Strategic Action Line LI4: High Efficiency and Zero Defect

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Abstract The objective of this chapter is to describe the strategic action line related to high efficiency and zero defect production (LI4). In particular, this chapter proposes research and innovation priorities aimed at studying models for efficiency in terms of: zero-defect technologies designed to reduce non-conformances, monitoring processes during the various phases like quality management, maintenance and internal logistics of a manufacturing system, upgrading and improving the capacity of equipment and industrial goods; robustness/flexibility as the capacity to face disruptions, due to the precarious supply of incoming materials and parts, and to the specific properties of the material (anisotropy, low rigidity, etc.); smart systems for optimized use of available resources (equipment, human operator, knowledge) and for the control and management of production systems through models (CPS, empirical models, etc.).

Keywords High efficiency · Zero defect · Advanced control · Maintenance · Artificial intelligence

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1 Introduction

Efficiency is the ability to reduce the effort associated with the achievement of a goal, optimizing the use of resources, materials and time. Quality plays a significant role in terms of efficiency in achieving the expected results, as it permits to avoid rework and waste of products and materials. Efficiency is an enabler of company competitiveness, since the ability to work efficiently in complex and variable conditions determines the possibility to operate in more demanding and competitive areas, such as product customization, adoption of new technologies, enabling of remanufacturing activities. Finally, the growing complexity of production systems also requires an efficient use of resources in a more general way. In this perspective, the efficient use of available machinery and equipment, the ability to exploit available knowledge and take advantage of advanced digital tools and artificial intelligence towards the implementation of next generation production systems (Fig. 1).

The goals of this strategic action line fall into three groups:

- **Zero defects.** Efficiency is considered in terms of reduction of non-conformities and their impact on the performance of the production system, and involves monitoring processes in their various phases, quality management, production systems' maintenance and internal logistics, updating and improving the capacity of equipment and industrial assets.
- **Robustness/flexibility.** Efficiency is considered in terms of ability to carry on operations during disturbances. In particular, the variability of incoming materials and pieces, and a material's specific characteristics (anisotropy, low stiffness, etc.) are particularly significant for the various types of applications. This is especially true in a circular economy, which involves rework and/or repair processes.

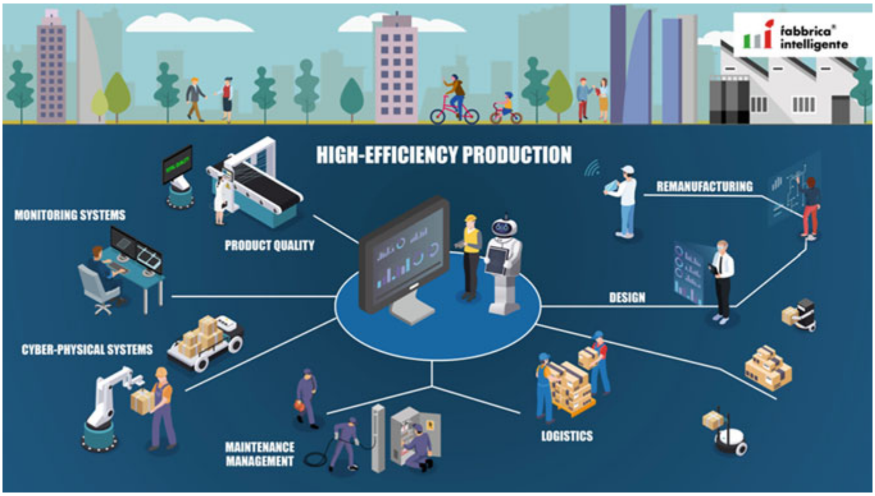

Fig. 1 Strategic Action Line—High-efficiency and zero defect

Furthermore, the expansion of the equipment's scope of application is explored also in terms of the possibility to operate multiple technologies at the same time and the use of robots for a wider range of applications.
- **Intelligent systems.** Efficiency is considered in terms of optimized use of available resources (equipment, human operator, knowledge). It is necessary to consider approaches and methodologies for the control and management of production systems through models (CPS, empirical models, etc.) and approaches that exploit artificial intelligence, to establish an efficient collaboration between human operators and automatic tools, as well as approaches and methodologies for the consolidation of knowledge.

The research and innovation priorities of the strategic action line on High Efficiency and zero defect are:

PRI4.1: Advanced monitoring and control of production processes (zero defects)
PRI4.2: Approaches for an integrated quality/maintenance/logistics management (zero defects)
PRI4.3: Updating, retrofitting and valorisation of capital goods (zero defects)
PRI4.4: High efficiency for repair remanufacturing (robustness/flexibility)
PIR4.5: Advanced industrial robot modelling and planning (robustness/flexibility)
PRI4.6: Cyber-physical systems (CPS) for smart factories (intelligent systems)
PRI4.7: Human-artificial intelligence for knowledge consolidation and human-machine cooperation in high-efficiency production systems (intelligent systems)
PRI4.8: Advanced production, planning and scheduling (intelligent systems)

2 PRI4.1 Monitoring and Advanced Control of Production Processes (Zero Defect)

Monitoring and control contribute to process efficiency, as all the elements of Overall Equipment Efficiency (OEE)—i.e. Availability, Performance and Quality—require accurate and precise measurement in order to:

- Achieve a specific understanding of cause-effect mechanisms and allow the implementation of advanced closed-loop control techniques;
- Improve the design, execution and maintenance of both physical (machine level) and virtual (organization level) assets.

Furthermore, the exploitation of sensor systems in combination with standard methods for collecting, filtering and archiving data will provide an unprecedented source of data, useful in understanding complex production phenomena and scenarios.

The goals of this research and innovation priority are related to:

- Improving data management through the adoption of standard ontologies, communication protocols and open software that can be easily reused.

- Enhancing HMI (Human Machine Interaction) and UI (User Interface) through techniques for the visualization of multidimensional data aggregation, to help users deal with the increased complexity of the reality under control.
- Exploring alternative UI mechanisms based on wearable devices and multisensory interfaces (visual, audio, tactile and AR/VR techniques)
- Developing a Digital-Twin-based control system, i.e. a control mechanism based on real time behaviour simulation.

The expected impacts from the introduction of advanced monitoring and control solutions will allow manufacturing companies to improve process efficiency from all three perspectives:

(1) More production lines will be available, thanks to an early detection of potential failures, the introduction of predictive maintenance and a better scheduling of maintenance operations;
(2) Performance: The process could be contained, or it could self-adapt, in real time, depending on production needs. Data would help understand the causes behind speed losses and micro-stops;
(3) Quality: Sensor data and fitting techniques will help reduce process variability and provide ways for an early detection and correction of deviations.

The integration of process and product parameters will encourage a holistic approach to the optimization of production processes, and promote waste reduction, a more energy efficient production and lower CO2 emissions.

Interaction with Other Strategic Action Lines

- LI1—Integration of the study of efficient programming systems to improve the availability of more intelligent machine tools for product personalization.
- LI2—Integration of advanced machine tool control for a significant increase of efficiency and reduction of waste and energy consumption.
- LI3—The new advanced functions of machine tools will remodel human–machine interactions and call for operators with advanced skills and analytical dexterity.
- LI5—The new advanced monitoring and control systems will be particularly beneficial for innovative manufacturing processes such as additive manufacturing and hybrid manufacturing. More complex machines will have higher costs, and an effective control system will be needed to avoid problems and increase efficiency.
- LI6—There is a very strong interaction, as more advanced control methodologies will only be possible by implementing machine learning techniques and smart components and sensors.
- LI7—The new capabilities of machine tools will certainly have an impact on management, production, organization and supply chain.

Time Horizon

Short-term goals (2–3 years):

- Development of standard ontologies and communication protocols.

- Development of basic requirements and regulations to enable the development of digital twins—3D geometric models of machine components, mathematical models for handling operations.
- Development of standard adaptive control techniques based on process sensors (power, temperature, force, vibration).
- HMI innovation through the introduction of virtual reality and basic signal-analysis functions.
- Development of standards for the creation of digital shadows.
- Off-line monitoring of machine tools with simple process parameter adjustments (override).

Medium-term goals (4–6 years):

- Introduction of self-programming and more advanced adaptive control techniques based on the indirect observation of process quantities using mathematical models.
- Innovation of HMI by introducing statistical analysis functions.
- Development of standards for integrating cloud digital twins into the manufacturing process.
- Complete off-line control of machine tools, including loading and unloading.

Long-term goals (7–10 years):

- Development of standards for the integration of advanced control logics in complex systems and production lines.
- Advanced sensor data analysis functions in combination with simulation.
- Development of standards for the integration of digital twins in the critical control cycle (edge).

3 PRI4.2 Approaches for Integrated Quality/Maintenance/ Logistics Management (Zero Defect)

Digital tools, together with formalized knowledge and data, offer the possibility to implement complex approaches to quality management, taking into account the wide range of factors that influence product quality, and improve efficiency of the production system as a whole.

These factors include: the control of production processes, the management and supply of materials and components, the maintenance of production assets and their updated performance, the logistics of the whole system and the interconnection of the different aspects and actors to determine their performance.

Building on knowledge and data, and exploiting integrated models based on quality, logistics and maintenance factors, the focus of this research and innovation priority is on methodologies and approaches aimed at improving the overall efficiency of production systems, in terms of productivity, qualitative characteristics of the products, use of resources, maintenance policies, etc.

The selected approaches should cover a wide range of products, processes and resources. For example, large products for which transportation, inspection and processing are specifically difficult. The considered approaches should be robust, including in the modelling the intrinsic uncertainty of real production systems, and any changes in decisions and planning when unexpected events occur, to mitigate the impact of such events on the systems' overall performance.

The main goals of this research and innovation priority cover the following areas:

- **Methods and tools for quality control in complex products** (e.g., product characterized by large dimensions, multiple materials, additive processes, etc.) as well as in low-volume and/or small-batch production (e.g., personalized products). In these cases, traditional approaches to quality control and management are inadequate, which creates a demand for new advanced approaches. Research will especially address the use of cyber-physical models for products and processes, adaptive approaches, artificial intelligence and machine learning, supervised and unsupervised learning, formalization and structuring of the knowledge of human operators. The general goal is to improve the ability to predict anomalies and implement the possibility of feeding and integrating these approaches with knowledge and data from digital models of production systems (Digital Twins).
- **Models and approaches for the integrated management of quality, maintenance and logistics for the entire production system.** These approaches are expected to define and support complex and integrated decisions in relation to maintenance, quality and logistics. For example, planning the maintenance of production resources, defining and planning quality controls, activating decisions for continuous improvement, planning and scheduling production. A possible class of approaches in this area is opportunistic maintenance, modelled to include jointly quality (deviations from product/process specifications), maintenance and system status. The goal is to reduce the impact of maintenance activities on overall system performance.

Interaction with Other Strategic Action Lines

- LI1—The availability of integrated quality/maintenance/logistics approaches will improve product customization by reducing the inefficiencies related to personalized products;
- LI2—Improving efficiency and reducing waste and energy consumption;
- LI7—The development of these approaches requires a strong integration with the digital platform that operates in the production system.

Time Horizon

Short to medium term goals (2–6 years):

- Models and approaches for an integrated management of decisions related to quality, maintenance and logistics, considering that a substantial amount of partial research results and embryonic products are already available.

Long-term goals (7–10 years):

- Methodologies and tools for identifying quality problems in complex products, since the main gap with respect to the state of the art is the absence of standard reference models (ontologies, definition of semantic data), while a secondary gap is the development of unattended machine learning approaches applied to complex systems (Cyber-Physical Systems of Systems-CPSoS).

4 PRI4.3 Updating, Retrofitting and Enhancement of Durable Equipment (Zero Defects)

A substantial portion of the durable equipment of manufacturing companies (for example, machine tools, assembly systems, etc.) has been designed to have a significantly long life, in many cases approximately 20–30 years. However, the recent rapid and radical evolution of production systems has accelerated the obsolescence of a large part of it, mainly because of the impossibility to integrate it with digital management and control infrastructures, rather than on its actual process capacity.

Therefore, retrofit and updating geared to the integration of modern digital functionalities into operating but dated durable equipment are extremely significant, and represent a sustainable, valid and effective approach for the management and updating of industrial equipment in terms of I4.0 technologies.

The goals of this research and innovation priority cover the following areas:

- **Toolboxes for the updating and retrofitting of machine tools and production systems.** Tools designed to provide operators with the functionalities and approaches necessary to transform sensors and interconnections of traditional machine tools. In particular, with regard to sensors, actuators, control devices and protocols, connection devices and protocols, cyber-physical models of machine tools' behaviour and performance.
- **Plug-and-play models for the integration of machine tools and production systems into modern digital control and management platforms.** Conceptual design of standard connectors to enable a set of standard/optional features. Standard knowledge-representation models based on semantic technologies will also be taken into consideration, with a view to enabling and ensuring interoperability between different factory objects (machines, conveyors, etc.) by exploiting existing standards (Supervisory Control and Data Acquisition—SCADA, Distributed Control System—DCS).
- **Assisted methodologies for the characterization of durable equipment for integration.** Durable equipment currently operating in production systems are based on a wide range of different management and control architectures which apply different control technologies, communication protocols, control approaches, electromechanical components. In many cases, they are the result of multiple upgrade and re-engineering phases. A consistent and secure integration of these assets into modern IT management and control platforms requires reference

standards to regulate and allow the modelling of the characteristics, functionalities and capabilities of industrial equipment in a general and unique way. Furthermore, the assessment of the operational and technological capacity of industrial equipment is influenced by multiple intersecting factors. Therefore, to ensure a coherent and uniform set of management and control tools, it is important to design and develop specific approaches as a basis to more general approaches for the evaluation and certification of performance in the different situations (architectures, machine characteristics, control approaches, etc.)

Interaction with Other Strategic Action Lines

- LI2: The possibility to update existing industrial assets has a clear impact on the sustainability of production activities in general. Furthermore, by its very nature this research and innovation priority applies a circular economy paradigm.
- LI7: The upgrading and retrofitting of industrial assets is primarily driven by the need to incorporate them into modern IT platforms.

Time Horizon

Short to medium term goals (2–6 yeas):

- Plug-and-play models for the integration of industrial assets into modern IT management and control platforms;
- Assisted methodologies for the characterization of durable equipment to support integration.

Medium term goals (4–6 years):

- Toolbox for updating and retrofitting industrial assets.

5 PRI4.4. High Efficiency for Repair and Remanufacturing (Robustness/Flexibility)

The transition to circular production models requires, from a technological point of view, processes, technologies, skills and capital goods for the maintenance, repair, updating and reworking of products and their components. Therefore, not only the production, but also the repair and regeneration of products require plants in which to operate. These plants must be able to work in collaboration with the supply chains of the original production plants, to manage the entire life cycle of the products.

This research and innovation priority arises from the need for durable equipment and production facilities to regenerate, repair and recycle products and components. The focus is on highly efficient technologies and approaches that can partially carry out processes and/or repeat a limited and/or alternative set of operations to obtain compliant/degraded and reclassified products. Furthermore, these processes will be expected to deal effectively and efficiently with the variability of incoming products, which is typical of reworked products that come from different kinds of uses.

The goals of this research and innovation priority concern in particular:

- **Systems for the automatic characterization of the state of materials and/or products** in support of the recovery/reworking/repair phases. In this context, DMC/RFID traceability/identification and computerized-vision technologies can be appropriately developed for characterization of defects/damage/wear.
- **Intelligent systems and HMI in support of recovery/rework/repair.** The goal is to provide decision-making and operational support in real time to operators dealing with recovery/reworking/repair processes in highly variable conditions and states of the materials to be processed. In this context, decision-support tools need to be developed, to identify the most suitable strategy for each specific product, in consideration of its conditions, defining manual/semi-automatic disassembly operations and subsequent restoration and/or completion operations, compliance of the reprocessed product and its new classification for reintroduction on the market. AI-based technologies will be investigated, particularly in support of their interaction with human operators, and for safety and ergonomics purposes.
- **Flexible and efficient production processes and systems** to ensure the integration of repairing and remanufacturing operations in the production flow, assuring capability of interruption, or partial execution of manufacturing processes, in support of reworking and repair. This topic includes diversified aspects, such as the characteristics of equipment and their control systems, the definition of modular and reconfigurable manufacturing processes, the development of standards that can explicitly support the functions described. The general objective is to ensure the possibility of a partial/interrupted execution of processes, while maintaining the performance levels of the production/reworking systems.
- **Repair technologies.** Repair operations are geared to restore the products' characteristics/functionality. For this purpose, it is necessary to develop specific production technologies that maximize the recovered value while optimizing repair costs in terms of energy, material consumption and disposal of non-recoverable items. In this context, examples are additive manufacturing technologies, which can play an important role in the formulation/definition of special repair processes, not only by facilitating the production of spare parts but by introducing specific methodologies (e.g. return of materials for the subsequent restoration of fastening/shrinking seats and/or worn profiles) or the reuse of recovered and reconditioned components to obtain new products.

Interaction with Other Strategic Action Lines

In relation to the strategic action lines of the CFI roadmap:

- LI2: Industrial sustainability.
- LI3: Factories for humans.
- LI6: Evolving and resilient production systems.
- LI7: Strategies and management for next generation production systems.

Time Horizon

Short-term goals (2–3 years):

- Systems for the automatic characterization of the state of materials.
- Intelligent systems and HMI to support recovery/rework/repair.

Medium-term goals (4–6 years):

- Flexible production processes and systems in terms of real/virtual demonstrators.
- Repair technologies in terms of real/virtual demonstrators.

Long-term goals (7–10 years):

- Flexible and efficient production processes and systems up to a Technology Readiness Level (TRL) suitable for complete industrial implementation and diffusion.
- Repair technologies up to a Technology Readiness Level (TRL) suitable for full industrial deployment and diffusion.

6 PRI4.5. Advanced Industrial Robot Modelling and Planning (Robustness/Flexibility)

The planning and control of industrial robots is essential in ensuring a safe, effective and reliable use of robots in applications other than those in which they are commonly used.

The objectives of this research and innovation priority mainly concern:

- **Advanced methodologies and sensors to support the safety of industrial robots**, to be used in collaboration with human operators. In this scenario, robots are meant to perform the heaviest operations or operations that require high accuracy or repeatability, and assist humans in their activities. Operators can thus focus on operations that require greater flexibility (for example those related to product personalization). As for collaboration between robots and operators, the state of the art cannot guarantee safety levels in line with regulatory requirements and the performance standards demanded by the industry. It is necessary to develop advanced methodologies and sensors capable of predicting human behaviour, thus avoiding risks and ensuring adequate performance. At the same time, robots that operate in these conditions have to be built (both in terms of hardware and control) in such a way as to minimize the impact of possible collisions with humans, through specific materials, low mechanical resistance, etc.
- **Modelling robots to execute technological processes in which the interaction between tools and parts generates remarkable forces** (e.g., milling). Applications of this type involve a considerable difficulty in terms of controlling the robot's movement, as it is impossible to ensure the necessary accuracy in the positioning of the end-effector when there are significant deformations in the robot's

structure. It is necessary to develop modelling techniques that can estimate the forces generated between the end-effector (tool) and the parts being machined, implementing appropriate control techniques to compensate actively for deviations from the ideal trajectory, rather than relying on the inherent rigidity that lightweight structures such as robots cannot provide.

- **Specific programming approaches capable of bypassing the need for a definition of specific trajectories,** focusing decisions on the characteristics of the process to be implemented and avoiding the difficulties associated with the adoption of robots in manufacturing processes. It is necessary to study advanced software that can support the programmer in defining the operations to be performed by the robot. These approaches will be based on features such as learning by examples, assisted and simplified programming, and the ability to modify and reconfigure the operations assigned to a robot in a simple and reliable way.

Safe and effective collaboration between robots and operators has strong impacts in terms of ergonomics and workers' well-being, as it contributes to relieve people of heavy and/or tiring tasks. At the same time, it can boost systems' performance in terms of flexibility, by calibrating workloads (for both operators and robots) depending on the volume and characteristics of the products.

Extending the use of robots to the execution of technological operations can significantly increase the flexibility of production systems. The processes involved include finishing operations (such as polishing, grinding, deburring, etc.), in addition to those concerning the removal of materials.

Greater ease in the implementation and reconfiguration of processes assisted or performed by robots would have a significant impact in terms of the diffusion of robots in manufacturing industries and their competitiveness in terms of cost, quality and flexibility.

Interaction with Other Strategic Action Lines

- LI1: The use of industrial robots in a wide range of processes supports product customization.
- LI3: A widespread use of robots must take into consideration issues related to the human being.
- LI5: A more reliable positioning of robots' end effectors can be used to implement and automate innovative processes.
- LI6: The robots' high flexibility ensures the adaptability and resilience of production systems.
- LI7: Digital tools and technologies are needed to support the broad adoption of industrial robots.

Time Horizon

Short-medium-term goals (3–6 years):

- Human–robot collaboration in production environments.
- Advanced planning approaches for robots.

Medium-long term goals (4–10 years):

- Use of robots instead of machine tools.

7 PRI4.6 Cyber-Physical Systems (CPS) for Smart Factories (Intelligent Systems)

The flexibility and reconfigurability of production systems require modular and intelligent architectures, as well as monitoring and controlling of logistics and system quality, compliance with process constraints and safety of man–machine interactions.

Traditional hierarchical control techniques rely on predefined configurations and statically-designed decision platforms, which do not provide the required degree of flexibility, adaptability and efficiency.

Furthermore, the behaviour of a production system is usually modelled as a chain of actions within a purely temporal domain defined in terms of events. The interaction with the underlying processes requires approaches based on continuous-time control or, alternatively, discrete-time control but with better temporal resolution. These two levels are not considered jointly, thus constituting a barrier to the overall optimization of the system's behaviour.

It is therefore essential to develop an integrated and distributed platform for monitoring, control and supervision. It should consist of intelligent and interacting units, based on Cyber-Physical Systems (CPS) and a hybrid paradigm, to consider simultaneously different temporal domains (discrete and continuous events) related to the modelling of the behaviour of a production system, at different levels.

This class of approaches is applied for example to modular robotic cells in scalable production systems, where adaptation to external conditions and to the processes to be carried out is fundamental. In those cases, coordinating the intelligent components that operate in a production system, and integrating them into management and control platforms are key factors in governing the network of complex interactions between physical, software, robotic and human components, human–robot interaction and human–robot collaboration.

Using CPS approaches for machines and machine-systems reveals new possibilities that go beyond current control approaches, evolving towards the possibility of automatic adaptive performance improvement, in terms of efficiency and safety (also in human–machine interaction) of the whole system at different levels.

The availability of a Digital Twin for a physical system determines the possibility of developing predictive control algorithms based on the updated status of the plant, as well as the possibility of using AI methodologies based on the available data.

CPS architectures of individual production units, based on the 5C paradigm (Connection, Conversion, Cyber, Cognition, Configuration), should therefore evolve towards a new 6C paradigm, where the additional level would be the Cooperation between factory objects. It is therefore necessary to develop an integrated level of control where intelligent agents can integrate and cooperate towards the collection of information and data, and the management and optimization of performance.

This level's key factors are techniques of Massive Data Acquisition, Data Analytics and Machine Learning, geared to create and integrate the cognitive, self-configuration and cooperation levels of intelligent CPS units, to drive flexibility, high performance, and efficiency.

Interaction with Other Strategic Action Lines

- LI2: CPSs offer tools to improve integrated product-process-system modelling.
- LI3: connections with technologies and methods for humans in the factory and Virtual/Augmented Reality (VR/AR) technologies and applications for product-process-system management (using a system's digital twin).
- LI6: highly flexible modular mechatronic systems.

Time Horizon

Short-term goals (2–3 years):

- Development of hybrid simulation/emulation techniques based on digital twins and predictive control for intelligent CPS units in simplified scenarios.
- Development of efficient technologies for the implementation of CPS
- Development of artificial intelligence systems to be implemented in single modular CPS units.

Medium term goals (4–6 years):

- Validation and comparison of different predictive and adaptive control systems for individual CPS units
- Development of artificial intelligence systems capable of coordinating the activity of single CPS modular units.
- Preliminary development of integrated multilevel platforms for the cooperation of different CPS and the interaction planning and monitoring activities.
- Validation of artificial intelligence systems to be implemented in single modular CPS units.
- Validation of simulation/emulation techniques based on digital twins for intelligent CPS units in medium complexity scenarios.

Long-term goals (7–10 years):

- Validation of artificial intelligence systems that can coordinate the activity of different CPS modular units.
- Validation of simulation/emulation techniques based on digital twins for intelligent CPS units in highly complex scenarios.

8 PRI4.7 Human-Artificial Intelligence for Knowledge Consolidation and Human–Machine Cooperation in High-Efficiency Production Systems (Intelligent Systems)

The challenges faced by production systems and technologies require the ability to combine the adaptability and flexibility of human intelligence, which can efficiently handle unexpected and evolving production scenarios, with the capabilities of artificial intelligence, which can process large amounts of data in real time and manage complex situations.

In this context, some emerging issues can be identified:

- The experience and knowledge of human operators are a significant part of a company's know-how, and represent a strategic asset to be formalized, preserved and enhanced in order to achieve efficiency. Artificial intelligence technologies afford the possibility of enhancing this knowledge corpus and the role of man in production environments. However, the difficulty in retaining and protecting this knowledge poses a major risk to manufacturing companies.
- Artificial-human knowledge can be structured and consolidated as long as one can define a sequence of formal steps to interpret the decisions taken both through automatic approaches (which can be explained through AI-related methods) and by human operators.
- The gathering, structuring and use of hybrid human-artificial intelligence have to be based on a network of intelligent systems, for example by applying distributed federated learning methods or inferring learning models from interconnected (artificial or human) intelligent nodes. Both flexibility and high efficiency can be achieved in resilient adaptive production scenarios using distributed learning methods capable of defining a balance between the analysis of possible optimized solutions and the use of corporate knowledge.
- Collecting and structuring human-artificial intelligence and knowledge requires qualified and competent personnel and R&D programs, to exploit modern digital technologies and integrate them into a manufacturing company's processes and know-how.

This research and innovation priority applies to the following areas:

- Structured and formalized approaches (for example, ontologies and semantic-web technologies) for the representation of knowledge related to production processes and systems. These approaches must be suitable to support interfaces for access and use by both human and automatic actors. This will require the ability to operate on the partial/incremental structuring of knowledge due to missing information and data, to sequential or incomplete formalization and structuring processes, to human operator errors.

- Automatic identification of possible inconsistencies in the knowledge (for example, Shapes Constraint Language—SHACL). These approaches aim to efficiently integrate human knowledge and artificial intelligence by providing tools for the validation of knowledge consistency. Based on the specification described at the previous point, these inference approaches will be expected to predict potential inconsistencies in the structuring of knowledge and interact with human/artificial agents to resolve conflicts.
- Human–machine interactions, protocols and interfaces that exploit artificial intelligence with the aim of quickly and efficiently structuring and consolidating knowledge in relation to production processes and systems. They are based on human/artificial inference processes, grounded on the methodologies and approaches described in the previous points.

New developments in this scientific and technological field are important for the competitiveness and efficiency of manufacturing companies in relation to future competitive scenarios. The formalization and consolidation of corporate knowledge bring out and capitalize on the experience and skills of operators. In combination with the support provided by artificial intelligence approaches, they are important elements in preserving and profiting from the know-how of companies. These factors are strategic in future manufacturing scenarios, characterized by the pervasive adoption of digital technologies, the need to interact and collaborate globally while preserving the intellectual assets of companies, and the drive towards platform-based collaboration paradigms.

Interaction with Other Strategic Action Lines

- LI3: Involvement of human operators in the process of structuring and consolidating their experience and knowledge.

Time Horizon

- Short-medium term goals (2–6 years)
- Structured and formalized approaches for the representation of knowledge.
- Automatic inference approaches for the formalization of knowledge.
- Human-machine interactions, protocols, and interfaces.

9 PRI4.8 Advanced Production Planning and Scheduling (Intelligent Systems)

The growing complexity of modern production systems requires advanced planning approaches to exploit the most of their features and functionality. The objectives of this research and innovation priority cover the following areas:

- Production planning and scheduling based on artificial intelligence. Approaches related to the latest developments in artificial intelligence (e.g. deep learning), as well as more traditional technologies (e.g. expert systems) can play a supporting role in the planning and programming of production systems. These approaches can eventually lead to an identification of the system's current state by expressly monitoring parts, components, state of production resources, through the analysis of tracing data and/or images relating to the production system. They can also help identify the state of the system based on pattern recognition approaches; select planning rules/policies based on historical data, identify system behaviour deviations from the plans and determine new planning.

- Robust production planning and scheduling based on risk indicators. In production systems, deviations from plans are the rule rather than an exception, due to the occurrence of unexpected events. Such events can be determined by a number of possible internal or external causes. Activities might be longer or shorter than originally planned, resources might not be available, materials might arrive late, supply arrival times and product delivery dates might change, and new activities such as reworking may be included in the schedule. Robust approaches are intended to react to unexpected events (reactive approaches) or mitigate their impact in advance as much as possible (proactive approaches). Innovative approaches will be developed based on risk measurements used in the financial sector (e.g., value-at-risk, conditional-value-at-risk, maximum regret) capable of defining a balance between performance and mitigation of the impact of uncertainty on the plan's performance.
- Model-based approaches for sequencing/control. The request to operate in variable conditions entails the possibility for a production system to work in configurations other than those for which they were designed. For example, production/assembly lines forced to operate in unbalanced conditions. In these cases, sequencing and control policies have a significant impact on system performance. They must therefore be defined and calibrated depending on the changing conditions in which the system operates. Model-based control approaches use a digital twin for the machine/system, thus providing an effective method for designing and optimizing sequencing/control policies. Approximate approaches based on surrogate/low fidelity models can also support a real-time update of the policies promoting the efficiency of production systems.
- Approaches for the propagation of planning and scheduling constraints. The complexity of modern production systems requires approximate approaches that can identify the most important decisions to be made, rather than trying to solve planning problems altogether. Constraint propagation and automated reasoning approaches can support the identification and search for appropriate planning and programming decisions based on complex (nonlinear) models. Furthermore, they support the identification of the disturbance event that triggers a new planning or scheduling.

Interaction with Other Strategic Action Lines

- LI1: Planning and scheduling approaches can support the implementation of personalized production approaches within the limits of the available capacity of production resources.

- LI2: Planning and programming can be applied to energy consumption, which would promote sustainability in operating a production system.
- LI6: Advanced planning and scheduling, especially proactive/reactive approaches support the adaptability of a production system.
- LI7: Advanced planning and scheduling are relevant approaches for the next generation of production systems.

Time Horizon

Short-medium term goals (2–6 years).

- Planning and scheduling based on artificial intelligence.
- Robust planning and risk-based production scheduling.
- Model-based control/sequencing approaches.
- Approaches for the propagation of planning and scheduling constraints.
- IT industrial platforms to support the interaction between human and artificial intelligence.

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