human-machine co-working (Breque, De Nul, and Petridis 2021).

This paper takes a step forward compared to current literature by integrating the concept of symbiosis between the industrial entities involved: inspired by natural biological systems, where the symbiosis of different

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species living together can bring to a co-evolution when the organisms reciprocally affect each other's evolution to achieve higher benefits, the industrial symbiosis has been theorized as a valuable approach to support the sustainable development ([Despeisse et al. 2012]). According to this view, the paper proposes a novel Smart Manufacturing System Design (SMSD) framework for I5.0, based on the human-automation symbiosis to achieve a higher level of system integration, efficiency, and flexibility. The final aim is to build socially sustainable industrial workplaces and enhance the operators' performance, wellbeing, and quality of life within the factories of the future. The proposed framework aims at effectively including human factors into the factory systems design and promoting process flexibility, system resilience and global sustainability, to effectively achieve the I5.0 goals. Moreover, in compliance with the recent international standard on Digital Twin (DT) (International Standard Organization, ISO 23247 2021), it introduces the idea of an 'augmented digital twin' (ADT), including both human and automation assets into the digital loop, able to power adaptive and proactive human-machine interfaces (HMIs).

This novel SMSD framework for I5.0 provides two main contributions to knowledge, considering the current scientific literature:

- Conceiving a high-level SMSD framework including human factors at a practical level, proposing to extend the DT concept including both automation and humans, by a proper reference data model. Such a model includes machines, robots, environmental data, people and user interfaces, and could be easily adapted to the specificities inherent to any working condition, to any type of interface and to different workers' requirements;
- Proposing the idea of the ADT able to integrate the Operator 5.0 concept with factory digital replica and representing the base for Artificial Intelligence (AI)-driven applications to combine in a meaningful way the human data with data collected from the machines and the environment to enable a higher level of comprehension;
- Defining AI-driven adaptive HMIs as a key feature to realize the so-called human-automation symbiosis in the I5.0 scenario, powered by the ADT capabilities of system simulation, prediction, and validation.

2. Related works on human-centric smart manufacturing system design

The SMSD approach overcomes the design of traditional manufacturing systems by facing new challenges under the smart manufacturing blueprint. SMSD refers not only to modelling, analysing, and optimizing the manufacturing system itself (considering production capacity, system layout, material handling, operation strategies) but also to managing data from multiple sources and coordinating the various manufacturing elements (e.g. machine tools, material, humans, equipment, and environment) to holistically optimize the operations based on a unified cyber-physical scenario (Leng et al. 2021). In this direction, the concept of digital twin (DT) can support the SMS modelling and analysis, thanks to its digital replica communicating with the real factory. A DT is defined as a digital mathematical model able to describe the physical attributes of a system across its lifecycle, integrating multi-physics and multi-scale simulation (Lattanzi et al. 2021). The DT concept mainly focuses on manufacturing applications (e.g. product quality prediction, production planning or human-robot collaboration), consisting of a data connection mapping between the physical product in the real world and the digital product in the digital space, characterized by a full, automated, bi-directional data flow between the two entities. In this context, an IoT platform allows collecting the factory inputs and outputs communicating by Internet data communication technologies. A DT is supposed to be able to optimize the physical SMS based on the updated real-time data synchronized from sensors, including the different manufacturing elements, such as products, assets, and process definitions. It serves as a living model that continuously updates and changes as the physical assets counterpart evolutions to represent status, working conditions, product geometries and resource states in a synchronous manner thanks to an Internet of Things (IoT) platform (Lu, Xu, and Wang 2020).

This vision enables industrial automation by coupling massive sensing and control with big data and analytics to accomplish advanced levels of optimization and efficiency. Anyway, current SMSD models are strongly related to the digitization, simulation and control of factory tangible, physical assets, such as machines, robots, materials, products, and poorly oriented to humans interacting with them. Although when humans were proposed to be included into the factory DT (Lu, Xu, and Wang 2020), attention in SMSD mainly relies on technologies (Prati et al. 2021).

In the last 2–3 years, research on the relationships between I4.0 and human factors has been growing, exploring new approaches for SMSD to accommodate the workers' needs and improve their wellbeing (Kadir and Broberg 2021). Few publications discussed about adopting a more human-centric approach in SMSD, shifting from a technology-driven to a more holistic perspective. Also, the global sustainable approach pushes industry to respect planetary boundaries and develop circular processes able to re-use, re-purpose and recycle natural resources, reduce waste and environmental impact, and ultimately lead to efficiency and effectiveness. As a result, smart factories are evolving and, at the same time, workers are assuming new roles, and contemporarily technology can help by adapting to the needs and diversity of human workers (Lu et al. 2021). In this scenario, the concept of Operator 4.0 (Romero, Stahre, and Taisch 2020) supports the development of human-centric SMSD, reflecting a trend towards the integration of Human-in-the-Loop (HITL) with technologies, to address challenges of human-machine relationships (Wang et al. 2022). The idea of human-cyber-physical systems (HCPS) is emerging to bring new insights into the development and implementation of human-centric SMSD. In this direction, digital tools can provide smart assistance from routine tasks, so operators can focus on more creative and value-added activities. Moreover, flexible work organization enables all workers to continue professional development more effectively and have a better work–life balance, also allowing 'frail' workers (e.g. older, unexpert, weaker, less skilled) to augment and improve their working lives. In addition, agile methodological approaches are necessary to support the decision-making accounting business models, material flows, relevant indicators and data-sharing circular strategies along the manufacturing value chains, such as circular and regenerative economy principles (Renda et al. 2022). Therefore, modern digital tools and services for the manufacturing industry must be designed to be simple, intuitive, relevant, usable, and accessible, in a word 'human-centric', throughout the whole manufacturing value chain, enhancing the circularity of industrial processes and products and enabling the workers' up-skilling and re-skilling (Xu et al. 2021). This trend has been formalized in literature thanks to the Operator 5.0 concept, based on human-machine systems' resilience: it provides a vision for the future of work in smart resilient manufacturing systems in the emerging I5.0 hallmark and suggests to include humans in the factory system design, by pushing the Operator 4.0 related technical solutions (Romero and Stahre 2021).

To sum up, the analysis of the current scientific literature highlighted the need to fully integrate technological, social, and environmental priorities in SMSD, including humans in the modern DT and including human factors in the design and development of novel technological solutions, to push a more sustainable and resilient industrial innovation and shift the focus from individual technologies to a systematic, human-centric design approach.

3. Study process and methods

3.1. Research approach

The proposed approach merges the analysis of SMSD solutions ready for industry and evidence from industrial practices, with the idea to integrate human factors in the design of smart, computerized industrial systems. The main novelty of this approach is the shift towards a human-centric view to design every element of the SMS (e.g. machines, services, processes), to finally offer a valuable User eXperience (UX).

UX is namely how the user feels before, during and after the interaction with a product or a system (Hassenzahl and Tractinsky 2006). UX is a fundamental aspect to consider in SMSD because it strongly affects the quality of the interaction and characterizes the interplay between the user and any other entity, influencing the quality in task execution, the achievement of the goals, and the overall process performance. Therefore, improving the UX means promoting efficiency and effectiveness and, at the same time, enhancing the system resilience capabilities and global sustainability in designing the future smart factories, according to the modern I5.0 programs.

The analysis of the current SMSD solutions was based on the review of the most recent scientific literature, while the analysis of industrial cases involved four cases taken from four differently sized industrial companies, within their plants located in Italy. Indeed, case studies are an efficient method for using qualitative data to develop theories inductively and bridging these theories to popular deductive research (Eisenhardt and Graebner 2007). They allow to put the user (e.g. the operator) at the centre of the design process, organized into four phases (i.e. research, design and prototyping, testing) (International Standard Organization, ISO 9241–210 2009). In fact, the user involvement and the close study of the user's needs and wishes are fundamental to guide the decisions during the whole design process. All the companies involved aimed to introduce I4.0 technologies into real industrial processes, by implementing different I4.0 tools as deeply described in section 2.3. For all cases, qualitative and quantitative data were collected by workshops, on-field observations, and interviews. Workshops were guided by a researcher expert in UX design and involved from three up to five persons from the companies, with different roles (i.e. an operator working on the field, a process manager, an HMI engineer, a maintenance technician). During the workshop, the moderator pushed people to talk about specific problems and open issues occurring in the use of I4.0 technologies. Research activities on the field and in contact with the end-users (e.g. user observations, demonstration of work with new I4.0 digital technologies, semi-structured interviews with employees and operators) allowed to have a clear description of the workers' daily tasks, identification of the main criticalities, definition of the main drawbacks related to the use of the current HMIs. In addition, direct interviews permitted to focus on more operational issues and to understand the users' point of view. Specific tools such as the 'user-task matrix' (Prati et al. 2021) helped the mapping of the human-system interaction for each use case; visualizing interactions helped organizing the collected information and understanding the best way to digitize them.

Merging the results from the analysis of current technological solutions and the knowledge on real cases, authors were able to map the smart factory assets, as well as formalize the related information and data exchange, as presented in section 2.4.

The research workflow is summarized in Figure 1.

3.2. Analysis of SMSD solutions ready for industry

The recent scientific literature proposed a set of novel architectures for the factory of the future (e.g. Asset Administration Shell (AAS), Reference Architecture Model Industrie 4.0 (RAMI4.0)) (Anumbe, Saidy, and Harik 2022), but all of them did not include the requirements of workers in the factory. In the context of SMSD, Leng et al. (2021) provided a survey on how the digital twin technologies can be integrated to promote SMSD including different key enabling technologies (i.e. IIoT, multi-domain physical-chemical modelling, virtual reality, data analytics, industrial artificial intelligence, blockchain, cloud computing). Also, in this case, humans are not included in this framework. Regarding DT, a valid taxonomy has been recently defined by (van der Valk et al. 2020), but without any relation to the human factors' integration.

Diversely, the emerging human-centric system paradigm is bringing to the definition of interesting human-centric system architecture where the system core features (e.g. connectivity, integration, intelligence, adaptation, and socialization) can be realized thanks to HCPS. In this direction, the recent international standard on DT (ISO 23247 2021) defined a reference framework to support the creation of DT applications and includes humans within the smart factory assets. It shows a domain-based reference model including four categories (i.e. observable manufacturing domain, device communication domain, DT domain, user domain). The user domain hosts the applications that analyse the DT models for

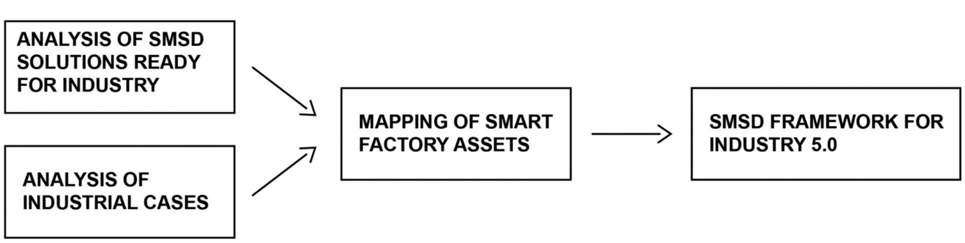

Figure 1. The research workflow.

humans and systems, but no details are given about the type of applications and the involvement of the different factory assets.

Several applications of HCPS in smart manufacturing are well illustrated by (Wang et al. 2022). It considers a HCPS framework consisting of the following items: 1) the core subsystems reflecting the interactive relationships between humans, cyber systems, and physical systems, 2) a set of enabling technologies and 3) related applications, including human-centric system design, intelligent production, and digitalized services, and 4) the key system features, such as integration, connectivity, intelligence, adaptation. Such a work is strongly user-oriented but not integrated with the DT paradigm.

The analysis of the current literature highlighted a gap in the definition of novel models compliant with the ISO 23,247 standard, able to fit AI-driven, user-oriented applications to collect and elaborate heterogeneous data from machines and humans, conveying information and instructions to the operators and machines contextually and intelligently. Moreover, HMIs need to be included in this scenario, since they are the first communication channel between humans and the factory automation (Krupitzer et al. 2020). Proper HMIs, enhanced with specific behaviours, could help the understanding of the human-machine interplay and the explainability of automatic systems, creating new forms of collaboration among the factory entities thanks to intelligent system adaptation and proactivity (Kaasinen et al. 2020). Therefore, SMS cannot be no longer conceived in a traditional way but require including humans in the digital loop.

From the analysis of the current literature on human-centric SMSD, the authors drew the following conclusions. On the one hand, advanced digital technologies need to be considered valid tools to design better and more efficient working systems when incorporated into the manufacturing workforce, as demonstrated also by the literature (Kaasinen et al. 2020). On the other hand, people in the factory are a precious source of knowledge and problem-solving; indeed, humans can naturally find new ways of overcoming obstacles and creating ad-hoc solutions to overcome unexpected conditions, ensuring manufacturing operations continuity and workforce wellbeing, as synthetized also by the Operator 5.0 concept. Thanks to the collection of data about the operators' performance, actions and reactions, via wearable technologies (e.g. biosensors, cameras) and HCPS, it is possible to combine human data with the machine' data collected by CPS, with the intention of improving the overall factory performance by means of smart, augmented human-machine interactions.

3.3. Analysis of industrial cases

This section provides a brief description of the four industrial case studies considered. Such cases supported the definition of the main evidence from the field on the implementation of I4.0 technologies, as described in this section, but also the validation of the proposed framework as described in section 3.2.

All cases offered a highly automated industrial system and referred to the introduction of I4.0 technologies to improve the company competitiveness, in different manufacturing contexts: automated systems to produce plastic caps (C1), automated packaging systems (C2), semi-automated tractors' manufacturing lines (C3), and collaborative human-robot lines in automotive industry (C4). Each case offered a different human-machine interaction scenario, where humans play a different role: from machine setting to process supervision, to maintenance and troubleshooting, until co-working and cooperation. The following paragraphs describe the main characteristics of each case in terms of the human-machine interplay.

C1 - The first case study referred to supervision and control of an automated line to produce plastic caps, offered by an Italian company which is a world leader in this sector, with over 1.900 systems already installed worldwide. Such lines are characterized by a very high production rate (up to 2000 caps/min) and great variability (caps can differ from colour, shape, and diameter up to 52 mm). The line comprises complex automatic machines (e.g. caps moulding and cutting) and auxiliary machines (e.g. conveyors and centrifugal feeder). Along the line, operators can perform different tasks for process setting (e.g. colour changeovers, format changeovers, production parameters setting variation) and supervision (e.g. task control, task planning, preventive maintenance). The modern version of such line is equipped with 4.0 sensors and an additional video-based quality control system to improve the production quality and reduce the waste by predicting and checking the caps non-conformities. However, these technologies have been introduced without an advanced consideration of the operator's experience and real interaction with the machine. In fact, the I4.0 revolution did not impact the HMIs: the system is still controlled by a set of graphical touch screens on panels located near the machines, in a fixed position. The case aimed at improving the overall human-machine interaction process by improving the HMI usability, considering the different types of users working along the production line, considering their needs and goals.

C2 – The second case study concerned with the supervision and maintenance of automated beverage packaging systems, offered by a European company as world leader in this sector, with an important plant in Italy. In particular, the system is composed of a sterilizing unit where all materials are sterilized, a shaping unit where the paper is formed into boxes, and the filling unit where boxes are filled with the process liquid (e.g. milk, juice). Such systems are characterized by a high production rate (up to 15.000 unit/hour) and poor variability. The process is continuous and fully automatic, but the operators oversee the process and refill the packaging material every 30 minutes. In the use case, the machines and the operators were equipped with I4.0 technologies to assess the human-machine interaction by analysing the human movements and the perceived workload. In particular, wearables optical infrared trackers were used to track the human movements, and a smartwatch was used to collect some human physiological parameters (i.e. heart rate, heart rate variability, electro-dermal activity), and an eye-tracker was adopted to monitor eye data (i.e. pupil diameter, eye blinks). However, also in this case the I4.0 revolution did not impact the human activities and did not introduce any specific improvements on the HMIs or workstation: the task was executed in a traditional way, without any implementation of cognitive or physical support. The case aimed at improving the physical and cognitive effort during the maintenance activities.

C3 – The third case study referred to semi-automated tractors' manufacturing lines of a world leader company in tractors' design and commercialization, with numerous sites and plants in Italy. Inside the production plant, numerous Computerized Numerical Control (CNC) machines are placed for the machining of mechanical components, with a very variable production in terms of batch size, rate and typology of products. Operators supervise the machines' production, control the overall process, perform the maintenance tasks, and solve any kind of problems causing the machine downtime or slowing down the production. Modern CNC machines are equipped with I4.0 sensors and an HMI positioned on a fixed panel on the machine. The HMI usually combines a graphical display and a physical keyboard. The case focused on assistive maintenance: sensors and cameras embedded in the machines allow to catch information about both machine and product status by monitoring several parameters (e.g. temperature, vibrations) and about the surrounding environment. The I4.0 technologies can constantly provide new data to support and guide the user's activities. However, a proper data visualization is necessary to correctly interpretate and use collected data in an efficient way during multiple and complex maintenance tasks. The case aimed at providing non-expert operators the necessary support to reduce time to perform maintenance tasks and troubleshooting activities, reducing the machine downtime.

C4 – The fourth case study regarded the design of a new collaborative workstation including humans and robots, developed within a research project in collaboration with a world-wide automotive player. The collaborative workstation replaced a traditional one, based on manual operations, to reduce the operator's physical and cognitive effort and increase the task execution precision. Specifically, a collaborative robot and an operator oversee the assembly of a specific group of the car: the operator positions a car monocoque in proximity of the robot workstation, then the robot autonomously inserts bonding fasteners on the monocoque. Moreover, during the automatic phase, the operator can perform parallel activities in other areas, by supervising the robot tasks and the overall process quality. In this complex scenario, the traditional graphical user interface didn't answer to the new human-robot interaction requirements (e.g. constant monitoring of the robot activities, communication between them) and was inappropriate for supporting operator's tasks (e.g. parallel activities in different positions). The case aimed at implementing new human-robot interaction solutions that answer to improve the quality of the collaborative tasks.

Table 1 provides a synthesis of the four cases, detailing the context, the project objective, actors involved and the main evidence from the field.

Figure 2 graphically depicts the four cases by describing the involved actors and the solution possibilities related to the different I4.0 projects.

The analysis of the case studies highlighted a partially successful approach to innovation: all companies were eager to introduce I4.0 technologies to promote their competitiveness and to realize more efficient processes, without really caring about the human factors and the implications of the new technology adoption for workers. The case-driven strategy adopted in this study highlighted that the current approaches to I4.0 are strongly technology-driven and lack of human-centricity.

Table 1. Industrial cases' analysis summary.

	CONTEXT	ACTORS	IMPLEMENTED I4.0 TECHNOLOGY	EVIDENCE from the field	OBJECTIVE
C1	Automated line for plastic caps' production	- Automated production line - Operator/s	- Sensors embedded in the machines - Video-based quality control system	- Lack of integration between the new I4.0 system and the HMI - Complex interaction and information research on the HMI	Improvement of the overall human performance in process control
C2	Beverage packaging machines	- Automatic machine - Operator/s	- Wearable tracker for human movements and physiological parameters	- Poor accessibility and visibility to some machine components - High physical effort	Improvement of the ergonomics during maintenance activities
C3	CNC machines in tractors' manufacturing lines	- CNC machine - Operator/s	- Sensors embedded in the machines - Sensors and stereo cameras in the environment	- High error rate during maintenance tasks - High mental workload - Long and complex troubleshooting activities	Reduction of time for maintenance and troubleshooting activities by non-expert users
C4	Human-robot collaborative workstation for car assembly	- Collaborative robots - Operator	- Collaborative robotics	- Difficulties to monitor and control the robot activities - Frequent downtime	Improvement of the quality of human-robot collaboration

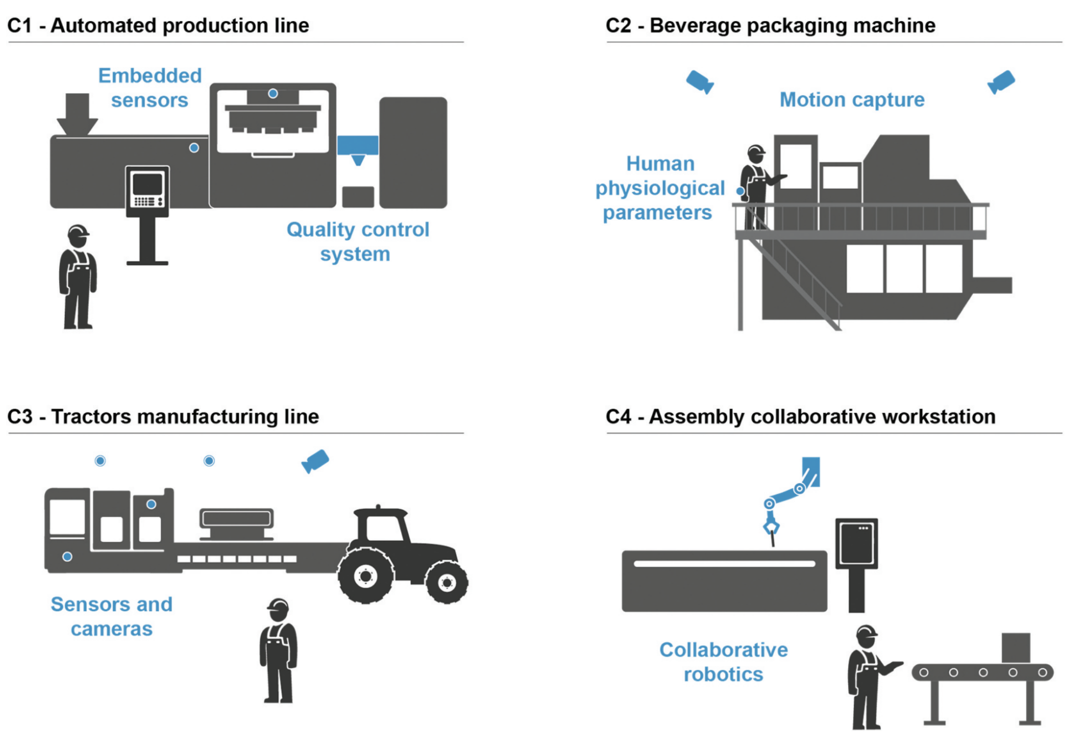

Figure 2. Context of interaction for the analysed case studies.

The following findings can be defined from the analysis of the industrial cases:

(1) I4.0 technologies have the potential to enable human-centric processes, but their adoption must be focused on human operators, which is often underestimated. In fact, despite the variety of scenarios, the analysis revealed that humans are still crucial in any process, even if highly automated: in any case, humans interact with the automation by means of one or more HMIs to satisfy a specific need, but they all face some difficulties, from a physical (visibility, reachability) or mental (complexity, misleading) point of view;

(2) even if HMIs have changed significantly over the last decades, driven by rapid technological advances, they are minimally improving the way people communicate with machines and automation in general. This is mainly due to the separation in the design of HMIs that are usually not designed synergically with the automation. Therefore, HMIs are considered as a separate entity from the machines and managed separately. Diversely, due to their impact on the human-machine communication and the ability to create a smart and smooth interaction, independently from the application scenario, HMIs should be conceived synergically 'with the users and the machines' and be strongly connected with them, as a fundamental element of the I5.0 evolution. This step is particularly important when smart wearable technologies are adopted (e.g. smart-watches, smart-gloves, smart-glasses, smart-speakers, smart-exoskeletons);

(3) the smart factory can provide a huge quantity of data, from the machines/robots, the environment, the users, and the HMIs, which is not currently used by SMS to evolve and teach each other. In this scenario, intelligent, AI-driven HMIs could play a crucial role in the realization of a I5.0 working space, where users and machines can adapt each other to increase health, safety, productivity, and work quality at the same time.

3.4. Mapping of the smart factory assets

The scientific review on human-centric SMSD and the analysis of the industrial cases led the authors to map the smart factory assets to be included in a future reference framework for SMSD for I5.0. Four main entities were identified as data source, namely: the environment, the machines (and robots), the humans, and the HMIs. The types of data shared within the factory are described for each data source according to the data sharing direction, i.e. if the data exchange is one-directional (OD) or bi-direction (BD), type of data, i.e. tangible (T) or intangible (I) and the level of maturity of data collection and management inside the factory, related to the available technologies, i.e. low (L), medium (M) or high (H). One-directional data exchange means that data can be sent only from the source to the DT, while a bi-directional data exchange means that data can be sent from and to the source, allowing the DT to support and control the assets. The type of data provides an overview about the nature of the data: tangible data are related to physical entities, while intangible data are related to digital or management/business entities (e.g. process lifecycle, performance, quality inspection plan). Finally, the level of maturity aims at identifying the current possibilities in realizing a novel I5.0 scenario, considering the currently available technologies: higher level of maturity is related to those data already used in a traditional machine-oriented DT or ready to be used, while a medium and low maturity indicates gaps to fill in.

Possible data collected from the environment are *Crowding*, *Noise*, *Workspace layout, Temperature, Pollution, Light*. Data from machines are *Equipment set-up*, *Process lifecycle, Product geometry*, *Product data*, *Performance*, *Production cost*, *Machine status*, *Quality inspection plan*, *Production parameters*. Also, the operators themselves can provide data about their physical characteristics and behaviours/feeling during working activities through, such as: *Posture*, *Anthropometry*, *Sweating*, *Eye tracking*, *ID recognition*, *Physiological parameters*, *Position and movements*, *Facial expressions*. At the same time, the operators can provide precious information regarding their way to interact with HMIs, such as: *Type of interactions*, *HMI Layout*, *Navigation path*, *Visualized pages*, *Interaction time*, *Click number*.

Table 2 summarized the smart factory assets' mapping and proposes some description for the above-mentioned type of data.

Such an analysis allowed the definition of the main entities of the 'observable manufacturing domain' as defined by (ISO 23247 2021) and paved the way to the definition of the SMSD framework for I5.0, as described in section 3.

4. The SMSD framework for Industry 5.0

4.1. The proposed framework

This research focuses on the definition of a conceptual framework for I5.0 where humans and machines can create a symbiotic, co-evolutionary relationship to positively affect each other's evolution by sharing resources, data, and technologies, learning from each other and mutually grow up, according to the concept of human-automation symbiosis as proposed by ([Tzafestas 2006]). Such framework allows the entire factory digital simulation to concretely adopt the I5.0 concepts in practice. Based on the smart factory assets' mapping, such a framework can be used to design modern SMS considering a more balanced relationship between machines and people. Such a model contributes to the smart factory knowledge creation, use and evolution, including humans, machines, robots, environment, and the HMIs, to build up a I5.0 scenario.

The framework includes four domains, as suggested by ([ISO 23247 2021]): *observable manufacturing domain*, *communication domain*, *DT domain* and *user domain*. Among this reference model, the present research provides a deeper description of the layers and modules included in each domain, and proposes

Table 2. Smart factory assets' mapping for Industry 5.0.

Data source	Type of data	Description	Data sharing with a DT: Direction	Type	Level of maturity
Environment	Crowding	Number of people in the considered working area	OD	T	L
	Noise	Level of noise recorded in the considered working area	OD	T	M
	Workspace layout	How machines and processes are organized in the plant or workstation	BD	T	L
	Temperature	The recorded temperature and its variation in the workspace	BD	T	M
	Pollution	Level of air pollution in the workspace	OD	T	M
	Light	Light conditions and variation in the workspace	BD	T	M
Machines	Equipment set-up	Use and organization of additional machines' attachments (e.g. tools, devices, sensors) to enhance their capabilities	OD	T	M
	Process lifecycle	Design and production phases	BD	I	M
	Product geometry	Physical shape, form, and dimensions of a product, including its overall structure, features, and relationships between its various components	OD	T	H
	Product data	Information of a product (e.g. materials used, production details, digital model)	BD	T	H
	Performance	Evaluation of the production quality, efficiency, and adherence to specific KPIs (Key Performance Indicators)	BD	I	H
	Production cost	Expenses incurred in the process of manufacturing a product	BD	I	M
	Machine status	Machines' working condition (e.g. running, off, waiting)	BD	I	H
	Quality inspection plan	Planning of quality control activities	BD	I	M
	Maintenance plan	Planning of maintenance activities	BD	I	M
	Production parameters	Aspects that characterize the manufacturing process (e.g. calibrating parameters, environmental impact)	BD	I	H
Humans	Posture	The position acquired by the operator to perform the different tasks	BD	T	M
	Anthropometry	Consideration of operators' body measurements and proportions	OD	T	M
	Sweating	Monitoring of the operator's level of sweating during the different tasks, as a possible symptom of stress	OD	T	M
	Eye tracking	Mapping of where the user looks at during task execution/visual attention maps for a specific goal	OD	T	M
	ID recognition	The unique identification number of the user	OD	I	H
	Physiological parameters	Monitoring of parameters like hear rate variability as symptom of stress	OD	T	M
	Position and movements	Mapping of the operators' position inside the workspace and the movements he/she must do for the task performance	OD	T	M
	Facial expressions	User's expression during the task execution	OD	T	M
HMIs	Type of interactions	The chosen interaction modality to interact with the HMI, such as vocal command, click	BD	T	L
	HMI layout	Visual and structural organization of the HMI contents	BD	I	M
	Navigation path	Sequence of interaction to accomplish a task in the HMI	BD	I	L
	Visualized pages	Which are the most visualized pages in the HMI	OD	I	M
	Interaction time	Time to accomplish a task (e.g. language setting)	OD	I	M
	Click number	Number of click to perform a task or the most clicked HMI components	OD	T	M

how to realize the human-automation symbiosis at the user level. The overall framework is depicted in Figure 3.

At the bottom of the picture, the observable manufacturing domain is mapped into the physical layer of the factory, including the four entities already defined as data source (i.e. environment, machines, HMIs, humans). The first step is to collect data from all the factory entities thanks to CPS and HCPS. With respect to existing architectures, HCPS enables the inclusion of both workers and interfaces into the factory IoT platform, exploiting human-related sensors (e.g. smart wearable devices, biosensors, wearable interfaces) and environmental sensors into the factory data collection process. Thanks to CPS and HCPS, such entities generate data for the upper communication domain, firstly for the communication layer devoted to data collection and management, including synchronization and interoperability issues. After that, thanks to Internet of Things (IoT) and Big Data Analytics, data became information related to the product, the process, and the HMI in the information layer.

The upper domain is related to the DT, consisting of two separate layers about modelling and digital simulation. Modelling is a crucial aspect of any DT framework because only a proper entities' modelling can allow a realistic and meaningful simulation at the upper level. In this framework, modelling includes more traditional models related to products and machines/robots', and more human-centric models, such as task analysis, human model, and HMI adaptive model. Such modules represent the system knowledge. More specifically, the HMI adaptive model is crucial according to a UX-oriented view because it deals with the definition of the ideal behaviours of an HMI and all possible adaptive behaviours that can

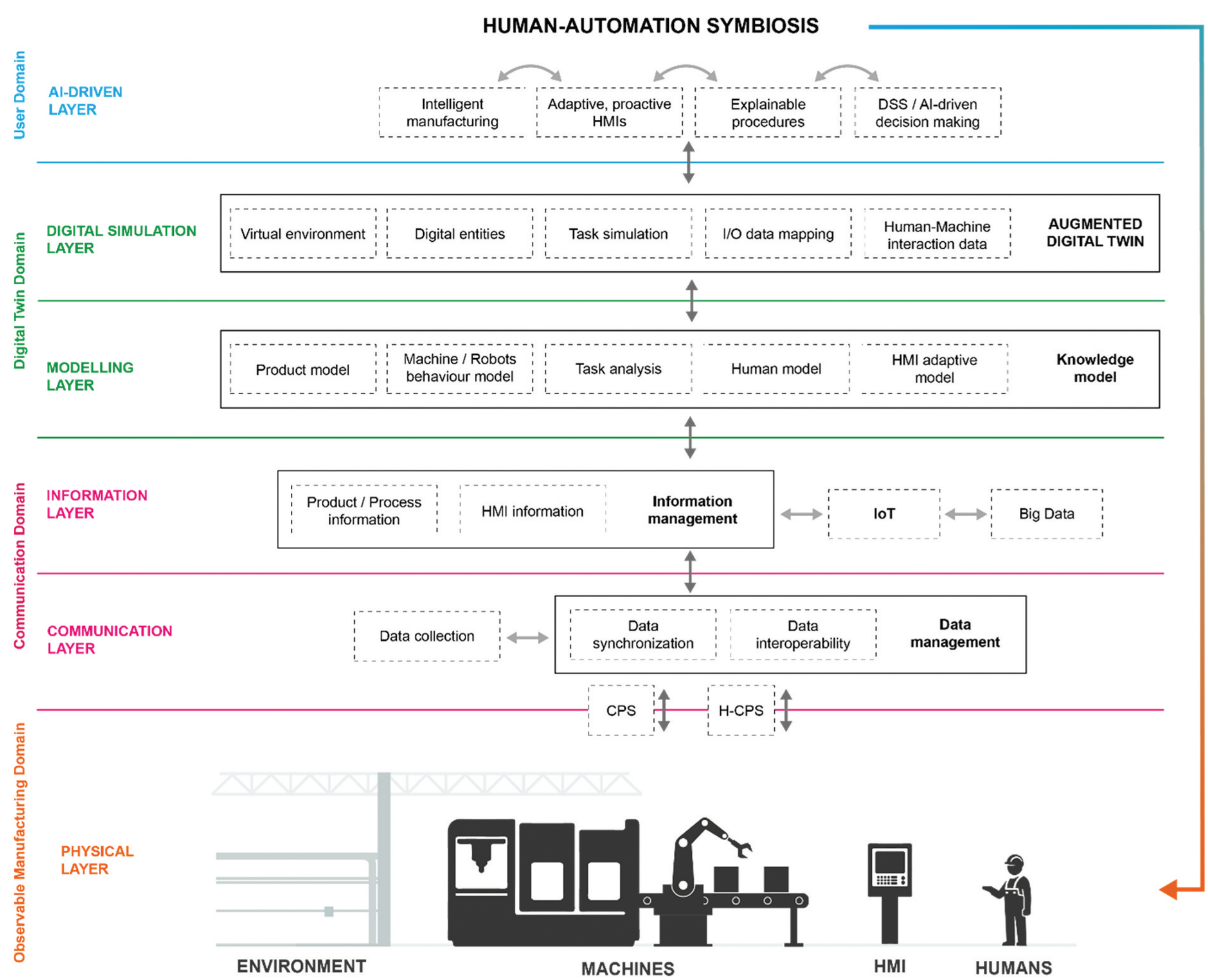

Figure 3. The SMSD framework for Industry 5.0.

improve the UX and the overall factory performance. HMI adaptiveness can offer the information needed, when needed, in the most efficient and effective way and in the best modality according to the specific context of interaction. For instance, the HMI can provide the best type of interaction (e.g. visual, touch, gesture-based, auditory) according to the specific conditions and/or change its visual aspects according to the user's individual abilities, the environmental lighting conditions, the machine status, the on-ongoing process, the products to be checked, and many more. Such adaptiveness can exploit all data from/to the different physical entities and will be exploited by the user-related application in the user domain.

After that, the digital simulation layer includes a set of digital replicas of all the factory entities, from the machines/robots to the humans, the environment, and the HMIs. As a result, the entire factory behaviours can be simulated in a so-called Augmented DT (ADT), which extends the digital replica of physical assets (i.e. machines) towards human-related aspects building the foundation of a whole digital eco-system. The ADT collects data from machines and robots with Industrial IoT, and from operators and their smart HMIs thanks to smart wearable technologies (e.g. smart glasses, smart gloves, smart watches, smart trackers) considering their identity, status, and activity (e.g. anthropometry, physiological parameters, interaction with objects, eye tracking), according to the Operator 4.0 and I5.0 model. The ADT is an advanced version of the DT that integrates connected digital models to offer a complex, multifaceted digital simulation space to include every factory entity at the same time and predict its behaviours to properly program and validate both intelligent manufacturing systems and smart, adaptive HMIs supporting the human work. Such ADT can collect data from the factory and send back human interaction data to the factory, to fuel new adaptive behaviours.

At the top of the framework, there is the user domain where AI-driven applications can support the human work within the factory. Alongside intelligent manufacturing applications, already known and well described by Lu, Xu, and Wang (2020), this layer can host user-oriented smart applications, such as adaptive and proactive HMIs, explainable working procedures, decision support systems (DSS) and AI-driven decision-making applications. Such application exploits the factory knowledge from the modelling layer and the digital simulation capabilities from the ADT to define personalized, contextual HMIs to support the human work and to promote the human-machine symbiosis. In fact, within the I4.0 factory, humans are no longer alone, but work in a close relation to the machines. Therefore, all modern processes are made up of automation-related stages (e.g. production of parts, heavy material movements, repetitive tasks, not healthy tasks) and human-related stages (e.g. process control, high-precision tasks, high-quality visual inspection, maintenance tasks).

In this framework, information related to humans, environment, machines, and HMIs can be elaborated together and exchanged among systems to create new knowledge and contribute to the system evolution and optimization, re-allocating the tasks between humans and machines and improve the mutual performance. Moreover, thanks to AI-driven applications and the ADT, both humans and machines can teach each other from the new knowledge built up in a collaborative way, and effectively support the transition towards a sustainable co-working between machines and humans, as envisaged by (Breque, De Nul, and Petridis 2021). Consequently, a co-evolution of machines and humans can take place, supporting a reciprocal learning process, in a symbiotic way: humans can learn from machines and machines can learn from the humans.

Moreover, such framework could support the definition and the development of novel AI-driven applications to realize the human-automation symbiosis.

Table 3 summarizes the main symbiotic actions that can be realized according to the proposed framework and the main benefits for users.

Thanks to this SMSD framework, a complete factory system simulation and prediction of factory behaviours and performance can be realized. For instance, VR-based DSSs could provide virtual interactive environments to immerse real users into the digital world, where users can interact with the virtual world in a realistic way, with autonomous control and multi-sensory feedback, to benefit the design of modern factories and human-machine collaborative tasks (Dianatfar, Latokartano, and Lanz 2021). The use of VR-based DSS has the potential to simulate cooperative processes in advance and to include workers and their individual behaviours into the DT simulation (Prati

Table 3. Human-automation symbiotic actions and related user benefits.

		Human-automation symbiosis	
Data source	Type of data	Symbiotic actions	User benefits (examples)
Environment	Crowding	People/task optimal management	Higher comfort, time reduction
	Noise	Use sound absorbing panels Systems for machine noise reduction	Higher comfort, health problems prevention, mental workload reduction
	Workspace layout	Layout optimization	Higher physical comfort, error prevention, tasks optimization (e.g. easier machines supervision)
	Temperature	Automatic temperature regulation	Working conditions improvement
	Pollution	Air purification optimization (e.g. air scrubber) Change of equipment	Healthier space, health problems prevention
	Light	Automatic light regulation/optimization	Working conditions improvement, error prevention, health problems prevention
Machines	Equipment set-up	Equipment optimization (e.g. tooling, tool changing)	Safety conditions improvement (e.g. robot's speed reduction based on human closeness)
	Process lifecycle	Higher process sustainability, process optimization	Effort reduction, higher productivity
	Product geometry	Process optimization	Higher product quality, error prevention, optimized data management, decision-support
	Product data	Increase of products' details and information	Optimized data management, decision-support, troubleshooting optimization
	Performance	Production and decision process improvement	Decision-support, higher productivity
	Production cost	Cost reduction	Decision-support, higher productivity
	Machine status	Process optimization	Optimized data management, decision-support, troubleshooting optimization
	Quality inspection plan	Inspection plan update in real-time	Higher product quality, time reduction
	Maintenance plan	Intelligent maintenance actions, maintenance plan update in real-time	Higher productivity, time reduction
	Production parameters	Process optimization	Higher productivity, higher product quality
Humans	Posture	Task redesign Exoskeleton adoption Layout redesign	Physical disorders' prevention
	Anthropometry	Tasks and workstation automatic adaptation based on the operator's anthropometry consideration	Task optimization, workstation layout optimization, physical effort reduction
	Sweating	Task adaptation to the operator role and status Temperature regulation	Physical and mental workload reduction, higher comfort
	Eye tracking	HMI redesign Optimized human-machine interaction	More intuitive interactions, user-friendly HMIs, higher comfort
	ID recognition	HMI personalization	HMIs personalization/configuration, faster login
	Physiological parameters	Optimized human-machine interaction Task adaptation to the operator's role and status	Physical and mental workload reduction
	Position and movements	HMI position HMI components adaptation (e.g. text dimension, sound volume)	Task optimization, workstation layout optimization, physical effort reduction
	Facial expressions	Task real-time update Autonomous HMI adaptation	Mental workload reduction, task optimization
HMIs	Type of interactions	Change of information type	More intuitive interactions, user-friendly HMIs, higher comfort
	HMI layout	HMI layout adaptation based on the received data (e.g. light condition, user conditions, user skills and role)	More intuitive interactions, user-friendly HMIs, time reduction
	Navigation path	HMI information architecture optimization	More intuitive interactions, user-friendly HMIs, time reduction
	Visualized pages	HMI information architecture optimization Shortcuts' implementation Suggestions and prediction of the necessary pages	Faster access to the more useful contents, time reduction
	Interaction time	HMI information architecture optimization/redesign	More intuitive interactions, user-friendly HMIs, time reduction
	Click number	HMI information architecture optimization/redesign	More intuitive interaction, time reduction

et al. 2021). In addition, AI approaches can be added to optimise the real factory and define the better production strategies, thanks to smarter and agile machine management and higher human-system collaboration, bringing to reduced time to market and higher product quality. In this framework, all data deriving from the different factory entities can be elaborated contextually to improve both the machine management strategies and the HMIs adaptive behaviours, to create better and smarter communication strategies with the workers.

In such a framework, HMIs assume a greater role in capturing and providing key information from and to the workers, as well as to guarantee the optimal UX, taking care about the workers' physical ergonomics and cognitive workload, promoting ease of use and agility. The ADT can simulate also collaborative interaction process (machine-humans) and anticipate the factory issues, considering all the agents involved. This allows to achieve the real 'resilience' of the entire system, thanks to the natural flexibility and agility of the humans.

To sum up, the proposed model allows:

- to collect data from all the factory entities and create holistic digital simulation, with a special focus on the connected workers;
- to provide on time feedback to the operators about machines, robots, the environment, other operators, and themselves;
- to program machines and robots according to the users' behaviours, activity, ergonomics alerts, not optimal workload conditions, in order to preserve human wellbeing;
- to simulate the adoption of specific technologies (e.g. AR, wearable HMIs, exoskeletons, voice, or gesture interfaces) and predict both the impact on the UX and the machine and robot behaviours, to manage them into a symbiotic, co-evolutive way;
- to improve the system robustness to external disturbances, predicting future scenarios and preventing errors and failures, thanks to the intelligent integration of machines, robots, people and interfaces.

4.2. Application of the SMSD framework for Industry 5.0

This section describes how the proposed framework has been applied to the industrial cases, as presented in section 2.3, to define AI-driven applications and related interfaces to realize the human-automation symbiosis. Moreover, the results obtained in the use cases demonstrated how the proposed approach addresses the I5.0 view, promoting human-centricity, sustainability, and resilience. In all cases, the I4.0 technologies were extended by including specific sensors for collecting data from humans and HMIs, where the preliminary set-up did not include them. This permitted the full application of the proposed SMSD framework for I5.0.

For this purpose, the results obtained from the case studies have been analysed considering the impact on the Future Industrial Worker (FIW) characteristics, as defined in the context of I5.0 by (Heikkilä et al. 2023). Such characteristics emphasize the smartness, interactivity, resilience, and health in future industrial working scenarios and acknowledge the key aspects of the I5.0 view.

C1 – The first industrial case aimed at improving the overall human-machine interaction. Thanks to the mapping of the smart factory assets, data from machines, operators and HMI can be combined to understand the interaction needs and to select the most proper type of HMI to support the operators' work. In this case study, a mobile HMI was found to better answer to the different users' needs during the various tasks to be carried out (e.g. supervision, parameters setting). The ADT was used to predict the behaviours of workers, machines, and HMIs within a virtual environment. Moreover, the real-time monitoring of HMI data, such as the navigation path and the most visualized pages, is used to define AI-driven adaptive behaviours to personalize the access to the HMI. A graphical HMI was conceived to intelligently adapt the HMI consents, layout, and visual style according to the users' role, health status, positions and movements, tasks, as well as to the process needs and environmental conditions. In this way, the HMI can automatically adapt its features and appearance according to the combined requirements of users, machines, process, and environment, to improve the UX, speed up operations, and reduce the cognitive effort. Moreover, these data allow to obtain a symbiotic co-evolution also in terms of process and workstation layout optimization, real-time maintenance plan generation and higher process sustainability. Smart and resilient FIW characteristics are realized in this industrial case; in fact, users receive support information that simplifies problem solving activities and increments the operators' readiness to manage all the situations.

C2 – The second industrial case focused on the use of wearable sensors to monitor the user's physiological parameters and movements, to define and develop adaptive DSS to support maintenance activities. Thanks to the mapping of the smart factory assets, data from the operators (e.g. position, postures, movements, efforts, health status) and the machine (e.g. process stage, maintenance procedures, locations of machine parts, machine layout) can be combined to understand the interaction needs and to select the most proper type of HMI to guarantee the operators' wellbeing. In this case, the ADT was used to create a human-centric DT, based on motion capture data and physiological data, to predict the human physical workload and to provide an early ergonomic assessment. Results support both machine/workstation layout optimization and human task re-design if needed. Moreover, it was defined to introduce a wearable HMI to support task execution, safety, and health, providing on-time feedback to the operator, thus improving the human-machine interaction and the whole UX. Interactive and healthy FIW characteristics are realized in this case; indeed, monitoring of both cognitive and physical workload allows to detect any potential dangerous issues and provide support to solve them (e.g. exoskeleton adoption, input reduction), respecting the user's resources, skills, and capabilities to facilitate his/her concentration and general wellbeing.

C3 – In the third case study, the SMSD framework guided in the comprehension of how to provide major support to operators during maintenance and troubleshooting activities on complex machines. In fact, the collected data from the operators and the I4.0 sensors embedded in the machines and environments were used to study how to improve the operators training process and provide more support during maintenance tasks. The ADT allowed the modelling and virtualization of the machine, the HMI, and the operator to understand the most efficient procedure ever to carry out the expected tasks, according to the specific conditions. Thanks to AI models, the ADT can also guide to the resolution of unexpected tasks, suggest maintenance actions and change information provided to the operator. An Adaptive AR-based HMI was defined to support and easily guide step by step the operator during maintenance tasks. Such an HMI promoted both system explainability and users' upskill, as well as individual motivation. Referring to the FIW characteristics, this case pushes the smart, interactive and healthy worker; in fact, adaptive AR-based HMI can autonomously adapt its information and contents based on the recognized activity, and can provide useful suggestions or layout optimization to simplify interaction and learning.

C4 – The fourth case required the design of a proper human-robot interface to improve the collaboration among humans and robots and the efficiency of the overall process, considering the generated UX. A VR-based ADT was developed to preliminary visualize and assess the human-robot interaction process, configuring different solutions and collecting data of both human and robot behaviors in the virtual world. The ADT allowed to identify the mutual needs and to define which type of HMI should support such a process. A monitor-based HMI in proximity of the robot position was selected to control and receive data on the robot performance. In addition, a wearable wristband HMI was selected to provide alerts/notification and on-time communications to the operator while performing activities far from the robot workstation. In this way, a human-automation symbiotic co-evolution is possible in terms of, e.g., equipment and process optimization, task and layout redesign, interaction and HMI adaptation. About FIW characteristics, this case refers to smart, interactive, resilient, and healthy worker; indeed, the realized HMIs provide the user with precious support during problem solving situations and allow a smooth communication and collaboration with the robot in a safe, flexible, stimulating workspace, without increasing the mental workload.

Table 4 summarizes the envisaged HMI solutions for each case study and defines the possible human-automation symbiotic actions to demonstrate how the proposed framework can help in building socially sustainable industrial workplaces and enhance the operators' performance, wellbeing, and quality of life within the factories of the future, considering the impact on the FIW characteristics, as defined in the context of I5.0.

Figure 4 graphically represents the application flow of the SMSD framework to the four industrial cases, highlighting the improved data exchange and the envisaged HMI solutions realized.

5. Conclusions

This paper has considered the benefits and limits of the I4.0 models and reflected on the human-machine collaboration into the smart factory in the context of I5.0, focusing of human-centricity, sustainability, and resilience. Indeed, up to now, humans are not completely involved in the factory simulation and the impact of technology on humans is usually underestimated. Adopting a technology-driven approach was found partially successful to promote global sustainability and factory resilience, and new models were required.

Table 4. Results on the case studies.

	CONTEXT	Envisaged HMI solutions	Human-Automation symbiotic actions (from Table 3)	Impact on the FIW characteristics
C1	Automated line for plastic caps' production	AI-driven adaptive, graphical HMI to support process control and inspection	- Layout optimization - Process optimization - Intelligent maintenance actions, maintenance plan update in real-time - Higher process sustainability - Task adaptation to the operator role and status - HMI information architecture optimization - HMI layout adaptation based on the received data (e.g. light condition, user conditions, user skills and role)	- Smart (complexity master, problem solver, proactive decision maker, sustainability oriented) - Resilient (flexible, continuous learner) - Healthy (capable, focused)
C2	Beverage packaging machines	Wearable HMI linked to the Human-centric DT for early ergonomic assessment	- Task redesign - Exoskeleton adoption - Layout redesign - Tasks and workstation automatic adaptation based on the operator's anthropometry consideration - Optimized human-machine interaction - Task adaptation to the operator role and status	- Interactive (Inclusive and intercultural, safety-oriented) - Healthy (motivated, balanced, capable, focused)
C3	CNC machines in tractors' manufacturing lines	Adaptive AR-based HMI for personalized maintenance support and explainability	- People/task optimal management - Intelligent maintenance actions, maintenance plan update in real-time - Task adaptation to the operator role and status - HMI redesign - HMI components adaptation (e.g. text dimension, sound volume) - Autonomous HMI adaptation - Change of information type - HMI layout adaptation based on the received data (e.g. light condition, user conditions, user skills and role) - HMI information architecture optimization - Shortcuts' implementation - Suggestions and prediction of the necessary pages	- Smart (complexity master, problem solver, proactive decision maker) - Interactive (collaborative, Inclusive and intercultural, safety oriented) - Healthy (motivated, balanced, capable, focused)
C4	Human-robot collaborative workstation for car assembly	UX-oriented HMIs for smart robot interaction (desktop + wearable)	- People/task optimal management - Equipment optimization (e.g. tooling, tool changing) - Process optimization - Task redesign - Layout redesign - HMI personalization - Optimized human-machine interaction - Task adaptation to the operator's role and status - Change of information type - HMI components adaptation (e.g. text dimension, sound volume) - HMI information architecture optimization/ redesign	- Smart (problem solver) - Interactive (communicative, collaborative, Inclusive and intercultural, safety oriented) - Resilient (flexible, continuous learner) - Healthy (balanced)

The research analysed different case studies taken from industrial projects in various industrial sectors, where companies wanted to introduce I4.0 technologies to support the manufacturing process. The study highlighted the main limits of the I4.0 programmes when humans play a crucial role. For this purpose, a new SMSD framework promoting I5.0 has been proposed, based on the human-automation symbiosis has been proposed. The core elements of this framework are represented by the idea of an 'Augmented Digital Twin' (ADT), and a set of high-level AI-driven applications based on adaptive, proactive HMIs, making people as active players of the modern factory. Indeed, the proposed framework can collect data from all the physical entities in the factory (i.e. machines, robots, humans, HMIs, and the surrounding environment), model each system functioning, simulate the entire system behaviour and predict the human-automation relationships, including humans in the loop. Thanks to the digital connection among the physical factory entities and the biunivocal communication between digital and real entities, the whole

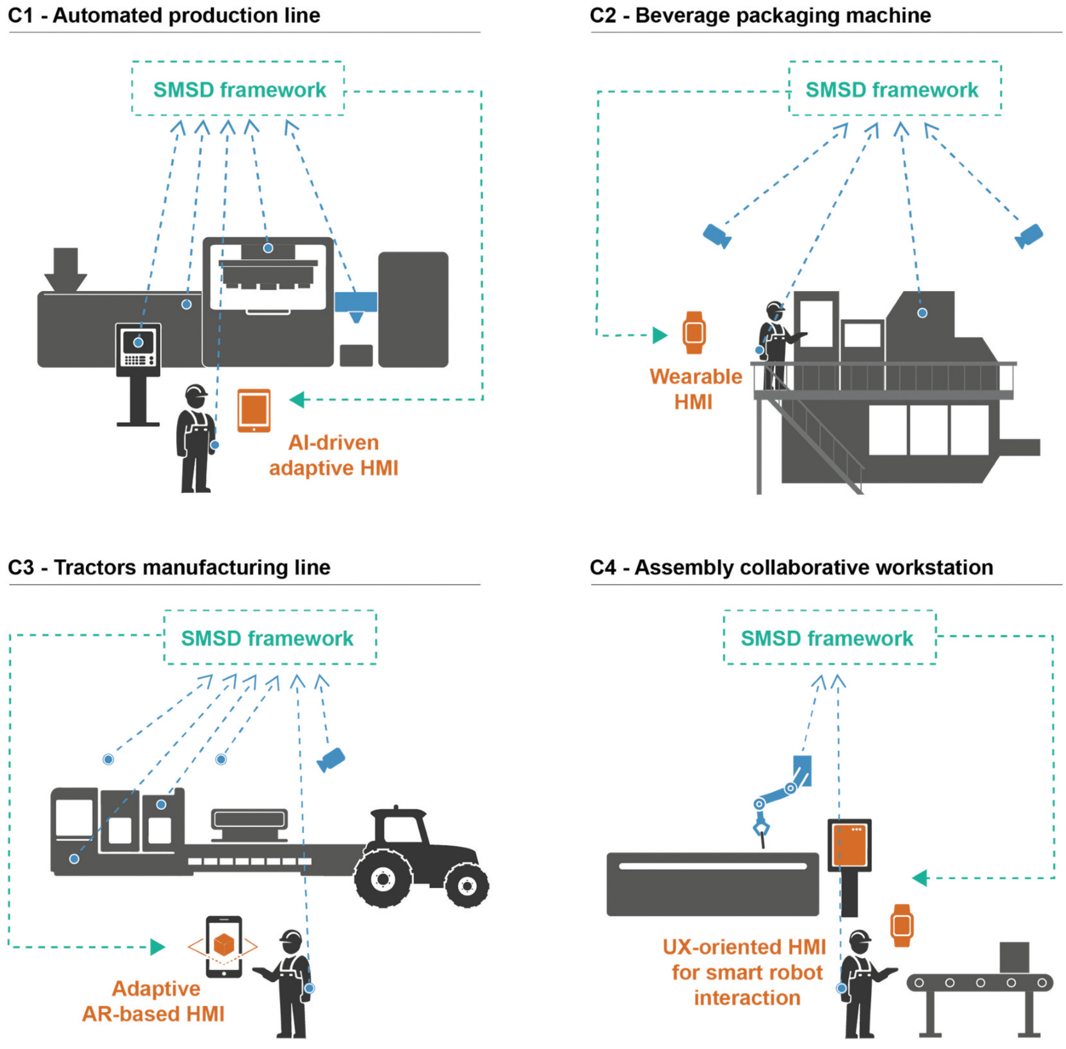

Figure 4. Application of the SMSD framework for Industry 5.0 to the industrial cases.

system behaviour can be controlled and assessed in real time to optimize the overall performance and modify the behaviour in real-time, including working instructions to the operators and interfaces' contents. Moreover, data from machines, robots, operators, and the surrounding environment are elaborated to provide create new knowledge and define intelligent, adaptive, AI-driven applications for HMIs and smart user devices. Such HMIs can assume adaptive features to convey information and instructions to the operators contextually and intelligently, enabling the understanding of the human-machine interplay and creating an effective collaboration with the industrial systems, supporting the virtuous two-fold learning process.

The proposed model enriches the intelligent manufacturing I4.0 capabilities with I5.0 features: the digitization process also includes humans to simulate the human activities, tasks and interactions with the factory systems, in order to provide them real-time custom support and instructions, including optimal sequence of operations and actions to achieve the best productivity and performance with the minimal effort. Humans are no more just spectators, but both generators and users of knowledge together with the machines. Such an enriched scenario supports an optimized decision-making thanks to the wider perspective. The ADT is connected to the factory, exchanging data from and to and to the HMIs supporting the human work. In this direction, the I5.0 strategic approach can be concretely implemented to significantly evolve the modern industrial systems and create a robust and adaptive industrial scenario, where humans and machines effectively cooperate and co-evolve.

The proposed framework has been applied to the case studies to define novel HMIs and AI-driven application to achieve the I4.0 objectives. Results have brought to realize the human-automation symbiosis in practice to overcome the main limitations of I4.0 models. According to the proposed framework, the smart factory can simulate their complex behaviour and can benefit from the integration and processing of multiple types of data. The integration of human data in the ADT can be realized by proper sensors and technologies for human tracking and monitoring, and adaptive HMIs. The proposed model can promote an interaction-based relationship between humans and machines, including automation, robotics, and artificial intelligence systems. Simulation can also support the strategic decision-making and can be adopted to both validate existing scenarios and to design new smart scenarios, also in the context of circular economy. Moreover, the modern factory can capitalize not only on smart machines' strengths and capabilities but also to empower their smart operators with new skills and interfaces, to fully take advantage of the opportunities being created by smart technologies. Finally, the proposed framework supports the achievement of new levels of efficiency, productivity, and resilience that neither human systems nor machine systems can achieve on their own, according to the human-automation symbiosis. Such a framework could be also integrated with the recently proposed AAS and RAMI4.0 system architectures, to better drive the factory innovation and support a socially sustainable and resilient decision-making to design the I5.0 smart factory, starting from the people needs and skills and not from what the technology can offer.

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