Rosanna Fornasiero · Tullio A. M. Tolio

Editors

The Future of Manufacturing: The Italian Roadmap

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The Future of Manufacturing: The Italian Roadmap

Springer

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Foreword

Manufacturing is the mainstay of many modern economies, capable of generating social, economic and environmental benefits, as well as helping overcome the great challenges of our times. The last two years have been particularly challenging for economies the world over, and Italy—with its wealth of flexible businesses, a diversified industrial culture and the ability to swiftly reconvert its processes—has managed to respond to the market-induced criticalities.

With its "Manufacturing a Resilient Country" document, the Cluster has already offered a proposal to face situations like the pandemic crisis, pointing out the need for Italy—as a country working together in a networked system—to adopt strategies that can leverage that solid industrial system to strengthen and develop processes, sectors and applications by creating collaborative ecosystems that pool regional specialization area excellences capable of working in national and international supply chains.

This roadmap is the result of intense work put in over two years, which has seen companies, universities, research bodies and associations come together to build a systemic vision for the themes of research and technological innovation with a medium- to long-term outlook. The aim of the document is to recommend paths for improving manufacturing's positioning in the international arena, facing challenges head-on and opening up new strategic opportunities to strengthen Italy's specific industrial leadership across the globe. The roadmap follows seamlessly from Horizon Europe's European research policies, developed in line with these policies and with what has been defined in the regional Smart Specialization strategies.

It is based on a collaborative approach whereby top-down analysis of the global development trends and scenarios generating the challenges for manufacturing are integrated with a bottom-up approach that engages the Cluster's members in bringing forward their research needs for the coming years.

The roadmap is structured along seven strategic action lines for which specific priorities for research and innovation have been identified, designed to seize and develop the opportunities offered by emerging and potential enabling technologies

(which have also been identified with the aid of Pathfinders) in relation to the challenges companies are fielding from the market (which have also been identified with the aid of Lighthouse plants).

This work was started under the previous presidency of the Cluster, Luca Manuelli, and has been completed under my mandate and represents a coherent and harmonized vision of the Cluster of Intelligent Factories over the years.

In presenting this document, first of all I would like to thank my closest collaborators of the previous and current management boards for their valuable support on the strategic development of this roadmap: the president of the cluster, Gianluigi Viscardi, Tullio A. M. Tolio, Antonio Braia, Ivan Boesso, Leda Bologni, Paolo Calefati, Mauro Castello, Paolo Dondo, Sauro Longhi, Alberto Longobardi, Luca Manuelli, Alessandro Marini, Maria Rosa Raimondo, Mario Ricco, Daniela Sani, Giuseppe Saragò, Marco Taisch, Flavio Tonelli, Lorenzo Molinari Tosatti, Daniela Vinci and Andrea Volpi.

A particular thanks to the previous and current members of the Scientific Board of the Cluster that gave the scientific direction to the development of the roadmap. Tullio A. M. Tolio (President), Paolo Calefati, Sauro Longhi, Alberto Longobardi, Marco Taisch, Flavio Tonelli and Gianluigi Viscardi.

This work would not have been possible without the continuous and strong commitment of the roadmap editors, Tullio A. M. Tolio and Rosanna Fornasiero, who coordinated the work of all the cluster groups, assured the consistency of the whole document and supported the definition of the coherent and complete vision of the content generated along the process of roadmap development.

My thanks go to Cluster Manager Paolo Vercesi who organized the work around the creation of the roadmap, organizing webinars, managing surveys and supporting actively discussions and various technical meetings.

This roadmap is the result of a collaborative approach involving all the members of the Cluster of Intelligent Factories who have provided their competence, ideas and vision on the future of Italian manufacturing through an interactive process. Companies, Universities, Research Bodies and Associations have lent their expertise in various capacities, called on by the Cluster to take an active part in this process.

In particular, I would like to thank the following groups that have dedicated continuous effort in the development of the roadmap.

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- Antonio Braia—Cluster Lucano Automotive for Basilicata Regional Council
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I think this roadmap is an essential tool for supporting members in determining their paths going forward and, at the same time, to inspire specific policies and actions for research and innovation as well as internationalization at the various stakeholder levels, including at a government level. It can be used to bring institutions—above all, Ministries in particular MUR, MIMIT, MAECI, MASE and MLPS—into the discussion, representing the visions brought into focus by the members of the Italian Cluster of Intelligent Factories. At the European level, it is a qualified point of view for possible interactions with the Manufuture platform, existing partnerships like Made in Europe, Clean Steel and Processes4Planet, the Chips Joint Undertaking and the new partnerships in the area of advanced materials, the KIC Manufacturing and all the other initiatives related to manufacturing. Lastly, this document can further be used for actions to support cross-fertilization between national and regional policies and to support bilateral discussions with other countries.

Bergamo, Italy   Gianluigi Viscardi
President of the Cluster of Intelligent
Factories

Preface

Manufacturing is the mainstay of many modern economies, capable of generating social, economic and environmental benefits, as well as helping overcome the great challenges of our times. From a broader point of view, the availability of advanced expertise, industrial culture, image, brands and reputation, availability of resources for innovation and research, and the right conditions to attract talent are all elements that can seal a country's success.

Over the last three years, it has become even more apparent that—based on the characteristics and availability of resources (such as skills, manufacturing plants and raw materials)—each country needs to develop a strategy to ensure a strong industrial sector, focusing on processes, sectors and applications that embody the uniqueness of the region's characteristics, with a view to achieving excellence in strategic areas of specialization.

Italy, more than most, has a unique heritage in terms of tradition, culture, skills, image, design and technologies, which represent the optimal environment for a manufacturing sector that produces high-added-value products and services exported worldwide.

The only conceivable engine for driving continuous evolution in a country is a research and innovation plan accompanied by a training plan designed to refocus the set of skills within the national industrial fabric in line with European policy objectives. A multi-year research plan must leverage the qualities of Italy's available production resources and must be aligned with research challenges and international trends in the manufacturing field.

The pandemic has put all companies and economies through the wringer, and no analysis of historical data is complete without also looking at current economic data, which nonetheless makes coming up with any forecast for the future much more difficult and calls for great caution in a context that is still very much evolving and marked by a great deal of uncertainty.

On the one hand, it is necessary to avoid the risk of being influenced by the latest trends that the shifting current scenario can easily overturn; on the other, it is necessary to define pathways that take into account challenges and the opportunities they bring for an overhaul of Italian manufacturing.

The Cluster's strategy is based on the fact that the development and application of scientific research outcomes is recognized as one of the most effective levers for improving competitiveness and creating products and processes that are more efficient and sustainable and, more generally speaking, better able to meet people's needs.

In addition, this has a considerable impact on society as it can help improve the quality of life of its citizens and the competitiveness of the system as a whole, tackling social challenges, such as sustainability, product customization and development of human resources.

A process of this kind is complex and involves various components and different roles, taking into consideration different points of view, interests and needs. Over the last 15 years, models capable of supporting an innovation process of this kind have been discussed at length and analysed at a scientific, industrial and political level with the goal of finding more effective ones. Today, one of the most widely adopted models of innovation is the so-called triple helix model.

According to this model, the growth of a country, capable of considering the needs and characteristics of the society and industrial system, can be achieved through proactive collaboration between research, business and government. On one side, the objective of the research activities is the development of innovation that can be applied to different contexts. On the other side, it is the task of businesses to ensure they are profitable, competitive and offer value for money.

Institutions must provide a regulatory framework supporting effective collaboration, assisting them during the initial phase from research to innovation through to actual industrialization, as they often prove unfeasible where they rely on market forces alone. Moreover, a virtuous system should be based on social and economic improvement, which researchers and companies should factor into the technological development models, possibly also backed by government bodies.

In this context, there is no denying the paramount importance of the Cluster's role: it becomes a facilitator of research and innovation networking processes, acting as a soft-governance body to bring together the needs of all these actors through processes designed to help define appropriate policies to support and stimulate research and innovation, and their implementation, with the aid of strategic documents such as the roadmap.

Therefore, with its ultimate goal of defining the new roadmap for research and innovation for the Italian manufacturing industry, this book groups the work of more than 200 people involved with different sessions of brainstorming, focus groups, expert elicitation and content analysis.

The first chapter "Defining a Collaborative Framework for Roadmapping Activities" proposes a collaborative framework and methodology that can be used for supporting roadmapping activities involving large groups of actors representing different interests.

The second chapter "Analysis of the Italian Manufacturing Sector" proposes an insight into the context of the Italian manufacturing sector, comparing it with other countries in Europe and across the globe, also offering a focused look at the sector's

response to the pandemic crisis, and with a focus on the machine tools sector and on system competitiveness.

This is followed by the chapter "The Role of Industrial Policies: A Comparative Analysis" with the analysis of the reference documents that are orienting industrial policy at the European, national and regional levels to study how these decisional levels can interact in terms of content and synergies of objectives.

The following chapter ("Building Scenarios for the Future of Manufacturing"), referring to a number of important environmental, social and technological trends, offers a number of reference scenarios that are emerging for having a significant impact on the manufacturing sector in terms of changes in production models along the time horizon from short to long term and that can be used to identify the strategic lines.

Chapters "Strategic Action Line LI1: Personalised Production"–"Strategic Action Line LI7: Digital Platforms, Modelling, AI, Cybersecurity" expand on the content in terms of strategic action lines each covering a specific macro-area and identification of related research and innovation priorities.

Padua, Italy   Rosanna Fornasiero
Milan, Italy   Tullio A. M. Tolio

Contents

Defining a Collaborative Framework for Roadmapping Activities

Rosanna Fornasiero and Tullio A. M. Tolio

Abstract Today, more than ever, it urges to increase effort for monitoring and investigating changes in environment, particularly in relation to events in the social, economic, political and ecological landscapes as well as new technologies. Roadmapping activities are based on techniques and practices to analyse the "state" of a system and to identify evolution of emerging drivers. Roadmapping methodologies can support in understanding the impact of drivers on the competitive position of system under consideration and on the advantage of answering to these drivers. This chapter proposes a collaborative framework, designing it with the aim to involve several stakeholders with an iterative approach to consult and validate the results collected from literature and state-of-the-art and to share knowledge in a context where system competitiveness is considered as a precondition for individual benefit. Overall, this work contributes to improve the effectiveness of strategic roadmapping and to increase its value added to the planning process of clusters and in general of large groups of interest, while providing helpful insight to public organizations that promote the competitiveness of related sector under consideration.

Keywords Roadmapping · Collaboration · Manufacturing · Systemic approach

1 Introduction

Literature recognises the relevance of technological roadmapping activities as fundamental elements supporting strategic decisions for R&D policy definition both at private and public level. In particular, the aim of roadmapping is to identify development paths to help a system to acquire competitive advantage facing exogenous factors while implementing reactive and pro-active actions. Trends and weak signals

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detection become of strategic importance in a context of turbulent environment and increasing complexity. Technological changes like acceleration in digital transformation, production systems innovation, social changes like increase in aging people, evolution of consumer tastes, etc., and political changes like protectionism, trade barriers etc. are only some of the possible factors to be taken into consideration when starting a roadmapping activity.

The roadmapping activities represent a process to be implemented both by single company willing to re-position itself in the market as well as by heterogenous group (i.e. associations, clusters, production networks) willing to understand environment and to position in a macro-scenario where several factors need to be taken into consideration. In this last case (heterogeneous group of interest), it is necessary to have a wide and comprehensive approach that involve many different actors and stakeholders each bringing to the discussion specific interests to balance appropriately these contributions. The perspective is different from the single company and the aim is to define strategies to be taken for the overall group and to bring to the attention of the policy makers a strategic view which is necessary to be shared.

The creation of the roadmap is a structured process based on visions of the future addressing multiple influencing factors and their inter-relationships. From the methodological point of view, there are several papers proposing review of methods and tools to be applied in the fields of future studies, foresight, forecasting, strategy for the future, etc. There is no standard classification of these methods, but when designing a roadmap framework, it is important to consider trade-offs in roadmapping like: top-down versus bottom-up, explorative versus normative, quantitative versus qualitative, and expert-based versus assumption-based.

A multi-stage approach should assure the coverage of different dimensions through quantitative and qualitative methodologies to integrate and cover the following aspects (Popping 2008):

- Evidence: collect evidence using methods based on codified information, data and indicators etc. like literature review, scanning, benchmarking to get the status of the things;
- Interaction: assure interaction using methods based on participation and shared views of technical experts and market experts, like workshops, multi-criteria methods, stakeholder analysis;
- Creativity: enhance creativity of experts by methods relying heavily on the inventiveness of individuals with strategic vision on the future (like general managers, highly qualified researchers);
- Expertise: gathering Expertise using methods to extrapolate tacit knowledge of people to gain relevant information with tools like expert panels, surveys, qualitative and quantitative scenarios.

Therefore, in the last years, the Cluster of Intelligent Factories has defined and tested a collaborative framework where methodologies like online consultation, scenario definition, expert panels, literature review and others have been set in an integrated way to support the development of a roadmap applied to an heterogenous

group of interest. This pool of methodologies was used as a strategic guideline for the medium-long term roadmapping not only at National but also at regional level.

The path followed by the Cluster to define the roadmap is based on honing a framework that—by integrating different approaches that have also been acknowledged in scientific literature—has allowed to gather and formalize the opinions of the various actors within the actual Cluster or operating within its orbit.

An analysis of the current landscape has been a necessary preparatory phase providing a snapshot of the Italian and global situation and an insight into how manufacturing is reacting to shifting market conditions, in an attempt to extrapolate the industry's strengths and weaknesses. In terms of empirical data, a number of databases, such as the World Bank, OECD, Eurostat, ISTAT, have been used to support the analysis of the general situation, and data from Italian manufacturers associations Federmacchine and UCIMU have been used for a more focused look at the machine tools sector.

In terms of policies, the roadmap's reference points are European documents (such as Next Generation EU, Manufuture's SRIA, and programming documents from the Made in Europe partnership), Italy's national PNR and PNRR documents, and the Regional Specialization Strategies.

This phase also drew on trend analysis documents and grey literature such as consultancy reports (e.g. Roland Berger, McKinsey, Deloitte, PwC and EY), and reports from associations (e.g. Confindustria think tank-CSC, Edison Foundation, trade associations) to understand what the social, economic, environmental and political trajectories look like, and define reference scenarios that include a number of major radical changes in the landscape that are inextricably linked to manufacturing.

The definition of scenarios is a starting point for understanding what the society and global economic structure change factors are and how they affect the industry. They also highlight that the combined effects of certain trends—such as an aging population, the shortage of resources and their overexploitation, climate change, technological acceleration, and opening up of new markets—create unprecedented challenges that call for a transformation of the Italian manufacturing system.

In light of these scenarios, the technological roadmapping activities conducted by the CFI Cluster to identify the priorities and technology trajectories of the area of specialization have been based on findings that have emerged from interaction over the last two years with all the actors within the Cluster's own ranks.

2 The Collaborative Framework

The management structure of the Cluster of intelligent Factories is based on the collaboration of several bodies that have been involved in the various phases of the roadmap's definition (Fig. 1) which are:
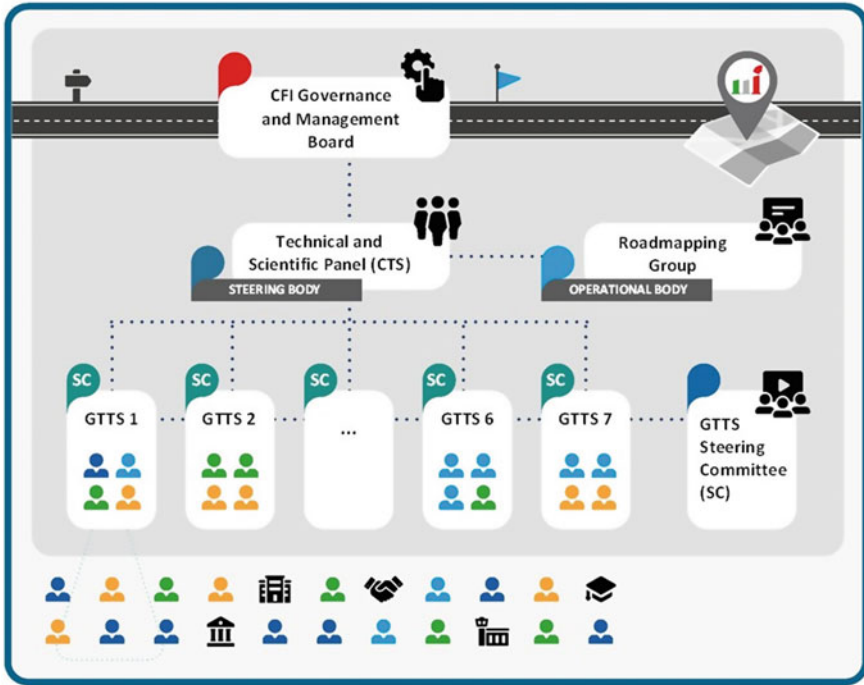
Fig. 1 Organisation structure of the cluster of intelligent factories

- Technical and Scientific Panel (CTS) with the role to orient and coordinate the scientific activities of the roadmap group and the technical groups (GTTS). In addition, CTS aligns with the Cluster's coordination and management board (OCG) for the purpose of document validation and to activate the process of member consultations.
- Roadmap group (GRM) with the role to support CTS in the definition and development of the methodology to be used in the roadmapping process, and provide operational support to the steering committees and GTTS in identifying the themes to be developed and in compiling the document.
- Technical groups (GTTS): 7 groups organized along the different themes identified by the Cluster. Comprising the Cluster's members, these groups are involved in the roadmapping activities through seminars, consultations, brainstorming sessions and workshops to determine the challenges and research and innovation themes.
- Companies with Lighthouse plant projects: Emblematic companies that, with the Cluster's support, develop Lighthouse projects (financed by Ministry of Economic Development and regional funding) based on cutting-edge plants powered by industry 4.0 technologies.

- Pathfinders: companies with a prominent position on the national and international stage for the development of enabling technologies for manufacturing. They are involved in the roadmapping processes to help identify the development trajectories of a specific technology in which they are leaders, and in the demonstration of those enabling technologies as part of the Lighthouse project and associated Supply Chain and Open Innovation activities.
- Members and supporting members involved on a regular basis through a variety of initiatives across the roadmap's various development phases, such as consultations, online surveys, workshops and seminars.
- Coordination and management board (OCG), in addition to its role of managing the Cluster from a strategic point of view, is also tasked for this specific exercise with approving and orienting roadmapping activities, coordinating with CTS on an ongoing basis.

More specifically, a significant role in drawing up the roadmap's strategic action lines was played by the 7 Steering Committees of the GTTS, which have guided the specific theme definition process. In particular, each Steering Committee is composed of 7–10 members appointed by their respective institutions to represent them based on a selection process involving stakeholders like industry (through the industry confederations Confindustria and Confartigianato), research bodies (through Deans and directors of Universities and Research organisations) and regional bodies (through regional associations and clusters).

The collaborative framework is based on several iterative steps like (Fig. 2):

- Periodic consultation with members, initiatives with Pathfinders and Lighthouse plants with methods like online surveys, interviews and focus groups;
- Analysis and elaboration of scenarios, analysis of industrial statistics; analysis of international, national and regional policy documents;
- Document preparation where GRM and steering committees of the 7 GTTS elaborate the contribution collected from the consultation and from the analysis to deliver reports to the CTS of the Cluster;
- Webinars and meetings with members to dissemination contents like through open innovation mechanisms or through meetings with regional authorities;
- Review and validation where the CTS reviews the content produced, interact with GRM and steering committees to improve content and to refine it for final validation by OCG.

The Table 1 below illustrates the most important steps of the collaborative framework taken over this two-year period (2020–2022), which have involved the actors listed.
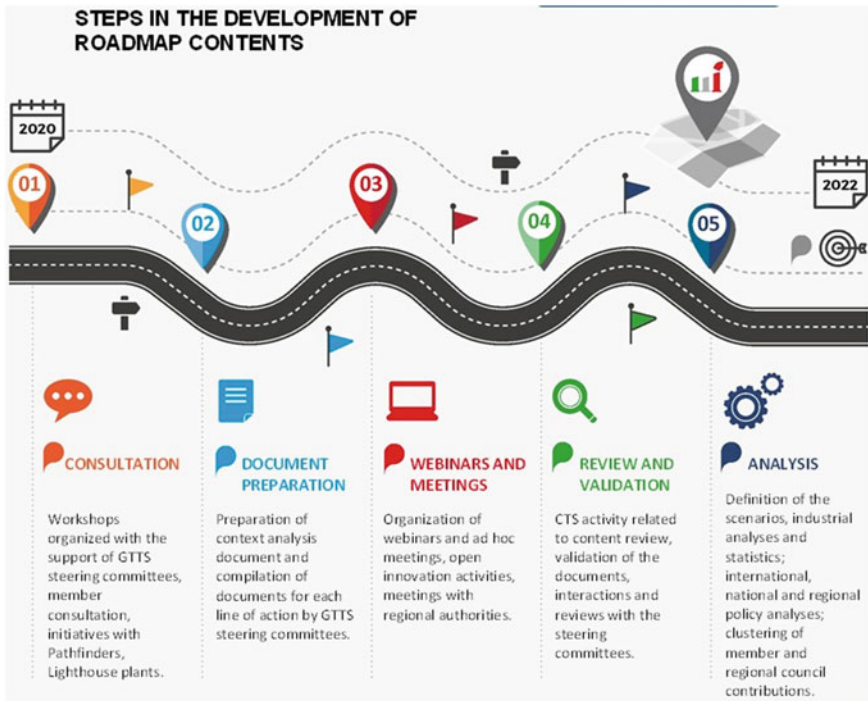
Fig. 2 Steps of the collaborative approach for the roadmap definition

3 Roadmap Structure for the Cluster of Intelligent Factories

The roadmap of the Intelligent Factories is set upon 7 strategic action lines that represent the paths along which Italian manufacturing's research and innovation priorities are developed. The objective of the strategic action lines is to respond to specific challenges generated by the market and by the acceleration of technological development.

More specifically, they represent trajectories against which companies can measure their own progress and develop research and innovation pathways, also taking into account the context scenarios, such as new consumption models, circular economy, electric mobility, knowledge management, digital platforms and climate change.

Each strategic action line comprises research and innovation priorities (PRI) within which research and development goals are defined that can help with the planning of short-, medium- and long-term actions both at company and at supply chain level and, above all, at the coordinated country level.

A number of strategic action lines has been identified that have been informed by the market and by the need to research and develop new models, methods and

Table 1 Steps and actors involved along the collaborative approach

Timing	Main actors involved	n. people involved	Activities
Q1-2020	Steering Committees, CTS and roadmapping group	60	Meeting for the definition of work structure, planning and timing
Q1-2020	Cluster members	200	Online consultation for gathering of research and innovation ideas and needs
Q1-2020	Initiatives with Pathfinders	50	Webinars for the definition of technology trajectories
Q2-0.2020	Initiatives with Lighthouse Plants	50	Webinars on their ongoing projects for the definition of the market trajectories
Q2-2020	Steering Committees of the GTTS groups	60	Content analysis and clustering of research needs gathered from members and formulation of research and innovation priorities (PRI)
Q3-2020	Cluster Members and GTTS groups	200	Meetings and webinars to present PRIs and gather other research needs
Q3-2020	Roadmap group and CTS	15	Analysis of statistics on manufacturing sector
Q3-2020	Steering Committees of the GTTS groups	60	Formulation of documents for each action line
Q1-2021	CTS and Steering Committee meetings	70	Discussion of documents and revision proposals by CTS
Q1-2021	Roadmap group and CTS	15	Definition of reference scenarios and analysis of European, national and regional strategies
Q2-2021	Cluster members and GTTS groups	200	Online consultation and validation of action lines and PRIs
Q2-2021	Regional bodies and Roadmapping group	20	Sharing of PRI contents with bodies representing the Regional Councils
Q2-2021	Pathfinders and Lighthouse plants	100	Sharing of PRIs through open innovation
Q3-2021	Regional bodies and Roadmapping group	20	Mapping of regional Smart Specialization priorities with Cluster's PRIs
Q3-2021	CTS and Roadmapping group	15	Final review of documents by CTS
Q1- 2022	CTS and Roadmapping group	15	Review of the reference scenarios

(continued)

Table 1 (continued)

Timing	Main actors involved	*n. people involved*	*Activities*
Q1-2022	Roadmap group and Steering Committees	*70*	*Final review and tuning the document*
Q3-2022	Cluster Management Board	20	*Release of the final document*
Q1-2023	Cluster Management Board	20	*Issue printed version of the roadmap*

technologies to meet the society challenges that companies find themselves facing (Fig. 3). The 4 action Lines are as follows:

- LI1: Personalised production
- LI2: Industrial sustainability
- LI3: Enhancing human resources
- LI4: High efficiency and zero-defect

Fig. 3 Intersection of market oriented strategic action lines
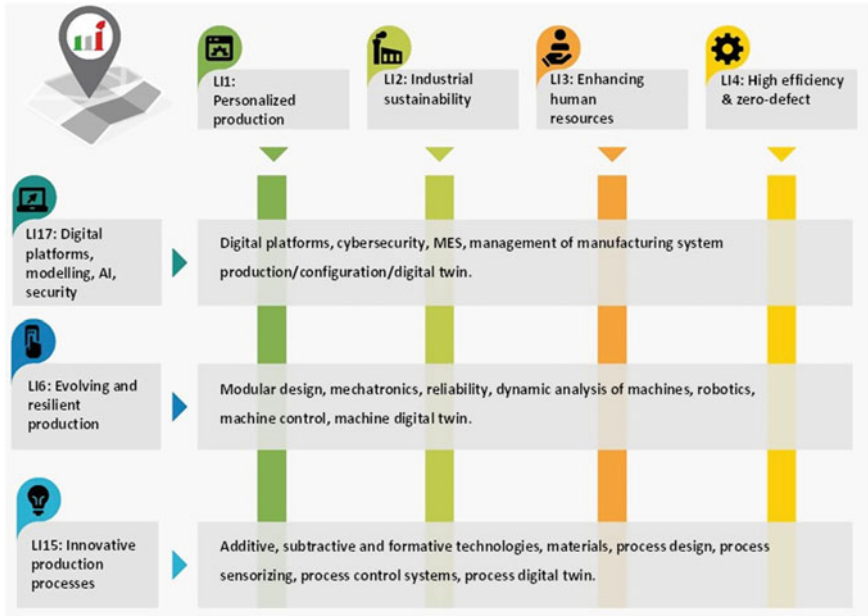
Fig. 4 Intersections of the technology push strategic action lines

The other 3 strategic actions lines have been identified as stemming from the need to research and develop new technologies that support the manufacturing sector at different levels (Fig. 4), namely:

- LI5: Innovative production processes
- LI6: Evolving and resilient production
- LI7: Digital platforms, modelling, AI, security

Below is a brief summary of the objectives of each strategic action line and the relevant research and innovation priorities.

LI1-Personalized production: the objective of this action line is to propose research and innovation priorities aimed at promoting industrial systems and models for the efficient manufacture of customized products that can be reconfigured with fast turnarounds to meet specific requests fielded from individual customers or small groups, and that deliver a high level of integration with the customers in order to ensure they become the main actors of the resulting solution. These design and production systems must be conceived to have the capacity to be reconfigured for the manufacture of products that can be required in certain times of emergency (such as health emergencies) or in response to events that can cause a sudden shift in system priorities and require the industrial system to transfer its focus to different categories of products to those usually made. In this action line, it will be important to research new supply chain management models and local manufacturing models as well as smart materials.

LI2-Industrial sustainability: the objective of this action line is to propose research and innovation priorities aimed at transforming the industrial processes involved in the design and manufacture of new products of the future in line with circular economy principles, in order to significantly reduce carbon emissions and improve energy efficiency, reduce and rationalize consumption of resources, facilitate and promote their recovery and recycling. In addition to recovering and recycling materials, it is important to orient future production models towards product re-purposing and the recovery and recycling of raw materials. These actions must be aimed at preserving the value of activities involved in transforming raw materials into products. These changes require the introduction of new processes, new machinery and new systems, resulting in a thorough overhaul of the national manufacturing base, opening up new capital goods markets that will see Italy claim a leadership position.

LI3-Enhancing human resources: the objective of this action line is to propose research and innovation priorities aimed at designing and developing new solutions to enhance the role of human resources and their skills, and contribute to their satisfaction and wellbeing; research and experimentation of new technologies for reducing physical exertion, cooperation with advanced support systems, with collaborative robots and with AI-powered technologies; mapping of knowledge generated on the job, especially implicit knowledge, in a way that is compatible with privacy requirements, introducing advantages both on the human wellbeing front—whether the individuals are users, operators or managers—and in terms of business strategies and procedures. In this regard, innovative factories will need to be increasingly inclusive, strongly geared towards the engagement and participation of individuals (users, operators and managers). These models must take a human-centric approach to look into/investigate new technologies and all the dimensions through which the new factory is defined.

LI4-High efficiency and zero-defect: the objective of this action line is to propose research and innovation priorities aimed at researching models for efficiency in terms of: zero-defect technologies designed to reduce non-conformances, monitoring of processes during the various phases, 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.).

LI5: Innovative production processes: the objective of this action line is to propose research and innovation priorities across various aspects of production processes, such as: digitization of conventional production processes in order to improve their interactions and handle different types of processing, even by means of hybrid processes; the growing role of additive manufacturing and its ensuing challenges in terms of both design and production; processing of standard and innovative materials, or materials with meso/macro geometries, including also nano- and

micro-manufacturing. In addition, process innovation also needs to take the shape of innovation in support of re- and de-manufacturing processes, to start with, through to the development of bio-inspired transformation models.

LI6-Evolving and resilient production: the objective of this action line is to propose research and innovation priorities aimed at researching and developing evolving and resilient production systems by exploiting a high degree of machine automation and self-learning, with levels of autonomy and adaptive intelligence designed to facilitate the operators' job. The priority research topics concern: modelling and simulation for the design and management of production systems, and hardware and software technologies for production system reconfigurability. The technology enablers are linked to the availability of smart modular devices that can be integrated wireless in a transparent, autonomous way, capable of monitoring and controlling manufacturing assets and products, and supporting decision-making, ensuring ready access to all necessary operational, configuration, fault and maintenance data.

LI7-Digital platforms, modelling, AI, security: the objective of this action line is to propose research and innovation priorities aimed at researching and developing innovative digital architectures for the monitoring, control and management of manufacturing activities and related assets, modelling new products/services and production processes, use of AI, Big Data and adequate Cybersecurity systems. More specifically, the LI7 line research and innovation priorities assume that criteria need to be defined for the management and transformation of raw production data into strategic information for decision makers, identifying the information to be collected from each digital access point by means of suitable enabling technologies and then delivered as appropriate. Digital platforms and cybersecurity also play a significant role in the definition of dynamic supply chain models.

It is expected that the impact derived from the implementation of the roadmap's contents embraces a number of different aspects, such as:

- Creation of new jobs in manufacturing and greater attractiveness of these positions, thanks to improved security, ergonomics and inclusion; the integration of industry into the urban environment will be facilitated to focus on specific consumer needs like comfort, health and wellbeing.
- Increase in the value added of manufacturing activities, through improved positioning of Italian businesses in the global value chain to cater to the needs of emerging markets, improving the competitive positioning of the companies in question.
- Reduction of manufacturing's environmental impact through reduced greenhouse gas emissions caused by manufacturing activities; reduced energy consumption and consumption of materials generated by manufacturing activities; reduced product waste from manufacturing activities; and the creation of green products and green technologies.
- Growth in R&D investments in manufacturing, exploiting the opportunities offered by the current technological acceleration mainly linked to the development and integration of digital technologies. The creation of integrated research

and innovation paths will also be promoted: starting with fundamental research, they will progress through research and innovation to lead to the development of knowledge in industrial fields.

- The development of specific local skills through the integration of actions at a national and regional level.

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Analysis of the Italian Manufacturing Sector

Rosanna Fornasiero and Tullio A. M. Tolio

Abstract When creating a roadmap, it is important to contextualise the sector under consideration. The work in this chapter is based on identification of relevant indicators which are analysed with a comparative approach both along the time horizon and with other countries and sectors. For this reason, this chapter is based on the extraction of data from International, European, national and regional dataset and describes the Italian manufacturing industry, exploring which are the most relevant sectors, which is the position comparing with European and international countries, and a focus is made on the machine tools sector. The system competitiveness is also analysed in terms of capability to bring innovation to Italy and to the sustainable development goals. The chapter closes with an analysis of the reaction of manufacturing to disruptions like the pandemic crisis and a proposal for a systemic recovery.

Keywords Manufacturing · Machinery · Statistical data · Innovation strategies

1 Industry Data

In Italy, the manufacturing sector achieved a turnover just short of €1,000 billion in 2019, employing 3.8 million people, with a value added of over €250 billion. The manufacturing sector took out the top spot at the European level, too, as it is clear from the NACE EU-27 non-financial business economy rankings in terms of value added and number of people employed, while it came second for turnover.

In 2019, the sector employed 23% of all Europe's workforce, and generated 29% of its value added. Overall, more than 30 million people worked in 2 million manufacturing companies, generating a turnover in the region of €7,800 billion and a value added of almost €2 billion (Table 1 and Fig. 1).

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Table 1 Non-financial business economy in Europe, 2019 (*Source* Data from Eurostat)

Non financial business economy EU27 (from 2020)	2019			
	Enterprises	Turnover (M€)	Value added (M€)	Employees
B: Mining and quarrying	16.932	86.394,3	33.055,3	392.246
C: Manufacturing	2.051.074	7.846.344,2	1.998.858,5	30.158.203
D: Electricity, gas, steam and air-conditioning supply	173.000	1.470.000,0	229.000,0	1.300.000
E: Water supply; sewerage, waste management and remediation activities	77.000	257.000,0	100.000,0	1.560.000
F: Construction	3.413.290	1.702.986,7	548.969,2	12.687.246
G: Wholesale and retail trade; repair of motor vehicles and motorcycles	5.718.891	9.028.880,1	1.281.510,7	29.428.945
H: Transportation and storage	1.251.019	1.437.385,3	510.297,6	10.448.964
I: Accommodation and food service activities	1.888.142	593.309,1	252.368,6	10.978.430
J: Information and communication	1.118.646	1.298.469,7	549.679,6	6.341.468
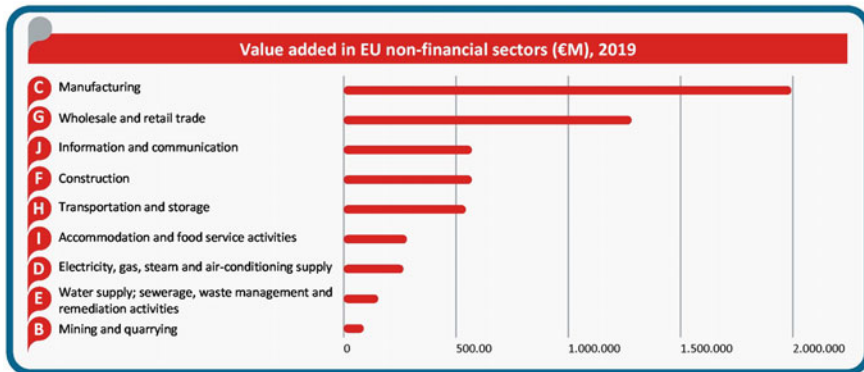
Fig. 1 Value added in EU non-financial sectors, 2019 (*Source* Data from Eurostat)

The manufacturing value added of the top 4 European countries accounts for 60% of the total value of European manufacturing, while the value added of the top 10 accounts for 87%. Over the last 10 years, the manufacturing value added of the top 10 European countries has increased to the extent that it now tops 1,800 billion in total, while Italy continues to play a foremost role on the European stage, placing second after Germany for value added (Figs. 2 and 3).

In Italy, within the manufacturing industry, there are a number of sectors that have demonstrated particularly impressive performance in terms of value added and turnover (Fig. 4). Most notably, the sectors concerned with manufacturing machine
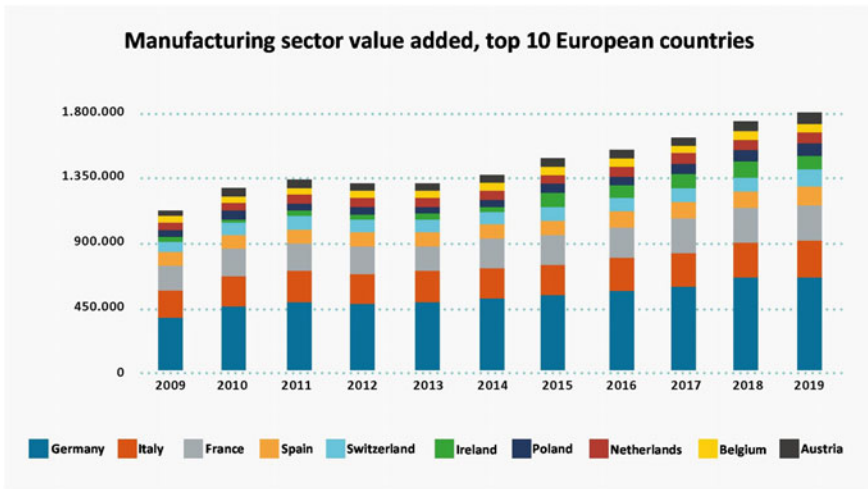
Fig. 2 Manufacturing added value (€M) of top EU countries, 2009.2019 (*Source* Data from Eurostat)
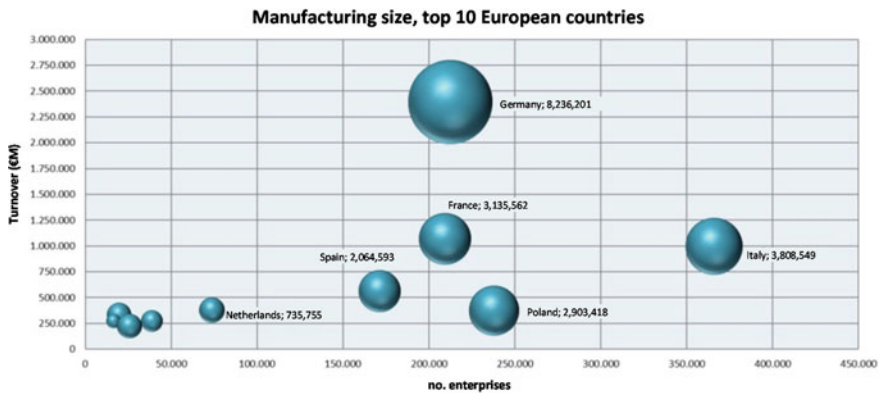
Fig. 3 Manufacturing size of the top 10 EU countries (dimension of the bubble is value added), 2019 (*Source* Data from Eurostat)
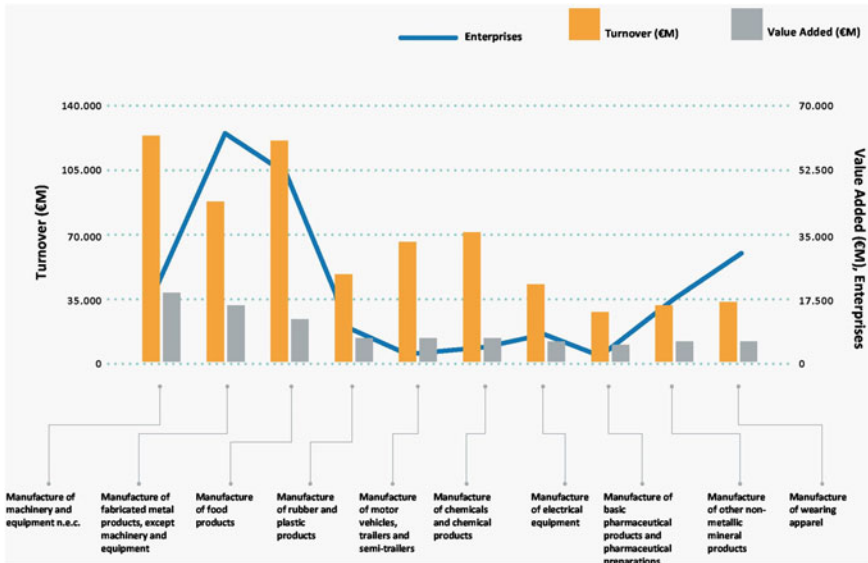
Fig. 4 Italian manufacturing sectors, 2019 (*Source* Data from Eurostat)

tools, fabricated metal products, food products and the fashion industry account for 46% of value added, 42% of turnover, and 41% of exports. These sectors, together with the furniture and timber industry, traditionally represent the "made in Italy" brand, consistently earning our country a place amongst the top European countries in terms of turnover and value added. Over the years, mature economies have lost their leadership position in terms of global share of manufacturing, but now it is possible to see the emergence of a new map of global manufacturing hubs after two years of changes brought about by the pandemic and the fallout from the Ukraine crisis.

The growth of manufacturing is no longer driven by foreign demand alone, it is also driven by the increase in domestic consumption stimulated by the potential of digitization and by the need to develop manufacturing and distribution models where geographical distance might still play a significant role.

High demand for new products has led to the evolution and redefinition of manufacturing models, with shorter planning horizons and life cycles, reduced lot sizes, hence entailing optimized use of resources in terms of streamlining, flexibility, agility and reconfigurability of the production process. The intensive use of the planet's resources, new production sites in emerging countries, and shortening of product life cycles have made environmental issues increasingly pressing, and the need to implement the circular economy is bringing forth important business opportunities at the global level.

Lastly, new standards impact heavily on production processes, while the lack of homogeneity between different countries results in unbalanced advantages, further

compounded by the difficulty in protecting intellectual property rights in the global context.

The shocks to the system caused by COVID-19 and the nearby war in Ukraine, and the push towards product and process sustainability, call for the country to adopt a new approach to resilience in order to mount an adequate response to the critical and unexpected events occurring all along the supply chain, which has proven remarkably fragile.

2 Global Positioning

2.1 Ranking of Global Manufacturers

The advent of the pandemic crisis resulted in a drop in manufacturing worldwide in the first six months of 2020, which was followed by a recovery over the rest of the year. Essentially, the positions of the various countries being compared in terms of their % share of global manufacturing value added (calculated at current prices) reveal a fundamentally stable situation, with the Chinese sector accounting for 30% of global value added, and Italy still falling within the top 7 countries for manufacturing with 2.2% (Table 2).

Table 2 Global ranking per manufacturing sector dimension (Value added in current$) (*Source* Data from CSC)

2016			2020	
Posizione	Valore	Paese	Valore	Posizione
1	26.3	China	30.1	1
2	17.1	US	16.6	2
3	8.3	Japan	7.1	3
4	5.8	Germany	5.3	4
5	3.2	South Korea	3.1	5
6	2.8	India	2.8	6
7	2.2	Italy	2.2	7
8	2.1	France	1.9	8
9	2.0	Great Britain	1.7	9
10	1.6	Brazil	1.1	15
11	1.2	Indonesia	1.6	10
12	1.5	Mexico	1.4	13
13	1.4	Taiwan	1.5	11
14	1.4	Russia	1.5	12
15	1.3	Canada	1.1	14

Table 3 Manufacturing value added of top 10 countries (current $) (*Source* Data from UNDATA)

Countries	2020 value added ($) at current prices
China	3.853.826.532.846
United States	2.272.000.000.000
Japan	1.033.602.190.884
Germany	697.292.449.376
Republic of Korea	406.373.281.725
India	383.714.449.103
Italy	280.398.636.543
France	247.025.036.875
Great Britain	239.677.053.149
Indonesia	210.396.303.053

* Output measured on a value-added basis in current U.S Dollars: Source: United Nation Statistic Division

However, there has been the odd exception, for example China's market share was up almost two percentage points, going from 28.6% of total value added in 2019 to 30.1% in 2020, further widening the gap with the United States (16.6%). South Korea and Taiwan—whose manufacturing systems have developed a strong specialization in electronics-related manufacturing—managed to climb up the rankings last year (by one and two places respectively). Italy claims its place as the world's seventh-ranked manufacturer, with a 2.2% share—consistent with its 2019 performance—followed by France (1.9%) and Great Britain (1.7%).

Analysing countries from the standpoint of the evolution of global manufacturing export and import shares in 2019, the world's top 20 exporting countries have continued to account for 80% of global exports for 20 years, and almost half of them (47%) are from Asia. Italy sits in ninth place with a 3.4% share of world trade and with a consistently positive trade balance (Table 3).

Notably, in terms of exports by the Italian manufacturing sector (Fig. 5), the machinery makes up the biggest exported product category out of the various manufacturing subcategories, totalling 82 billion euros for 2019, and still managed to retain the same 14.5% share of Italy's total exported value in 2021 despite the serious falling-off in the wake of the pandemic. When it comes to sectors driving development, a comparison of contributions by the various industry segments to the change in manufacturing value added of the different countries reveals the clear dominance of two sectors that have acted as an engine driving global industrial development.

Both constitute an important component of the current paradigm shift to the new digital economy: on the one hand, the manufacture of machinery and equipment, which incorporate enabling technologies for industry 4.0; and on the other, the manufacture of electronic components and hi-tech goods, thanks to the widespread application of technologies such as advanced sensor equipment, Internet of Things (loT), AI and big data. The contributions of each sector to the percentage growth of the manufacturing value added of China, the United States, Japan, Germany and
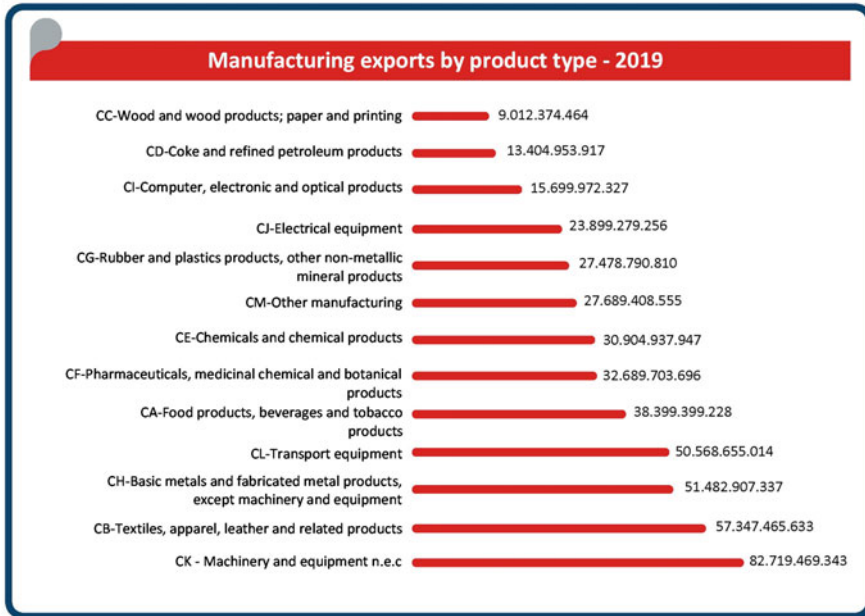
Fig. 5 Manufacturing exports by product type, 2019 (€) (Source data from Eurostat)

South Korea highlight that both sectors appear in the top four on the list of sectors driving industrial development.

As pointed out at length in the Confindustria study on Italian industry (CSC, 2019), the strong push towards digitization of industrial processes has had significant impact on national manufacturing of capital goods (the sector making the biggest contribution to growth over the last two years) and on related industrial machinery installation and repair activities. However, at the same time, it does not appear to have stimulated the electronics segment, which continues to account for only a marginal portion of Italy's total manufacturing value added, with a virtually unchanged share over the past 20 years or so of roughly 3.5% (in nominal terms), with a high trade deficit.

3 Focus on Machine Tools and Capital Goods

Following robust growth in recent years—during which the machine tool sector strengthened its position in the global market—in 2019, Italian manufacturing of machine tools, robots and automation came in at 6,510 million euros, down 3.9% on 2018.

Consumption has dropped, by 6%, to 4,855 million as a result of the fall-off in deliveries in the domestic market (−6.5%, 2,911 million). In terms of global

manufacturing, the manufacture of machine tools fell to below 59 billion euros in 2020, with Asia claiming the top spot accounting for 55% of global manufacturing, followed by Europe on 35%. In the manufacturer ranking, China is followed by Germany and Japan, with Italy in fourth place (Fig. 6).

Exports have also plummeted, falling victim to restrictions on the movement of goods and people, with Germany claiming the title of top exporting country, and Italy again sitting in fourth place with 2,625 million euros. According to the UCIMU report compiled from Italian statistics (Istat), in the June–July 2020 period, Italy's main export destinations were: the United States (152 million euros -18.2%), Germany (113 million euros -39%), China (105 million euros -36.4%), France (73 million euros -39%), Spain (48.6 million euros, -28.4%).

In terms of capital machinery and equipment in general, represented by 12 sectors making up Federmacchine—Italy's national federation of associations of manufacturers of capital goods—the total turnover of the 5 thousand companies just topped 41 billion euros in 2020, corresponding to 2.5% of GDP (Fig. 7). The most significant contribution to the Italian economy by the sector comes from foreign sales: with 27.8 billion euros, machinery sales abroad account for 5.7% of all Italian exports, a figure that climbs to 6.4% including goods export. Employment in the capital goods sector, in 2020, accounted for 4.3% of employment in the Italian manufacturing industry.

A distinctive trait of the Italian capital goods industry is a strong focus on exports that, in 2020, accounted for 67.1% of turnover, with a consistently positive trade balance with European Union counting for 29% of the total. Other primary outlets for Italian machinery are Asia (10.3%), North America (10.3%) and Eastern Europe (9%). South America, Africa and the Middle East account for smaller shares.

The Italian capital goods sector consistently rates highly in world rankings, placing amongst the country's top industrial sectors for turnover, exports and value added. This attests to Italy's specialization and strength in the capital goods sector, in a European context marked by German dominance and the marginalization of other countries (Table 4).

4   System Competitiveness

Research and development (R&D) is a strategic variable in economic competitiveness of a country as it allows high levels of knowledge content to be incorporated into the production of goods and services, with positive effects on overall economic results.

There are many indicators that can be used to assess a country's capacity for innovation. Information on intra-muros R&D is the main component of statistical indicators on R&D used in the European arena to assess policies in support of research and improvement of a country's capacity for innovation and competitiveness.

Even the UN's Sustainable Development indicators include a number of R&D-related indicators. On the global stage, only the United States, Japan and Korea outperform Europe in terms of improvement in their innovation indicators between 2014 and 2021.
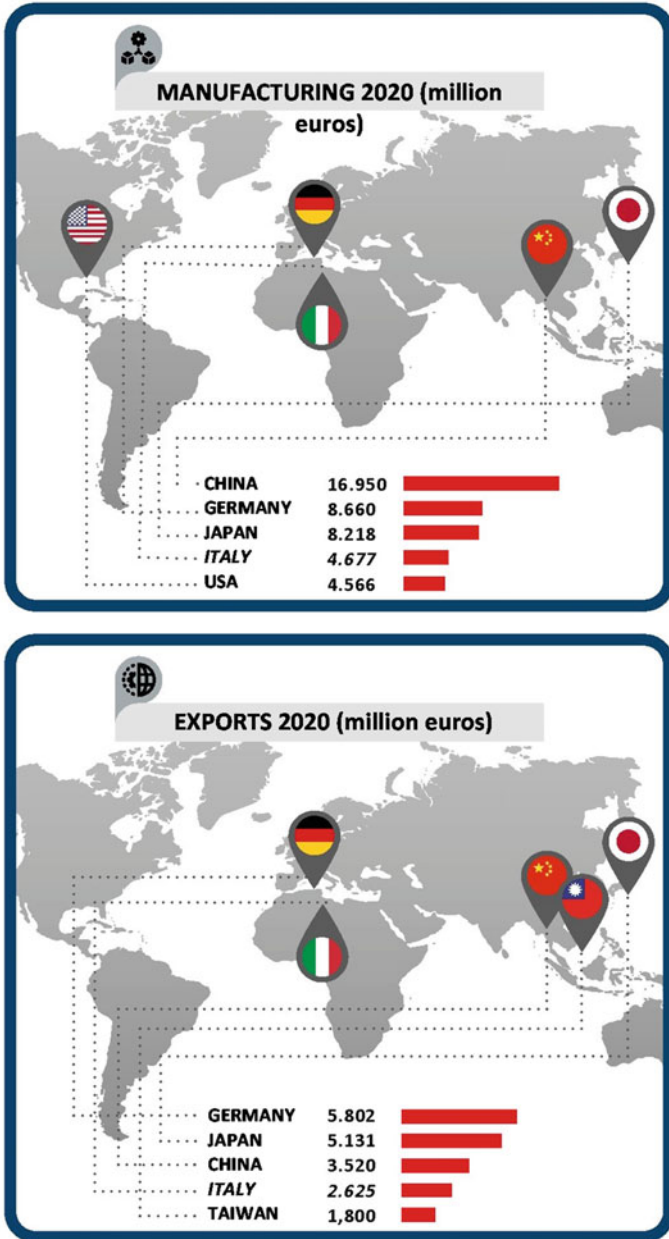
Fig. 6 Manufacturing and export shares in 2020 (mln euro) (*Source* Data from UCIMU)
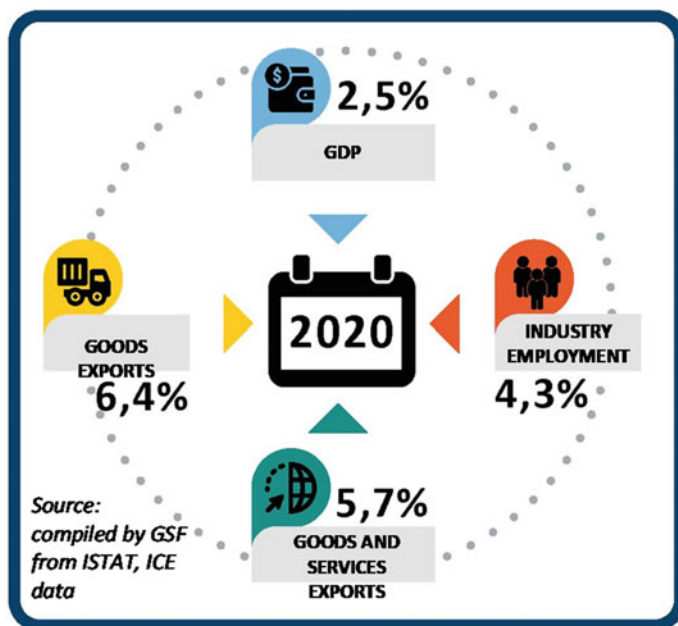
Fig. 7 Capital goods in Italy, 2020 (*Source* Data from UCIMU)

Table 4 Machinery and equipment sector in Europe, 2019 (*Source* Data from CSC and Eurostat)

	N. enterprises	Average turnover (mln euros)	Average n. of employees
Germany	15.393	18,9	77
France	4.294	13,9	50
Great Britain	7.592	8,5	26
Italy	22.587	5,6	22
Spain	5.552	4,0	20
Other EU	34.582	5,6	28

The 2021 European Innovation Scoreboard has updated the indicators, which now include a number relating to digitization and environmental sustainability to bring it into line with the EU's political priorities. Italy has a performance score that is higher than the European average for innovation-related indicators, as well as certain environmental sustainability indicators. Italy is one of the five countries that have seen a 25%-plus improvement in performance since 2014, while still falling into the "moderate innovators" category, albeit closing the gap with the European average.

The ISTAT census data offer an up-to-date picture of the level of evolution in innovative strategies pursued by Italian manufacturing companies, which allows us to assess whether, and to what degree, the intangible asset investment lever (in its various components) is actually being used within the national manufacturing system and,

above all, how it is paired with tangible investments in a logic of complementarity. More specifically, in terms of research and innovation activities carried out over the 2016–2018 three-year period by Italian manufacturing companies with at least 10 employees, the following levers were considered: (i) R&D carried out in-house or outsourced; (ii) procurement of licences, software and databases; (iii) personnel training; (iv) procurement of machinery, equipment and hardware.

The first three items capture the importance of investments in intangible assets, the fourth in tangible assets. The information collected by companies concerns whether or not each of these activities is present in innovation projects, without considering the amount of financial resources channelled into each (Table 5).

The first finding to emerge from the analysis of the data is that two thirds of the 69 thousand companies included in the census state they invested in at least one of the four aforementioned activities, with 36% of innovators in Italian manufacturing actually pulling just one of the four innovative investment levers in question, and an additional 33% pulling just two of them. Hence, the most complex forms of innovative strategy are a prerogative of just a minority of companies (9%).

As Table 6 reveals, investments in tangible goods account for 71% of the innovation levers most widely used by Italian manufacturing companies, although the incidence of innovating companies engaged in R&D activities (59%) and in the purchase of digital goods (46%) is also high. On the other hand, on average, just 29% of companies have personnel training in place for innovative projects. Increasing levels of complexity in innovative strategies are associated with a greater ability to bring about the dual digital and green transition.

On this note, out of all the innovating companies, about one third has invested in industry 4.0 digital technologies (loT, advanced robotics, big data analysis, additive manufacturing, virtual and augmented reality), and within this percentage there is a considerable jump from the 20% of innovators who have pulled just one investment lever to the 58.3% of those that have pulled all four of the levers analysed.

Table 5 Manufacturing companies per investment levers, 2021 (*Source* Data from ISTAT and CSC)

Investment levers	% Companies investing in innovation (%)	Companies using:			
		1 lever (%)	2 levers (%)	3 levers (%)	4 levers (%)
Machinery, equipment, hardware	71	48	73	93	100
R&D activities	59	39	55	80	100
Software, licences, databases	46	9	49	79	100
Training on innovation	29	4	23	49	100

Table 6 Complexity of innovation strategies, 2021 (*Source* Data from ISTAT and CSC)

Performance indicators	Non-innovative companies (%)	Innovative companies (%)	Companies using:			
			1 lever (%)	2 levers (%)	3 levers (%)	4 levers (%)
Investiments in I4.0		32.6	19.5	29.3	42.6	58.3
Reduction of environmental impact	67.6	81.8	77.2	82.4	85.6	89.5
Revenue growth rate jun-sep2020	12.0	17.6	16.3	16.3	18.7	21.1

Moreover, 82% of the innovating companies were engaged in reducing the impact of their activities on the environment, with peaks of almost 90% within the group of innovators pursuing the most complex strategies.

Companies that manage to simultaneously implement a number of actions in innovative strategies register an improved turnover growth performance, too, and the percentage of those that have experienced an uptrend in revenue for the 2020 June–September quarter was higher than that of non-innovating companies; while it was once again the highest within the group of innovating companies who have invested with more complex strategies (namely, pulling all four of the levers in question at the same time).

Hence, the analysis would suggest that the greatest return on innovative investments is achieved by pairing tangible assets—on which Italian manufacturing companies have focused most efforts to date—with intangible ones. There are several reasons why these strategies are not yet particularly widely practiced by companies, and concern both the different reference landscape in which they operate (quality of the ecosystem for innovation, financial constraints on investments, market structure) and their different ability to profitably handle the complexity associated with innovation, which in turn depends on the quality of technical and business knowledge amassed within the organization.

Generally speaking, the Italian R&D system is characterized by a series of limits that affect the management of relevant policies like fragmentation of actions, with numerous initiatives at both the national and regional level; delays in implementing measures and high variability in terms of availability and size of budget.

One of the goals to be achieved with the upcoming programming is to reduce regional disparities and speed up growth in Southern Italy, which is still suffering from marked inequality in terms of development, for example, of technological activities, income and infrastructures.

5 The Role of Manufacturing in Implementing Sustainable Development Goals

In 2015, the United Nations adopted the development agenda titled: "Transforming our world: the 2030 Agenda for Sustainable Development" (UN, 2015). The 17 Sustainable Development Goals (SDGs) making up the agenda refer to different areas of social, economic and environmental development, and industrial processes also play a part in promoting this development in a sustainable way.

The list of SDGs features numerous references to the wellbeing of people and equitable sharing of benefits arising from development, clear references to the use of resources and to the environmental impact of activities. For each SDG, specific goals have been defined that are to be reached over the course of the years and are monitored by means of almost 250 system indicators.

More specifically, when it comes to goal 9 "Industry, innovation and infrastructure", an analysis of the indicators in this area reveals that, in 2020, the pandemic containment measures resulted in a reduction in the manufacturing industry's per-capita value added, while industry's contribution to the economy as a whole in terms of value added and employment remained unchanged.

As Fig. 8 below shows, the contribution of companies to indicators related to R&D spending is better than 10 years ago on all fronts, while it is up from the year before in terms of research intensity, number of companies with innovative product and process activities, and investments in research and development out of total investments.

When it comes to goal 12 "Sustainable consumption and production", progress in curbing material consumption—which has characterized Italy since 2010, allowing our economy to gain in efficiency in production processes—has levelled out over the last five-year period, but Italy is one of the EU countries with the lowest domestic material consumption (DMC) both per capita and per unit of GDP, claiming first place in the per-capita rankings and fourth place per GDP. In 2019, the DMC per unit of GDP was stable compared to the 2017–2018 two-year period (0.28 tonnes per 1,000 euros). On the other hand, the circular material use rate—namely the portion of all

SDG ref.	Indicator	Compared to SDG indicator	Value	Compared to 10 years before	Compared to previous year
9.5.1	Research and development expenditure as a % of GDP				
	Research intensity (Istat, 2019, %)	Identical	1.45		
	Companies with innovative product and/or process activities (per 100 enterprises) (Istat, 2016/2018, %)	Within Italy	55.6		
	Proportion of investments in ICT equipment out of total investments (Istat, 2019, %)	Within Italy	4.1		
	Proportion of investments in intellectual property products out of total investments (Istat, 2019, %)	Within Italy	17.5		
	Proportion of investments in R&D out of total investments (Istat, 2019, %)	Within Italy	8.2		
	Proportion of investments in software out of total investments (Istat, 2019, %)	Within Italy	8.7		

Fig. 8 Reference indicators for SDG9, value for Italy (*Source* Data from ISTAT)
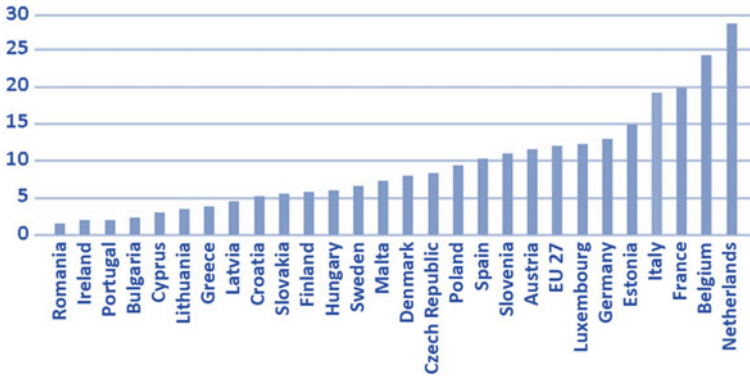
Fig. 9 Rate of circular material usage, 2019 (% value) (source: data from ISTAT and EUROSTAT

material recycled and fed back into the economy—has seen an improvement between 2010 and 2019, in Italy, whose rate thus comes to 19.3% compared to the EU 27 average of 11.9%; the data also show a greater improvement in Italian performance than the EU 27 average, both over the last decade and over the last year, putting our country in fourth place in the European rankings, after the Netherlands (28.5%), Belgium (24.0%) and France (20.1%) (Fig. 9).

When it comes to goal 13 "Action to combat climate change", a steady reduction in emissions was recorded in the period between 2009 and 2019, both within institutional sectors (families and companies) and within the various activities, albeit with differing intensity. For companies in general, in 2019, the level of the emissions rating was 81.8 (2009 = 100), while for the manufacturing industry, the rating fell to even lower levels than 2009 (75.4). Therefore, manufacturing is a key factor in achieving these sustainable development goals and it is necessary to consider how they can be broken down into actionable research and innovation priorities when defining medium to long term research and innovation strategies in the sector.

6 Manufacturing and the Pandemic Crisis

6.1 Global Situation

Over the last few years, the international landscape has been dominated by the financial crisis triggered by the effects of the COVID-19 pandemic, while the war currently playing out in Ukraine could further disrupt reference scenarios, already beset by significant dynamics of change.

In terms of the pandemic crisis, the measures required to contain the spread of the virus—the adoption of which, from the very start, followed different timelines from one country to the next—have had a profound effect on the social and economic fabric,

resulting in a real shock that has simultaneously affected both supply (businesses forced to close and temporary interruption of value chains) and demand (plummeting consumption, increased unemployment, reduced income).

To counter the effects of the lockdown on the economy, all the main central banks promptly and repeatedly intervened with emergency measures to bolster demand, pumping cash into the economy. At the same time, many governments have introduced expansive fiscal measures aimed at shoring up the incomes of their citizens and manufacturers hit hard by the lockdown measures. Despite these best efforts, last year, with the exception of China, all major economies recorded a marked drop in GDP (CSC, 2021).

Structural delays (application of stricter health protocols for unloading cargo, personnel shortages in the transport and logistics sectors), along with "anomalous" growth in the demand for goods—resulting from manufacturing companies and businesses needing to replenish stocks, which had been depleted during 2020—were compounded by chance factors (temporary closure of a number of ports in China or blockage of the Suez Canal).

All the above led to a considerable increase in transport costs and additional bottlenecks in international supply chains, which have had a negative effect on global industrial production growth. Manufacturing's recovery after the most acute phase of the pandemic is following very different trajectories according to sector.

The explosion of the health emergency sent demand skyrocketing for the pharmaceutical industry, at the front line of Covid-19 medicine and vaccine development, and the electronic device industry (due to the accelerated digitalization dictated by isolation, at first, and then by social distancing measures), recording a boom in production volumes worldwide between the fourth quarter of 2019 and the months of June-July 2021 of 15.4% for pharmaceuticals and 12.2% for electronics respectively.

The recovery of capital machinery and equipment has been driven by growing sectors calling for new or reconfigured machinery to help them manufacture products required by the pandemic event (such as face masks, drugs, dedicated packaging).

6.2 The Reaction of the Italian System

In Italy, following the drastic drop in production of over 40% recorded two months out from the introduction of the March 2020 restrictive measures, business volumes began to increase as early as the second quarter of 2021, with production sitting comfortably at its late 2019 levels, experiencing a return to pre-crisis levels that has yet to be seen in the other major European industrial economies.

With the figures characterizing the current phase, Italy no longer plays the role of "follower" behind the other major eurozone economies in terms of manufacturing growth, and—unlike the situation that unfolded in the years following the previous global financial crisis (the 2008–2009 period)—the country's behaviour changes in terms of its ability to respond to shock: this time around, finding itself in the position of driving the area's recovery in production volumes.

The reason for this performance lies, above all, in the dynamic of the domestic component of the demand for goods that—thanks to the government's initial income support measures, followed by spending stimulus measures—has made a crucial contribution to manufacturing's recovery, marking a far cry from the events following the outbreak of the 2008 financial crisis, when national industry's growth was structurally curbed when part of domestic demand was wiped off the board.

While export turnover—due to ongoing challenges in the international context—in August this year was up barely 2.8% in value on the pre-crisis peak of February 2020, domestic turnover recorded a 7.0% increase over the same period.

Since late 2020, the global landscape has been characterized by significant increases in commodity prices: price hikes are widespread and concern not just metals (copper up 51% on the end of 2020, and iron up 73%), but food, cotton, timber and oil, too (World Bank data). These price rises greatly affect both Italian companies and consumers, because Italy is a manufacturing country that is heavy on processing and has high volumes of imported commodities.

Between January and March 2021, the increase in turnover was seen across many of the manufacturing sectors, with rates varying to great degrees: while performance was good in the furniture, metallurgy and electrical equipment segments—up almost 30%—and automotive and machinery sectors—up 25% on the first quarter of 2020—there was a noticeably more subdued recovery, or plateau, for sales in some traditional manufacturing segments (textile, clothing) that, in the first quarter of 2020, had experienced some of the most severe drops in turnover of the entire sector (Istat, 2021).

A key factor in the recovery has been the low level of exposure of Italian manufacturing companies to the bottlenecks that are plaguing global value chains at this juncture. According to an analysis by Confindustria, with reference to the beginning of the third and fourth quarter of 2021, "just" 15.4% complained about restrictions on manufacturing supply due to a lack of materials or shortage of equipment, compared with an EU average of 44.3%, and with an even more weighty 78.1% of respondents in Germany. Italy's overseas trade in goods, following the freefall recorded in the second quarter of 2020, has picked up quickly and strongly, climbing convincingly back above pre-crisis levels. In the months of June–August 2021, exports at constant prices topped late 2019 levels by 2.6% (exports up 7.3% in value). Exports of intermediate inputs and investment goods, above all, enjoyed positive performance, while consumer goods, as yet, have seen only a partial recovery. Within the asset category, growth has been driven chiefly by electrical equipment, while capital machinery and equipment have not yet recovered fully.

For what concerns employment, the increase in industrial production starting in summer 2020 was reflected in a significant recovery in the number of job hours, even though, at the end of Q2 2021, it was still below pre-pandemic levels (−4.2%). Manufacturing companies' expectations on the labour demand appear to be improving constantly and significantly, which comes with an increase in the number of companies who are reporting increasing difficulties in procuring the labour required for the production cycle, in a context with a progressive increase in the plant utilization rate.

The business climate is continuously evolving and, following the pandemic emergency, it has become clear just how hard it still is to predict the fallout from the Russia–Ukraine conflict: in addition to generating a crisis in a number of supply chains (prime examples include rolled metal, metal castings and grain), the conflict has also generated a series of unprecedented economic measures against Russia and a parallel increase in the cost of procuring gas, the impact of which on society and on the manufacturing sector is still hard to predict.

6.3   Proposal of a New Collaborative Model: Manufacturing a Resilient Country

Italy clearly emerges as a country characterized by a strong manufacturing sector that, despite the market's economic criticalities in terms of both supply and demand, has managed—even over the course of the last two years—to evolve and reinvent itself, seizing market opportunities to tackle criticalities and the most challenging of economic times.

Having different production sites offers countless economic and social advantages for a country working in a networked system, and the "intelligent factory" (meaning a factory that adopts emerging enabling technologies designed to assist human capital in an efficient way) is becoming a well-established reality thanks also to the efforts of different actors across the country, including the Cluster itself, promoting actions to improve awareness of the role played by manufacturing at the national and European level.

More specifically, during the early stage of the pandemic, the Cluster created a task force to define strategic actions to support manufacturing, their work culminating in the compilation and proposal of the document entitled "Manufacturing a Resilient Country".

The document suggests three types of action intended to cast manufacturing in a leading role for the recovery of the country during emergency periods.

These actions are classified into:

(i).   Immediate actions aimed at helping companies transform in the direction of resilience and competitiveness, taking into account the state of emergency, using solutions available in the market;

(ii).   Specific medium-term actions based on research and innovation activities that can produce new solutions to handle emergencies appropriately and enable systems to improve performance in changed competitive landscapes;

(iii).   Long-term systemic actions where the direct intervention of public bodies is supported by partnerships with companies and with Universities and Research bodies.

More specifically, drawing on the strong manufacturing base already present in the country and pooling the best existing skills, the Cluster's proposal is for a model to exploit a certain amount of the existing manufacturing capacity and put it in a

position to be able to rapidly act on goals determined in times of emergency, without prior warning.

The term manufacturing capacity is used here to mean all activities required to make and deliver the product to its point of use within the right timeframe and in the right conditions. Hence, an implementation model is proposed that must be based on the creation of new collaboration opportunities that can be used for the activity in question, but which can also be harnessed for other initiatives.

The plan is to create a public–private collaboration model that, if activated in times of crisis, would enable companies to swiftly produce the necessary volumes of all products required to handle the situation, and to help geographical areas that do not have such an emergency response system in place by supplying necessary products in situations of global significance, increasing their resilience.

When this system is activated under normal circumstances, it allows the country to progress thanks to the new products stemming from the creative interaction between various stakeholders, the creation of products and machinery for pioneering sectors, the creation of new products in the health industry and civil defence sector and, more generally speaking, products and solutions for societal challenges in the event market rules are insufficient to automatically create trigger conditions.

7 Evolution of Italian Manufacturing and the Roadmap Objectives

There are various explanations for Italy's apparent paradox of a high capacity for innovation coupled with low R&D spending. Firstly, the small average scale of manufacturing companies in the country, which results in most innovation activities not being formalized. Then there is the fact that the Italian industrial system has a strong presence in sectors in which innovation mostly takes the shape of incremental development of production processes and products (learning by doing, learning by using and learning by interacting), incorporating new technologies into machinery or into patents and licences, while less prevalent is innovation based on the introduction of radically new tech, necessarily entailing underlying scientific research activities (ranging from fundamental to applied research).

Supply chains are currently undergoing a shake-up that—paired with the technological discontinuities stemming from the dual digital and green transition—represents a structural change factor in the competitive landscape, which leads to a profound transformation in value-creation mechanisms.

Emergent collaborative models are requiring companies to demonstrate a new capacity for innovation since it is proving increasingly necessary to:

 (i). engage with customers to provide solutions to complex production problems rather than simply applying a make-to-order approach;
 (ii). increase the level of coordination with other actors in the supply chain to boost resilience to shocks and maximize knowledge spillover;

(iii).   keep up with the constant evolution of market needs.

Investment along these lines is not limited to aspects directly related to production process efficiency, and instead increasingly encompasses the various company functions both upstream and downstream, from design to configuration all the way through to distribution and after-sales, embracing a logic of growing the intangible component of the product's value.

This gearing towards new strategies today calls for increasingly structured and "coded" forms of innovation, with formal product research, development and design activities being promoted alongside the existing unofficial exchange of information. At the same time, companies should be systematically making use of the data available to them with the aid of digital tech for activities such as process and product monitoring—which also ties in with sustainability—analysing market changes, and engaging employees in the formalization and use of knowledge, and in the development of knowledge and skills through training.

This is also required to cater to the growing demand from end consumers, financial markets and legislators for information on the sustainability of production processes and supply chains. Italy has a unique heritage in terms of tradition, culture, skills, image, design and technologies, which represent the optimal environment for a manufacturing sector that produces high-added-value products and services. More specifically, the distinctive resources on which Italy is privileged to draw are:

- The ability to customize products and services, making them unique for their customers.
- An impressive degree of manufacturing flexibility achieved through an extremely creative approach and a widespread entrepreneurial spirit.
- The hi-tech nature of production systems made in Italy, which helps national manufacturers purchase advanced equipment.
- The ability to combine design and cutting-edge technology.
- The tradition of the Made in Italy brand, which generates international credibility and a prominent image.
- The high standard of human resources and professional skills in a number of sectors and industrial niches, found in industrial communities with strong ties to their local area.
- The ability of small and medium enterprises to join together in clusters and networks to achieve a critical mass with the aim of competing on the international stage.
- A first-rate training system capable of supporting production processes and innovation.

The engine behind this transformation should be a research and innovation process based on collaborative approach along supply chain, accompanied by a training plan designed to refocus the set of skills within the national industrial context. A multi-year research plan must leverage the qualities of Italy's available production resources and must be aligned with research challenges and international trends in the manufacturing field.

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The Role of Industrial Policies: A Comparative Analysis

Rosanna Fornasiero and Tullio A. M. Tolio

Abstract The aim of this chapter is to analyse and compare European, Italian and regional industrial policies aimed at promoting the research and innovation activities, with focus on manufacturing sector. The analysis is based on secondary data collected from websites, documents issued by related governmental bodies and grey literature which are compared along scientific topics of interest. Moreover, the chapter discusses how these policies are expected to have an impact on industrial competitiveness and how these policies are interconnected each other. A comparative analysis of the regional and national priorities is also proposed as the result of an iterative collaboration with regional actors. The chapter closes with the analysis of the role of the cluster in supporting industrial policies.

Keywords Industrial policy · Research policy · Public–private partnerships · Europe · Italy · Regions

1 The European Research Strategy and Actions

The ongoing plan Horizon Europe set out in 2021 is an ambitious research and innovation programme to allow the EU both to strengthen the outcomes achieved with H2020 and fortify Europe's frontline position in the research and innovation sector at the global level. Horizon Europe's purpose is to boost the scientific, social and economic impact of European research funds. Several programmes have a strong focus on close-to market activities including innovative financial instruments, and aspires to meet research needs by placing emphasis on widespread generation of knowledge generated through activities supported from basic research to the market.

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The strength of Europe starts on the back foot, grounded on delivering 17% of worldwide research and 25% of high-quality scientific publications with an average investment in research and development amounting to 1.5% of GDP, which is still very low compared to other high-tech countries, such as the US (2.1%), Japan (2.6%) and Korea (3.6%) (EU, 2020).

With a budget of 95.5 billion euros, the programme Horizon Europe is implemented over the course of 2021–2027 through 3 pillars (Excellent Science, Global Challenges and European Industrial Competitiveness, Innovative Europe). Horizon Europe stands out from previous programmes for its more integrated approach of pooling various financing instruments and, above all, is much more focused on achieving tangible application outcomes.

Of the three pillars, two are explicitly geared towards applied research in areas defined as priority areas for European industrial competitiveness in response to major global challenges (Pillar II) and towards radical product and process innovations by European companies (Pillar III) respectively, with a view to helping them achieve commercial success in global markets.

Within pillar II, the most important area for the manufacturing sector is cluster 4 "Digital, Industry and Space", whose goal is to support investments in competitive and trusted technologies for a European industry with global leadership in key areas, with production and consumption models that respect the planet, maximizing benefits for society in the different social, economic and regional contexts in Europe.

The overarching aim is to create a competitive, digital, circular, low-carbon industry, with the goal of ensuring the sustainable supply of raw materials, developing advanced materials, and introducing innovation to meet global challenges in society. More specifically, within the cluster 4 programme, medium-term goals (referred to as destinations) have been defined that, in turn, are broken down into calls for collaborative projects (like RIA, IA and CSA); for the first two years of Horizon Europe, these goals are:

- Climate neutral, circular and digitized production;
- Increased autonomy in key strategic value chains for resilient industry;
- World-leading data and computing technologies;
- Digital and emerging technologies for competitiveness and fit for the green deal;
- Open strategic autonomy in developing, deploying and using global space-based infrastructures, services, applications and data;
- A human-centred and ethical development of digital and industrial technologies.

Going in particular to analyse the manufacturing sector, Made in Europe is the new partnership established as part of the Horizon Europe Framework Programme (2021–2027) specifically focused on this sector. The creation of the Made in Europe partnership has been discussed between the relevant bodies involved, European Commission, member states and EFFRA association since 2019. The partnership's reach and ambitions were defined in the Made in Europe orientation paper and, in 2021, the Strategic agenda for research and innovation was published.

The European partnership involves the whole manufacturing value chain in Europe to support the promotion of manufacturing excellence among companies, especially

SMEs, to ensure competitiveness and sustainability across the European manufacturing industry, defending Europe's technological leadership around the world, as well as the prosperity and wellbeing of employees, consumers and society.

Made in Europe will make a substantial contribution for facilitating the networking between the main actors who steer and/or implement manufacturing innovation initiatives at the national and regional level, and its goal is to engage in dialogue with new actors, such as local authorities tasked with drawing industry to their cities and municipalities. In particular, the goal of the Made in Europe partnership is to propel European manufacturing ecosystems towards global leadership in manufacturing technologies in line with sustainability principles. The partnership is working to create a competitive, green, digital, resilient and human-centred manufacturing industry in Europe.

More specifically, manufacturing will be central to the twin transition (green and digital) in line with the European Commission's Green Deal, given that the sector is both an engine driving such changes in other sectors and it is itself on the receiving end of these innovations.

There are several European initiatives supporting industry and one of the most recent with the actions that may affect manufacturing is the Chips Act. The European Commission has proposed a comprehensive series of measures aimed at ensuring supply security, resilience and technological leadership for the EU in semiconductor technologies and applications. The European Chips Act has the goal of strengthening Europe's competitiveness and resilience, and it can help bring about both the digital and the green transition.

The European Commission has set out to mobilize over 43 billion euros in public and private investments through measures designed to prevent, prepare for, anticipate and respond rapidly to any future supply chain interruptions, together with member states and our international partners, with the aim of achieving its ambition of doubling its current market share in this sector to 20% by 2030.

More specifically, the objectives of the European Chips Act are:

- Strengthen European leadership in research and technology development towards smaller and faster chips;
- Build and reinforce its capacity to innovate in the design, manufacture and packaging of advanced chips;
- Put in place an adequate framework to increase its production capacity to 20% of the global market by 2030;
- Address skills shortage, attract new talent, and support the emergence of a skilled workforce;
- Develop an in-depth understanding of global semiconductor supply chains.

The Chips for Europe initiative will pool the resources of the Union, member states and third-party countries involved with the Union's existing programmes, as well as those of the private sector, by means of the "Chips Joint Undertaking" resulting from the reorientation of the existing Key Digital Technologies Joint Undertaking.

A substantial 11 billion-plus euros will be made available to support research, development and innovation in the sector and to ensure the use of advanced semiconductors, in innovative applications. Actions will also be identified aimed at training and reskilling in the industry, and at the development of the research and innovation ecosystem and relevant value chain.

There are plans for a new framework to ensure supply security by attracting greater investments and manufacturing capacity, required to promote innovation in advanced nodes, and innovative, energy-efficient chips.

Moreover, a Chips Fund will facilitate access to funding for start-ups in order to assist them in bringing their innovations to fruition and attracting investors. It will also include a share investment mechanism focused on semiconductors as part of the InvestEU programme to support scale-ups and SMEs to facilitate expansion of their market.

2 The Matching Between Cluster Objectives with European Goals and SDGs

In defining the roadmap objectives, the Cluster of Intelligent Factories refers to a number of strategic documents at the international and European level. More specifically, the Cluster aims to contribute to the definition of research and innovation themes aligning with a number of important European policies and, beside the aforementioned, other policy documents are: A new industrial strategy for Europe (EU 2021), The European Green Deal (EU 2019), A Europe fit for the digital age (EU 2021), An economy that works for people/Building a strong social Europe (EU 2021).

The Cluster works closely with the Made in Europe Co-programmed partnership and with the Manufuture European platform—since a number of actors within the Cluster also operate at the European level—and sets out to define research and innovation priorities that help manufacturing achieve the following European goals:

- Making manufacturing a carbon–neutral sector by 2050;
- Raising manufacturing's share of GDP to 20%;
- Reducing the use of virgin raw materials by 20% over the next decade;
- Increasing technological leadership and the resilience of ecosystems.

At international level, the Sustainable Development Goals (SDG) of the United Nations (UN 2019) are considered as a parameter to evaluate the impact of manufacturing in terms of performance. Moreover, in defining research and innovation priorities, the Cluster endeavours to analyse how manufacturing can contribute directly to the pursuit of the following UN goals:

- Goal 8: Decent work and economic growth
- Goal 9: Industry, innovation and infrastructure
- Goal 12: Sustainable consumption and production patterns
- Goal 13: Action to combat climate change

During the activities set up with the Scientific Board of the Cluster aimed to identify the overall goals, it was possible to identify the links between the Cluster's goals, the EU's strategic documents and UN goals (see Table 1).

Table 1 Breakdown of EU and SDG goals versus the Cluster's goals

EU strategic documents	SDG goals	Cluster CFI goals
• A new industrial strategy for Europe • A Europe fit for the digital age	Goal 9: Industry, innovation and infrastructure	The Cluster firmly believes that companies must have access to physical and digital infrastructure, and to innovative technologies, in order to operate within distributed collaborative networks. Companies need stable conditions and need to be able to operate in innovation-oriented environments. The Cluster's aim is to support the research and development of advanced technologies in this direction.
• An economy that works for people/ Building a strong social Europe • A Europe fit for the digital age	Goal 8: Decent work and economic growth	Manufacturing can create new jobs, with improved human–machine interaction. The Cluster believes that manufacturing should be human-centric, and that machines must be conceived to support operators and facilitate their work. Manufacturers must set goals of promoting worker growth with empowering actions.
• The European Green Deal	Goal 12: Responsible consumption and production	Industry must make substantial progress towards circular and carbon–neutral manufacturing It is important for the Cluster to promote the research and development of new clean technologies, and technologies that reduce dependence on virgin raw materials, as well as tools and solutions for assessing the environmental impact of processes and products. In addition, it is hoped that technologies can be developed to remanufacture products and materials to enable their continued reuse.
The European Green Deal	Goal 13: climate action	Industry is responsible for a third of greenhouse gas emissions, and the Cluster strongly believes that research and innovation activities should also be oriented to develop new products and processes to enable more efficient use of energy and resources. More specifically, manufacturing can make the products to reduce atmospheric emissions, to facilitate the use of renewable energy and to store energy. Moreover, it can make products designed for environmentally friendly use.

3   The National Research Strategy

In the last years, the Italian Government has set some strategies to support industrial policy with research and innovation activities that can be mainly recognized in the multi-year National Research Programme (PNR) and the National Plan for Recovery and Resilience (PNRR).

The National Research Programme (PNR) is a periodic document that orients research policy in Italy, identifying priorities, goals and actions aimed at supporting coherence, efficiency and effectiveness across the national research system, defining guidelines at the national level (PNR 2020). The ongoing PNR 2021–2027 has been structured to track alongside the Horizon Europe programme in terms of timelines and themes, breaking the six clusters included in pillar II into six broad research and innovation areas developed through intervention areas such as:

- Health;
- Human-centred culture, creativity, social transformations, inclusive society;
- Security for social systems;
- Digital, industry, aerospace;
- Climate, energy, sustainable mobility;
- Food products, bioeconomy, natural resources, agriculture and environment.

Thus, the national strategic vision is aligned with European programmes, including elements of complementarity aimed at promoting interventions to help Italian research system to increase its competitiveness and to become an increasingly key player on the European stage.

The potential ensuing advantages are not limited to the possibility of achieving shared access to R&I funding, instead there are inherent benefits to collaborative research, most notably those resulting from sharing outcomes and collaboration with other countries' national R&I systems.

These R&I areas covered in the PNR also allow to tie in with the goals of the European Green Deal, hence making the PNR a tool designed to provide a significant contribution to the green transition, in which the conservation of natural capital, biodiversity and the processes that depend on it—and on which the very life of the planet depends—becomes a necessary common condition for the pursuit of the goals of prosperity and wellbeing identified by the European Green Deal.

Another of the priorities identified in the plan is promoting the flow of knowledge and skills between research organisations and the manufacturing system, and exploiting research outcomes through a virtuous cross-fertilisation process to ensure the country's competitiveness, even more in the current twin transition, both green and digital.

The document states that public intervention is required to help kick-start this cross-fertilisation, and indicates the challenges to be tackled, the goals to be achieved and setting out consistent action lines. The PNR stresses that in policy planning, it is necessary to take into account the starting conditions and, above all, the gap by which

Italy lags behind other European countries in terms of the propensity of businesses to cooperate on innovation.

This gap is also underlined in the European Innovation Scoreboard (EIS 2020), which, for years, has been putting our country in the "moderate innovators" category, with performance trailing behind the European average in terms of collaboration between enterprises, and between enterprises and the public research system. Hence, promoting innovation necessarily goes hand in hand with strengthening relationships between research and the manufacturing system, fostered by mobility programmes between the research institutions and industry, and targeted technology-transfer strategies that facilitate the transition from fundamental and applied research to ideas delivered to the market more successfully.

As part of the National strategy for research and innovation, it is useful to analyse also the National Plan for Recovery and Resilience (PNRR) conceived as a planning document for specific investments and reforms for Italy after the response of the European Union to the pandemic crisis with Next Generation EU (NGEU). The document is set for planning investments and reforms to speed up the green and digital transition, improve worker training and achieve greater gender, regional and generational equity.

For Italy, NGEU represents an opportunity for development and investment that it cannot afford to squander. Italy must modernize its government bodies, strengthen its manufacturing system, and step up its efforts to fight poverty, social exclusion and inequality. NGEU might be just the opportunity to resume a sustainable and lasting economic growth path, removing the obstacles that have stood in the way of Italian growth in recent decades.

The PNRR has been formulated following an intense preliminary analysis and research phase, and comprises sixteen components, grouped into six Missions:

- Mission 1: Digitalization, innovation, competitiveness, culture and tourism
- Mission 2: Green revolution and ecological transition
- Mission 3: Infrastructure for sustainable mobility
- Mission 4: Education and research
- Mission 5: Cohesion and inclusion
- Mission 6: Health

With this document, the government plans to update national strategies around development and sustainable mobility; environment and climate; hydrogen; automotive; and the healthcare supply chain. In addition, the PNRR contains a very important chapter on training for companies to ensure the growth of human capital required to successfully bring about the twin digital-sustainable transition.

In terms of the competitiveness and resilience of the manufacturing system, the PNRR plans to pull different levers to strengthen and modernize the operational capability of companies in our country; more specifically, part of the plan is to promote digital transformation processes in Italian companies, and boost tools for the digital transition of the manufacturing system, and complete the digital infrastructure rollout process through the twin digital-sustainable transition.

4 Regional Specialization Strategies for the Manufacturing Sector

A look at the way the manufacturing sector is distributed across the Italian regions reveals heterogeneous situation in terms of concentration, value added and other important indicators. In particular, there is a strong concentration of manufacturing companies in Lombardy, which accounts for 27% of Italian value in terms of turnover and value added, with values across all 4 dimensions (companies, turnover, value added and number of employees) representing at least double the value individually reported by the next 3 top-ranked regions (Veneto, Emilia-Romagna and Piedmont).

In the international rankings, four of the European Union's top ten manufacturing regions are Italian: Veneto, Emilia-Romagna, Lombardy and Piedmont. According to the NUTS2 rankings, Lombardy is the EU region with the second highest number of employees in manufacturing companies, behind the French Paris region, Île de France. Out of the top ten European manufacturing regions, Veneto sits in second place for the ratio of manufacturing employment to population, with 10.6 employees in manufacturing companies per 100 inhabitants, behind Stuttgart (14.4 manufacturing company employees per 100 inhabitants). Emilia-Romagna, Lombardy and Piedmont placed 4th, 6th and 8th respectively, with 9.9, 8.9 and 8.1 employees per 100 inhabitants. Moreover, Emilia-Romagna has a per-capita manufacturing value added of 7899 euros against the Italian average per-capita value of 4,278 euros, followed by Veneto on 7,335 euros per capita and Lombardy on 7,030 euros per capita.

Looking at research spending in 2018 (Fig. 1), over a third of R&D is conducted in the Northeast, while the combined contribution of the Southern regions and islands comes to almost 15%. Notably, 68.1% of total spending, amounting to around 17.2 billion euros, is concentrated in five regions, namely Lombardy on 20.6%, Lazio on 13.7%, Emilia-Romagna on 13.0%, Piedmont on 11.8% and Veneto on 9.0%.

Overall, companies in the five major manufacturing regions account for 75% of national research in the sector. More specifically, out of the most virtuous regions, Lombardy makes the biggest contribution to total spending with 25%. In 2018, Lombardy, Lazio and Emilia-Romagna were again the regions where universities had invested the most in R&D and, together with Campania and Tuscany, they accounted for 55.7% of total R&D spending in this sector. Looking at the incidence of R&D spending as a percentage of GDP (Fig. 2), the regions' rankings range from Piedmont's top rate (2.17%) to Aosta Valley's lowest rate (0.48%). In addition to Piedmont, the regions with the highest R&D spending as a percentage of GDP are Emilia-Romagna (2.03%), Lazio (1.75%), Friuli-Venezia Giulia (1.67%), Province of Trento (1.56%) and Tuscany (1.55%).

In terms of research policies, national and regional research and innovation strategies for smart specialization (RIS3) are integrated, place-based economic transformation agendas designed towards five important actions:

(1) Focus policy support and investments on key national and regional priorities, challenges and needs for knowledge-based development;

	2019			
REGION	N° OF COMPANIES	TURNOVER (CM)	VALUE ADDED (CM)	EMPLOYEES
Lombardy	84.912	257.055.437	66.024.163	903.826
Veneto	47.750	130.946.007	35.244.765	537.800
Emilia-Romagna	37.976	123.065.073	33.741.998	452.620
Piedmont	32.884	97.613.276	24.767.236	359.063
Tuscany	40.558	72.457.306	17.743.987	303.263
Lazio	22.043	45.159.262	10.144.480	143.622
Campania	28.767	35.768.375	8.740.878	185.153
Marches	16.684	29.135.676	8.188.043	154.772
Friuli-Venezia Giulia	8.239	26.930.981	7.503.655	106.809
Apulia	22.070	29.635.209	6.111.431	144.032
Abruzzi	9.379	19.747.087	4.694.134	81.725
Liguria	7.894	21.546.332	4.378.840	59.138
Sicily	21.735	24.240.246	3.491.126	90.364
Umbria	6.787	12.408.055	3.310.975	57.681
Independent Province of Bolzano	3.424	8.957.025	2.596.016	36.470
Independent Province of Trento	3.406	8.803.324	2.268.035	33.473
Basilicata	3.083	6.346.891	1.265.372	26.538
Sardinia	7.539	8.954.785	1.483.287	32.114
Calabria	8.281	3.181.759	901.368	26.683
Molise	1.771	2.585.958	618.852	12.159
Aosta Valley	669	1.082.831	278.027	4.659
	415.851	965.620.895	243.496.668	3.751.964

Source: Istat

Italian manufacturing, region-by-region breakdown of n° of companies and employees

Fig. 1 Italian manufacturing distribution per Region

Region	Value
Piedmont	2,17
Emilia-Romagna	2,03
Lazio	1,75
Friuli-Venezia Giulia	1,67
Ind. Province of Trento	1,56
Tuscany	1,55
Veneto	1,38
Liguria	1,34
Lombardy	1,33
Campania	1,30
Molise	1,28
Marches	1,07
Umbria	1,03
Abruzzi	0,91
Ind. Province of Bolzano	0,84
Sicily	0,83
Sardinia	0,81
Apulia	0,79
Basilicata	0,64
Calabria	0,54
Aosta Valley	0,48

Source: Istat

Intra-muros R&D spending by region. Year 2018 (% of GDP)
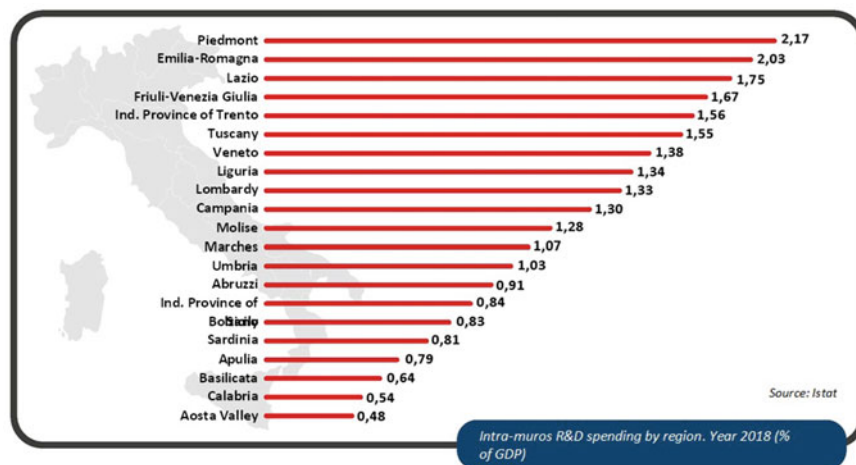
Fig. 2 Intra-muros R&D spending by Region, 2018 (%GDP)

(2) Build on each country's or region's strengths, competitive advantages and potential for excellence;
(3) Support technological innovation and stimulate private sector investment;
(4) Get stakeholders fully involved and encourage innovation and experimentation;
(5) Take an evidence-based approach that includes sound monitoring and evaluation systems.

All the regions participating in the Cluster CFI activities, as part of their respective specialization strategies, have defined priorities and goals that concern the promotion of models, methods and technologies to support the implementation of intelligent factories, as a path to the economic and industrial growth of the region, as well as the improvement of social integration with a new role for industry.

These policies have been developed based on analysis of the industrial and research system's local conditions, compared with state of the art of technologies and global trends, backed by the application of foresight and roadmapping methodologies.

The regional strategies analysed as part of the Cluster's activities share a common far-reaching vision of innovation, with approaches based on—but certainly not limited by—technology and the main, cross-cutting drivers associated with it. They have all paired a monitoring system with shared output, specialization, transition and outcome indicators coordinated nationally for monitoring of the national S3.

All regional authorities have worked over this period on defining the proposal on how to update their individual S3 for the 2021–2027 period, formulated in light of: the changes observed in the regional manufacturing system and relevant innovation challenges identified; the strategic-planning reference framework at the European, national and regional level; the outcomes from various exchange and feedback sessions with regional stakeholders; and also building on the experience gained over the 2014–2020 agenda period.

During the course of 2020, under the aegis of the Cohesion Agency, the Cluster has turned the spotlight on the interregional table, which involves both the regional authorities already formally partnering with the Cluster, as well as candidate authorities (Friuli-Venezia Giulia, Province of Trento, Umbria and Basilicata), for the sharing of new specialization strategies.

For the sake of this work, the roadmapping group of the Cluster, with the support of the bodies representing the regional authorities in the Cluster Management Board, carried out a deep analysis of the strategies for research and innovation developed by each region in the RIS3 to align the Cluster proposals with these requirements, endeavouring to map the research priorities and strategic lines of the two analysis levels (regional and national). As illustrated by the diagram below (Figs. 3 and 4), the Cluster research and innovation priorities (which will be described in the coming chapters) can be seen as a macro container collecting the interests of the various regional stakeholders. Each region has its own specificities, and some regional priorities have been mapped along different strategic action lines.
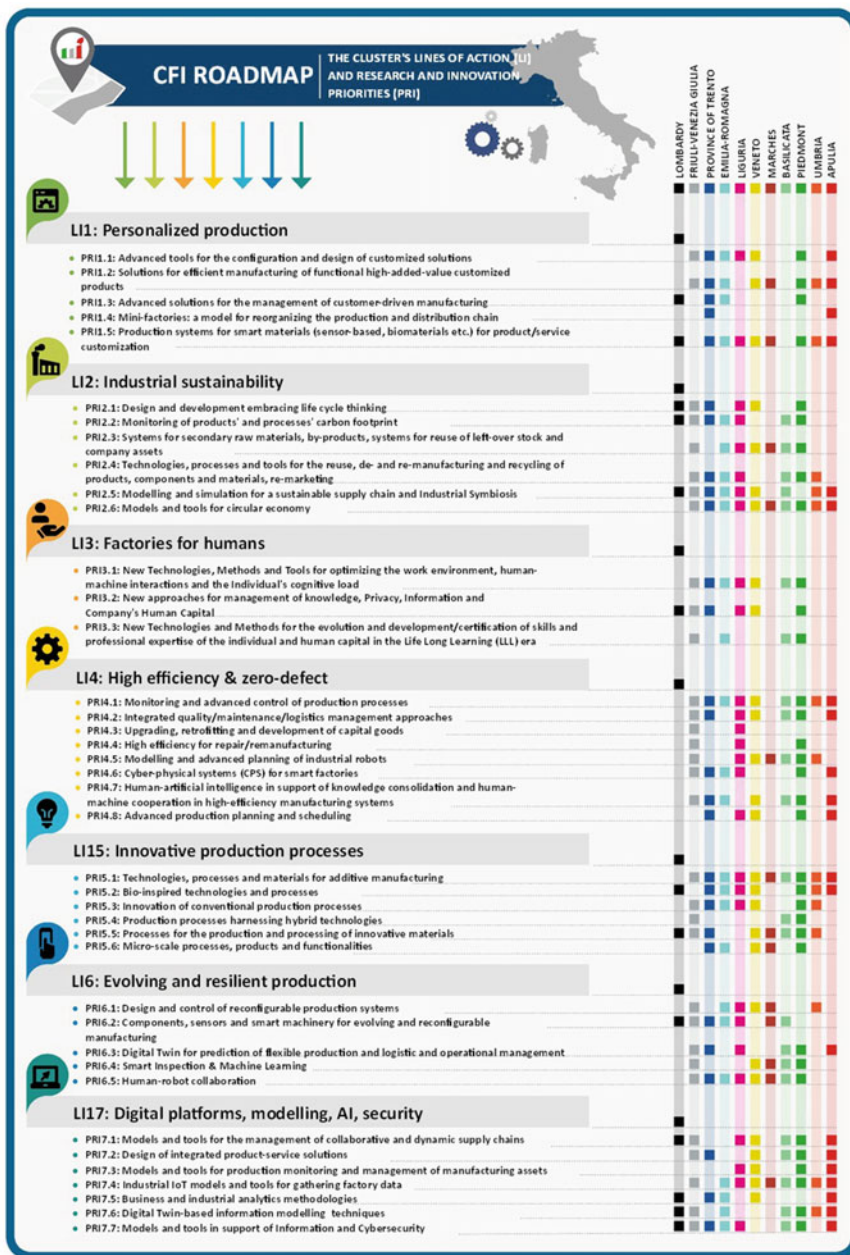
Fig. 3 Mapping Cluster research and innovation priorities to regional RIS3 objectives

Fig. 4 Cluster research and innovation priorities per Region

5 The Role of Clusters in Definition of Industrial Policies

From this analysis, the definition of research and innovation roadmaps (at any level) leverages on the interconnection between the manufacturing system and public research and policy definition and this is where public–private collaboration models also come in, and initiatives like national and regional Clusters serve as a valuable tool in this direction. In countries where manufacturing accounting for such a significant portion of GDP and employment, it is clearly important to successfully overcome the strategic limit of the actual strategies, giving enough space to sectors that have demonstrated—backed up by figures—their worth as producers of wealth. Moreover, a new governance model should be developed to assign a leading role to partnerships that have been operating across the country for years, such as national and regional clusters, and design mechanisms to highlight specific priorities for capital goods. The role of networking stakeholders, mapping research needs, helping institutional communication, helping knowledge and technology transfer is enabled by these actors of soft governance.

Hence, the Cluster sets out pathways for the evolution of Italian manufacturing, bringing stakeholders like industries and researchers together into a national collective to support an ongoing dialogue with Ministries, Regional authorities and institutions, even at the European and international level, with a national vision for the manufacturing system defined through this roadmapping initiative.

To cement a stable position in the global competitive arena in the field of manufacturing, Italy must innovate its manufacturing sector to leverage the resources available to it and generate added value in both traditional and new markets.

This innovation must include, on the one hand, achieving greater productivity and, on the other, the development of new strategic industries, leveraging the existing successful production structure. In view of this, the roadmap defines visions for future manufacturing that can:

- Support policy makers (ministries, regional authorities, EU) in their efforts by proposing a consistent research, development and innovation framework that takes into account evolution on the international level and, at the same time, allows for the specificity of the national situation and of the individual regions.
- Provide a blueprint for defining initiatives for the achievement of common ends to the benefit of the country's strategic positioning and competitiveness.
- Provide a starting point in bilateral and multilateral relations with other countries to define cooperation programmes and shared actions.
- Provide a blueprint for developing national and regional S3s.

This role of the Cluster promotes coherence between the various practitioners, to overcome fragmentation issues, and improve the ability to implement actions that are coordinated and, where possible, concerted so as to ensure the sector's harmonious growth. This organic framework is set to benefit businesses as well as universities and research bodies, i.e. the practitioners of research and innovation.
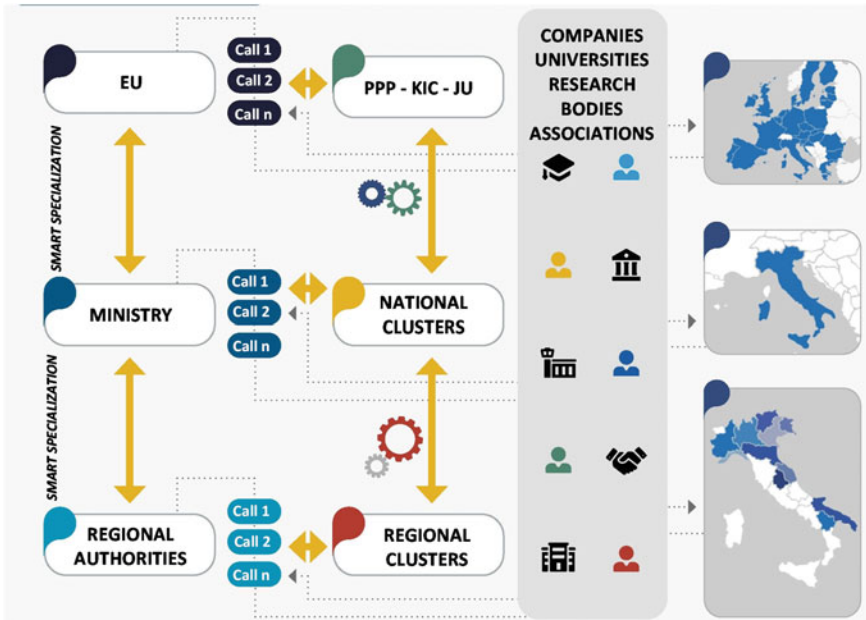
Fig. 5 Framework of integration between regional, national and European policy level

Backed by such a framework, each actor will actually be in a position to take part in regional, national and European initiatives through projects that—starting with the local and progressing to national and, ultimately, international projects—build on the expertise gained along this growth path. On the other hand, low TRL outcomes on the European or national level can be allowed to evolve further within the regions, possibly through demonstrators and pilot plants (Fig. 5). Lastly, multi-regional initiatives taken in different countries can lead to European-wide initiatives (e.g. Vanguard).

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Building Scenarios for the Future of Manufacturing

Rosanna Fornasiero, Tullio A. M. Tolio, Melissa Demartini, Walter Terkaj, and Flavio Tonelli

Abstract Forecasting future scenarios is an approach that enables companies, governments, and countries to interpolate the most important trends unfolding in a certain context to help tackle the uncertainties of a world that is changing ever more rapidly. The future outlook can be influenced by many different variables and it is reasonable to consider different possible scenarios. This chapter briefly describes the scenarios discussed and validated by the National Cluster of Intelligent Factories as some of the most promising to influence and change production systems. The work is based on the analysis of various trends from economic, social, technological, and environmental dimensions that have been clustered. The expected influence on the manufacturing sector has been discussed and validated with the support of a group of experts.

Keywords Future scenarios · Consumption trends · Electric mobility · Circular economy · Digital economy

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1   Introduction

Future scenarios can be forecasted to enable companies, governments and countries to interpolate the most important trends unfolding the external environment to tackle the uncertainties of a world that is changing ever more rapidly (Amer et al., 2013). Scenario planning is used to support public policy decisions and industrial policy in various contexts using qualitative methods to gather the approval of industry experts and quantitative methods to forecast phenomena based on the interpretation of historical data (Georghiou, 2008).

It is important to create different scenarios, taking into account a number of dimensions, namely economic, social, technological, environmental trends, as sources of possible changes to have a vision of the future based on causal relationships between exogenous and endogenous variables with the aid of experts from various fields or with the use of forecasting methods.

The pandemic has further accelerated sudden changes, while the crisis linked to the Russia-Ukraine war likewise has a profound impact on energy scenarios, the supply of materials and production supply chains, as well as an impact in terms of outlets for specific sectors. In this context, it becomes even more important, beyond the individual trends, to understand the possible interactions between current and forecast changes, and develop potential future scenarios that can serve as a reference for manufacturing's development.

The creation of future scenarios facilitates the ability to set up strategies to deal with ongoing changes and can give a country or its manufacturing system a competitive edge. In addition, if informed by appropriate industrial policy actions that intervene at the national and regional level, this ability is a starting point for the future.

Herein, a mixed approach has been applied while starting from statistical data on exogenous trends. A group of experts from the Cluster for Intelligent Factories has been involved through focus groups with an iterative method to support the following phases:

- Clustering the exogenous trends for defining the scenarios: experts have been involved in order to analyse exogenous trends (political, economic, social, technological and environmental) and to group them in six macro areas.
- Brainstorming and definition of the impact of these trends on manufacturing in terms of new methods and technologies necessary to face them. Having in mind a time horizon of 5 to 10 years, this has brought the focus group to create six scenarios.
- Upon these scenarios, the focus group Identified opportunities arising for the future in terms of research and development useful for the definition of the Cluster Strategic Action Lines.

The roadmapping group of the Cluster has managed to involvement of the experts along the six scenario definition taking into consideration their expertise. Both experts

from academia and industry have been involved with brainstorming sessions and interviews.

Six scenarios are presented in this chapter, focusing on relevant topics such as electric mobility, new consumption models, circular economy, knowledge management, digital economy, and climate change. Each scenario is introduced with its current context and possible future evolutions. Then the impacts on manufacturing and action lines are outlined to support the preparation and adjustment of manufacturing strategies.

2   Scenario 1: Electric Mobility: A Supply Chain Challenge

In 2019 more than 2.1 million electric cars have been sold worldwide, outperforming 2018—which was already a record year—for a grand total of 7.2 million electric cars (which also includes plug-in hybrid electric vehicles).

While accounting for only 2.6% of global car sales and approx. 1% of the global car installed base in 2019, electric cars are recording a 40% year-on-year increase (IEA, 2020). With the advancement of new technologies in vehicle, bus and truck electrification and their growing market, electric vehicles are expanding significantly. In recent years, ambitious policy interventions have been key to stimulating the launch of electric vehicles in the main markets.

Moreover, the 2019 indications of a shift from direct subsidies to more systemic approach, based on regulatory measures on zero-emission vehicles and new fuel economy standards, provided clear signals to the automotive industry and consumers that an economically sustainable transition can be achieved in the medium to long term, also with the help of governments.

Italian car manufacturers are also working on electric vehicles and related technologies to meet an exponentially growing demand. In Italy, there is a significant ecosystem of both electrical component and power electronics manufacturers, relying on the expertise of many product design and engineering hubs. The role of machinery manufacturing companies in the industrial production of components — already providing manufacturing solutions to the electric mobility industry—is also significant.

Major structural interventions are required on several fronts to facilitate the transition to electric mobility:

- Development of adequate infrastructure for electric car charging with investments for a smart grid and for postponing charging to night-time when energy demand and prices are lower.
- There is a need to grow the ecosystem of the production of lithium-ion cells and their reuse, as well as the recovery and recycling of batteries in Italy, since these account for an important part of CO_2 emissions related to the manufacture of electric cars, a gap which is recovered during their use.

In particular, investments are required in treatment plants for the re-purposing, reuse for static uses and material recycling of batteries from various applications.

- Investment in electric motors, which represent a significant part of the mobility electrification scenario and require major investments to ensure, on the one hand, ever-increasing performance together with weight reduction and, on the other, the implementation of circular economy solutions that allow the reuse of functions and materials (some of which are among Europe's critical materials such as permanent magnets).
- Review of the production chain and relationships between manufacturers and component suppliers due to the technological shift.

To understand the potential effects on the automotive value chain, it is worth noting that 50% of the industrial cost of an electric car is not present in a traditional internal combustion engine car. And the effects are not limited to the powertrain, but also extend to the body, chassis and interior.

An average of 6.2 h of labour are required to assemble the engine and transmission of internal combustion engine cars. In the case of plug-in hybrid cars, the number of hours increases to 9.2, since the electric motor and batteries must also be assembled. On the other hand, for a full electric car, the number of hours decreases to 3.7, i.e. 40% less, because the engine and transmission are simpler.

Therefore it is necessary, at the Italian level, to organize and orient academic and industrial expertise, coordinating stakeholders like researchers, design and product engineering companies, industries (automotive, electrical and electronic component, chemicals and SW development excellences), utilities and transport companies, in order to "work as a system" and facilitate the creation of supply chains aimed firstly at the development and production of electric vehicles fully made in Italy. The contribution to the country's GDP and industrial resilience that this sector represents is given by the 100 billion turnover of the automotive supply chain (including lower tiers suppliers), 258,000 workers, with a worker multiplication factor equal to 3, and 3.9 billion investments in the industrial sphere that should be oriented by national industrial policy precisely towards the production of electric vehicle components.

In terms of current supply chains, electric is a fast-growing sector even though, as mentioned, figures compared to traditional cars are still very much on the low side for now.

Therefore, the traditional car business cannot be excluded from the equation, as this will still be the main market for at least another decade. Italy is well positioned as a country working together in a networked system, especially regarding automotive components.

Moreover, it is necessary to monitor the development of electric mobility since this may not be the end point but simply a stage in the transition to more environmentally friendly mobility, where the combination of hydrogen with electric, for example, could be the solution for industrial vehicles.

The expected impact of the scenario on R&D activities is associated with the observation that investments in electric mobility are yielding results in the short term. Still, structural interventions are essential, potentially leading to significant

transformations in the medium to long term. These interventions can help minimize the inherent national dependence on those controlling the necessary raw materials during this transition.

This scenario should be studied from the point of view of the following action lines:

- LI2: Industrial sustainability,
- LI4: High-efficiency manufacturing,
- LI5: Innovative production processes,
- LI7: Digital platforms, modelling, AI, security.

3 Scenario 2: New Consumption Models

Before the Covid-19 pandemic, 30–40% of luxury goods sales were generated by consumers passing through airports and abroad. However, with the restrictions on travel and movements during lockdown, global tourist spending has halved, while domestic luxury purchases have doubled.

Generally speaking, there are consumption models that are changing radically and prevailing over others. One of these is the luxury market in China, where last year sales increased by 48%, sitting at around 350 billion yuan ($54 billion), bolstered by domestic consumption due to a reduction in overseas travel (and hence purchases).

Partly thanks to pop-up stores used by brands to sell directly on social media, the Chinese market has increased purchases from overseas, encouraged by a much lower tax rate than on the Chinese portals (namely 9% compared to 40–50%). The winners from this trend were not just the big Italian luxury brands, but niche brands, too, since anyone who managed to communicate effectively through the right channels during lockdown enjoyed a real surge in sales (McKinsey, 2021).

This surge has contributed to the doubling of China's total share of the global luxury market in 2020, going from about 11% in 2019 to 20% in 2020, with an additional increase forecast by 2025. A drop in international tourism contributed to two- or even three-figure increases in the rate of domestic luxury goods spending for some brands. Growth rates varied wildly across the different regions, brands and categories.

When it comes to engines fuelling the birth of new consumption models, generation Z and millennial consumers are expected to continue spending on luxury goods and customized products as almost three quarters of them say that they will increase or maintain current spending levels on these kinds of goods. Consumer online shopping behaviour has changed for good, having overcome the obstacles of recent years (i.e. digitalization).

Moreover, most brands feel that the online penetration of luxury goods (including omnichannel retail) will reach 20–25% within three years. Between 2019 and 2020, e-commerce has grown by at least 50% in Europe and China, as well as in the United States, according to McKinsey.

In the second quarter of 2020, Farfetch sales were up almost 75% on the previous year, hitting a turnover of $365 million. Brands like Nike and Louis Vuitton have seen an increase in online sales, which they attribute partially to the customization of the shopping experience delivered across all sales channels. To achieve this, fashion brands are defining new customer experience solutions blending of AI and other technologies. This also needs to be backed by adequate design and production systems to provide the luxury or customized goods demanded by the market.

Social shopping can be a channel to support the luxury market and product customization, while the presence of increasingly environmentally conscious and concerned consumers prompts a change in the type of offering, which must be based on traceable and environmentally friendly products.

This scenario can represent a driving force for Made in Italy manufacturing in various sectors and opens up new challenges linked to the need to have production systems in place that allow companies to increase their product customization capacity, and cater to the demands of some geographical regions, both by defining products specifically tailored to their needs, and by offering product configuration systems that are interfaced with the production systems.

As for technological development, the potential of the Internet of Actions (IoA) will enable companies to review their offerings, facilitating the sensory experience linked to the purchase of certain products, delivering a new customer experience in store and online thanks to the development of vision systems and virtual and augmented reality.

While the growth of the social component at the sales and loyalty stage opens up a challenge when it is implemented through multichannels, at the same time it also presents an opportunity since it gives companies access to huge amounts of data about customer preferences, attitudes and needs, allowing them to predict and understand the demand for the design of new product generation and related manufacture increasingly tailored to customer requirements.

The expected impact of the scenario on R&D activities is linked to the ongoing evolution of new consumption models. Urgent interventions are needed in the short term to support design and manufacturing activities with new models and methods.

This scenario should be studied from the point of view of the following action lines:

Ll1: Personalized production,
LI5: Innovative production processes,
LI6: Evolving and resilient production,
LI7: Digital platforms, modelling, AI, security.
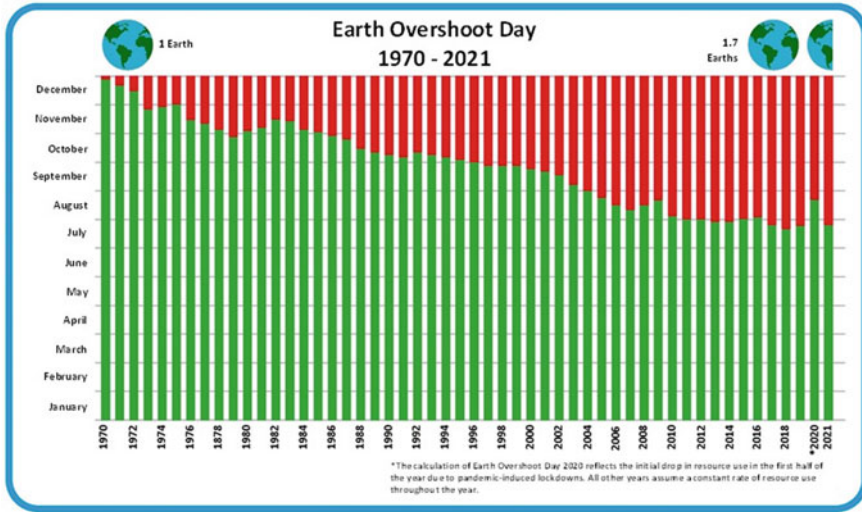
Fig. 1 Earth Overshooting day

4 Scenario 3: Circular Economy

Relentless population growth over the last two centuries (from 1 billion in 1800 to 7.9 billion in 2022) has led to a progressive increase in the demand for natural resources, which includes raw materials, water, energy and arable land, as highlighted by "overshoot day" calculations (Fig. 1).

This value measures humanity's environmental footprint and the ability of the Earth—both at the global level and with reference to individual nations—to regenerate the resources consumed over 365 days, including in terms of its ability to absorb emissions released into the atmosphere.

Over the last 50 years, the overshoot day has fallen progressively earlier, meaning that humans are consuming resources quicker than the Earth can regenerate them. The increase in demand for these resources puts a lot of pressure on the environment and, at this rate, material consumption worldwide is expected to increase roughly eightfold by the end of 2050.

Another important trend that adds to the pressure on the environment is the increase in urbanization, which entails an increase in the use of raw materials for construction, such as roads, bridges, dams, sewers, and the need to step up transport systems.

In addition, the rapid shift in the global scenario characterized by crises—such as the COVID-19 pandemic, socioeconomic conflicts, and raw material and energy shortages—has exposed the fragility of our current linear system. There are loud calls to "rebuild better" with a green recovery—thus repairing the impacts of the pandemic and including the climate crisis—as documented by the recent Recovery Plan for Europe budget.

Consequently, it is necessary to improve how resources are being handled currently to identify opportunities for greater wealth for people, while still employing environmentally responsible practices.

This shift is based on the circular economy concept (MacArthur 2015) that considers factors capable of reducing waste and monitoring the consumption of resources more closely. The circular economy reduces the need for new raw materials, instead reusing product functions and existing materials. This practice that can be implemented by rethinking the function of the product in a closed loop.

This extends the life of resources and includes strategies such as reuse, repair, regeneration, recycling and reducing overall negative effects of manufacturing activities on the environment, which call for a thorough overhaul of companies' activities.

The circular economy not only brings challenges for companies, it also allows them to obtain economic, environmental and social benefits, such as giving impetus to innovation and economic growth, increased resilience and competitiveness, reduced pressure on the environment, optimized availability of raw materials, and job creation.

In addition, consumers can buy long lasting products that save money, are innovative, and capable of improving quality of life. Embracing circular economy systems and strategies thus entails macro- and micro-level changes.

At the micro level, companies need to rethink and redesign their production processes to use renewable sources of energy and materials, extend the products' life, create sharing platforms, reuse and regenerate products or components, and rethink products as services.

At the macro level, the European Union sponsored the Circular Economy Action Plan in 2015 to prompt countries to invest in the circular economy area and monitor investments through the Circular Economy Monitoring Framework. This tool is used to analyse and compare the various countries in terms of circular economy.

Figure 2, for example, features a Sankey diagram of material flows in the European Union and the circular material use rate, or circularity rate, namely the amount of material recycled and fed back into the economy.

Both the Sankey diagram and the circularity rate are part of the EU circular economy monitoring framework (Fig. 2). The purpose of a circular economy is to retain the value of products, materials and resources for as long as possible, integrating them back into the production loop once they reach the end of their life cycle, minimizing the waste generation.

Materials like biomass, metals, minerals and fossil fuels are extracted from the environment to make products or produce energy. At the end of their life cycle, products can be recycled, incinerated or discarded as residual waste. These material flows are a core component—effectively the only component—of the circular economy. The fewer products are discarded and the more recycled, the fewer materials are extracted, for the sustainability of society and the environment.

While this scenario may therefore represent an opportunity to increase companies' resilience and competitiveness, at the same time it also poses a challenge for Italian manufacturing—on the one hand, there is the opportunity to reap benefits from a circular system (i.e. reduced production costs, increased resilience, job creation,
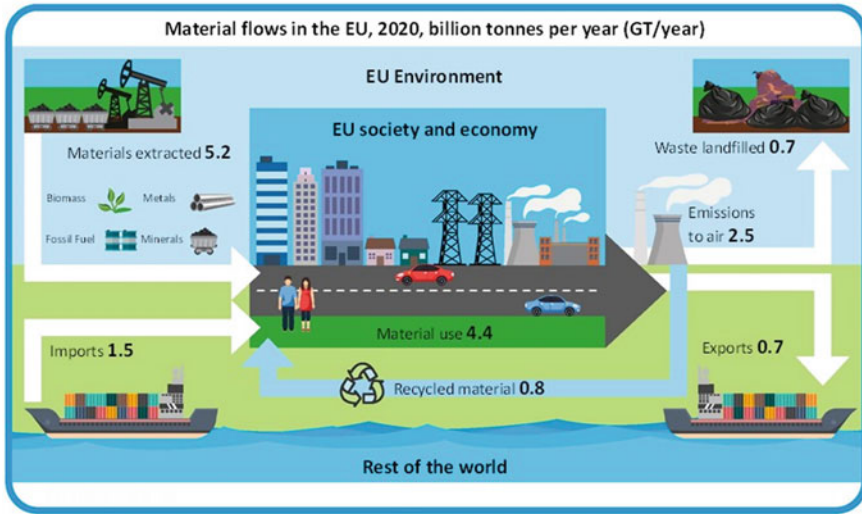
Fig. 2 Material flows in EU, 2020 (bln ton per year)

benefits for both the environment and quality of life); on the other, this change calls for financial and structural efforts with serious impacts on products, processes, governance and the supply chain, such as:

- Impacts on products/processes: Products play a crucial role in the economy, serving the needs of society, and helping build individuals' identity. Designing products better, extending their service life and changing their role within the system will be crucial for developing a circular economy. Moreover, research into new technologies and equipment for the circular economy can help improve production processes and is a major opportunity for Italy and Europe. This translates into an improvement in efficiency and a new capacity to reuse, repair and regenerate products, components and relevant functions.
- Impacts on strategies: The adoption of a circular economy approach calls for companies to transition from linear production to business models that allow them to design and produce goods intended for extended use, disassembly, reuse and recycling. In addition to an impact on companies' business models, this change may also entail sourcing new competencies and skills.
- Impacts on the supply chain: supply chains allow for coordination with partners adopting environmentally conscious practices. This coordination becomes a key factor in achieving a successful circular economy as supply chains also allow companies to align in terms of environmental and social goals. Circular supply chains entail new approaches to design that incorporate the concept of extended service life, reuse/recycling processes, and collection, re-manufacturing and resale activities.

The expected impact of the scenario on R&D activities is significant, given the ongoing implementation of various circular economy initiatives that are making a powerful short-term impact. Planned investments in R&D are mainly focused on the medium term in several directions. The focus is on enhancing processes like recovery, recycling, re-manufacturing, aiming not only for sustainability but also for efficiency with the support of emerging technologies.

This scenario should be studied from the point of view of the following action lines:

- LI2: Industrial sustainability,
- LI4: High-efficiency manufacturing,
- LI5: Innovative production processes,
- LI7: Digital platforms, modelling, AI, security

5   Scenario 4: Knowledge Management and Internet of Actions

The rapid and pervasive spread of the Internet, digitalization, and cyber-physical systems (CPS) is clearing the path for a novel technological transformation facilitated by the Internet of Things (IoT). In addition, manufacturing is becoming more data and knowledge-intensive (Grigorescu, 2020), thus enabling remote monitoring and interactions for the stakeholders, including managers, operators, and customers.

One development scenario that is progressively solidifying involves the concept of the Internet of Actions (IoA) as a solution. IoA enables entities to share not only data but even sensations and actions thanks to state-of-the-art smart sensors and actuators (Forbes, 2020).

Effective IoA systems will necessitate the precise replication of sensations to generate interactive and adaptive (re)actions by humans and devices (Xu, 2021). Above all, the development and exploitation of sensors and actuators will play a pivotal role in establishing a remote sense of presence and facilitating accurate and safe remote actions (Javaid, 2021). Devices employed in IoA architectures will need to manage interactions with both the environment and human beings.

Factories provide an ideal testing environment for investigating and developing suitable IoA systems since factories already incorporate many of the underlying technologies that drive IoA. Subsequently, IoA systems can be extended to other domains. For instance, IoA enables operators in industrial plants, even when situated at substantial distances from one another, to exchange data, information, and actions, thus ensuring that all operators have the same vision and perception. Complete remote support and maintenance can offer relevant advantages (Silvestri, 2020), particularly where there is a shortage of local specialized workers and when it becomes imperative to operate in intrinsically hazardous or unsafe environments, such as during a lockdown.

This scenario would enable the manufacturing sector to devise strategies for achieving comprehensive remote support and maintenance for manufacturing facilities. Digital technology can effectively support operators to impact the real world with actions generated in a mixed-reality environment (Seiger, 2021). In the long term, once the technology is more mature, applications can be extended to many other unstructured environments, such as the home, entertainment, shopping processes, inspection and exploration.

This scenario entails the development of IoA devices and systems with processors, sensors and actuators, while further developing and integrating various enabling technologies, such as augmented and virtual reality (AR/VR), High-Performance Computing, Cloud and Fog Computing, Cyber-physical production systems, Big Data Analytics, ultrafast communication infrastructure and standards, AI, data archiving, sensors and monitoring, wearable devices and actuator technologies (Tolio, 2019).

More specifically, in the Italian context—characterized by many small- and medium-sized enterprises (SME) facing challenges in adapting to the digital transformation of products, processes and technologies—manufacturing companies will have to address complex production phenomena using solutions based on expertise, wherein the operator may play a central role. Consequently, it is equally crucial to strategically invest in these enabling technologies to support user-centred activities (e.g. operator training and maintenance support through feedback and visual, auditory and tactile interactions) together with the development of digital twin models incorporating appropriate semantics and ontological representations of information and knowledge in support of the reuse of expertise (Terkaj, 2024).

This scenario offers opportunities to SMEs that market products globally, especially durable assets and capital goods, ensuring their capability for remote maintenance and assistance. The IoA approach is also founded on the possibility of operating physically from anywhere worldwide while centralizing product and process knowledge in specific locations, with Italy potentially being one of these.

The expected impact of the scenario on R&D activities is intertwined with the ongoing development of effective knowledge management systems, which, in the short term, require an enhanced ability to interact with operators and consumers. Significant investments need to be strategically scheduled in the medium to long term, particularly in the fields of sensors, actuators and cybersecurity.

This scenario should be analysed considering the following action lines:

- LI1: Personalized production.
- LI3: Enhancing human resources in factories.
- LI6: Evolving and resilient production.
- LI7: Digital platforms, modelling, AI, security.

6   Scenario 5: Digital Economy

In the contemporary economic landscape, which is increasingly interconnected and complex, businesses operate on a global scale whereby digital platforms enable consumers and enterprises to virtually interact and share information, meet customer needs, and improve their ability to manage company processes. Therefore, stakeholders in the digital platform economy can swiftly create new products and services that cater for consumer preferences and habits. They can also create entirely new offerings by reconfiguring innovative products and services based on information acquired through these platforms (McKinsey, 2020). KPMG estimates that turnover linked to the platform economy will go from 7 thousand billion dollars made in 2018 to over 60 thousand billion by 2025 (KPMG, 2019).

In business models founded on the platform concept, the sale of products and services is integrated—in a transparent way for the user—thanks to the provision of value-added services (shared design, product configuration, maintenance, insurance, after-sales support), offering modular solutions, which leverage the combined offering of different operators who are often in different areas of business, but who are seen as a single entity by the company client/end consumer.

Notably, the progressive implementation of the platform economy through digital technologies (such as sensor-based systems, Internet of Things, Big Data, AI) has been one of the distinctive traits of companies that have thrived during the crisis. On this note, several hi-tech companies have exploited digital platforms as a core part of their business model to go from design to rapid remote prototyping, to handling maintenance and product sales, and have managed to meet market demands even when the presence of operators on site could not be guaranteed.

Similarly, in e-commerce, major retailers have exploited digital platforms—even platforms employing different data management models (some more centralized and rigid, others open and flexible to handle their processes)—to handle the above-mentioned processes.

Digital platforms supporting manufacturing processes must be conceived to provide a "digital" extension of functionalities to physical assets (Effra, 2020). In particular, services provided through digital platforms can aim to support:

- Collaboration during the engineering of manufacturing plants;
- Monitoring of manufacturing processes;
- Data analytics through advanced data science techniques;
- Manufacturing control based on interaction between different agents, including machine-to-machine communication;
- Introduction of machine self-learning capabilities;
- Simulation of manufacturing processes;
- Assistance to workers and engineers also with the support of virtual and augmented reality;
- Production planning, predictive and automated maintenance, etc.
- Digital integration of value chains (e.g. real-time or near-real-time sharing of production, distribution and sales data).

- Interoperability of decentralized processes and production systems.

These services can be offered by different providers in a multi-actor ecosystem, supporting processes both inside and outside the factory. The preconditions for improving digital platform development in Italian manufacturing contexts include the definition of agreements between providers, as well as between providers and manufacturers, on industrial communication interfaces and protocols, common data models and data interoperability and hence, on a broader scale, intercommunication and interoperability between platforms, ensuring an open approach.

This kind of model still has a margin for expansion in Italy and there are several challenges still to be tackled to study open solutions supporting process management, especially at the manufacturing system level. The opportunity to develop solutions that are federated between different providers is also promoted by the European Commission through the funding of various European projects (Gaia, 2022), and Italy's role is of paramount importance as an advocate for the interests of companies whose task, as either manufacturers or users of machinery, is to bring to light the user requirements of these platforms.

Some of the aspects that need to be worked on over the coming years to improve the digital economy for the manufacturing sector are:

- The possibility to connect to additional services according to the plug-and-play philosophy, considering the ecosystem of service providers, platform providers and manufacturing companies.
- Mechanisms for commercial or open-source provision of digital services through appropriate marketplaces.
- The modularity of platforms using standards such as RAMI4.0 or other standards.
- Data and information integration from and to legacy systems (hardware and software).
- The creation of trust systems that facilitate the exchange of information between companies.
- Definition of new semantics in support of interoperability.
- Specific requirements of different manufacturing sectors (process industry, consumer goods, capital machinery and equipment,…).

Platform-Based Manufacturing, then, clearly needs to focus not just on handling logistics, but also on the actual transformation processes. This completely changes supply chains and the way businesses deal with customers. Hence, new actors (managing the platforms) are expected to rise, while existing actors change their functions and how they operate. A radical change offering new market opportunities may be key for machinery manufacturers. In addition, these platforms are quick to go global, posing questions around country-level industrial strategy.

The expected impact of the scenario on R&D activities is related to the fact that digital platforms have a powerful short-term impact improving communication and collaboration across different decision levels in manufacturing. Indeed, they urge for investments in R&D in the medium term to support SMEs and technology providers in

developing and implementing open solutions that facilitate communication between different actors.

This scenario should be studied from the point of view of the following action lines:

LI7: Digital platforms, modelling, AI, security.

7   Scenario 6: Climate Change

The global warming observed over the past 150 years is probably triggered by human activities, hence resulting in an anthropogenic greenhouse effect that adds to the natural greenhouse effect. With the industrial revolution, humankind has suddenly dumped millions of tonnes of carbon dioxide and other greenhouse gases into the atmosphere, causing a huge upsurge in the amount of CO_2 in the atmosphere (Enel, 2021).

The average temperature of the planet has increased by 1 degree on pre-industrial levels and, judging from the trend observed from 2000 to date, if no action is taken, this value is forecast to be as high as $+1.5\,°C$ by 2050. "Fire seasons" have become longer and more intense; from 1990 to date, every year there has been an increase in extreme weather events, such as cyclones and flooding, which are even hitting outside the periods of the year that would typically experience this kind of event in the past, and with increasingly devastating consequences (Enel, 2021).

The greatest damage is being caused, above all, by the consumption of coal, oil and gas, which are responsible for most greenhouse gases. According to McKinsey's Global Energy Perspective 2019, fossil energy sources in 2019 accounted for 83% of total CO_2 emissions, while coal-fired electricity generation alone accounted for 36%26, although in 2020—as a result of the Covid-19 pandemic—emissions then plummeted (McKinsey, 2019).

It has been estimated that the current rate of CO_2 emissions from coal combustion is responsible for about one third of the $1\,°C$ increase in annual average temperatures on pre-industrial levels, making it the number one source of emissions in human history. Oil is the second biggest source of emissions by far, having produced 12.54 billion tonnes of CO_2 in 2019 (86% of that produced by coal).

There is also a political issue surrounding fossil fuel at the moment, since the recent tensions over Ukraine could put 155 billion cubic metres a year of natural gas imports into Europe at risk—tensions due to Russia cutting supplies—amounting to 30% of Western Europe's annual gas demand (Rystad, 2020).

European gas markets have been plunged into great instability, gas stocks are at a five-year low, and international prices are highly volatile. These are just some data showing how important it is to define development scenarios based not just on renewable energy—wind, solar (thermal and photovoltaic), hydro, geothermal and biomass power—as a fundamental alternative to fossil fuels.

Their use enables a reduction not just in greenhouse gas emissions resulting from the generation and consumption of power, but also in our dependence on fossil fuel

imports (especially gas and oil), hence improving Italy's position from the standpoint of energy resource procurement, a crucial point for the economy in general and an essential factor in manufacturing when it comes to competitiveness.

To achieve the ambitious EU-defined goal of renewable energy accounting for a 20% share of its energy mix, efforts thus also need to be stepped up in energy-related sectors in terms of production systems and innovative products. More specifically, some of the open challenges for manufacturing concern:

- Supporting the hydrogen value chain through the development of innovative technologies, such as the production of high-power-density, high-efficiency turbines, and processes for the use of combined heat and power fuel cells;
- Technologies for decarbonising of CO_2-emitting processes through the production of Carbon Capture, Utilization and Storage systems.
- Technologies and systems for fossil fuel conversion aimed at achieving efficient, environmentally neutral and flexible systems (to be better suited to compensate for the variability and uncertainty of renewable sources);
- Promoting greater efficiency in manufacturing plants that, for the same energy source, are capable of optimizing its use through appropriate resource and usage time management mechanisms, possibly with the implementation of demand response models for power usage management;
- Designing long-lasting products that use less power during their life cycle; environmentally and energy-efficient products;
- Developing technologies and products for the energy sector, such as components for wind turbines, mini wind generators, technologies for harnessing marine resources, advanced components for solar panels and production of biomass energy;
- New circular economy mechanisms for energy products, such as: recycling solar panels; strategies and technologies for the reuse of electrochemical energy storage systems; systems for the regeneration of electric/hybrid vehicle batteries, which can also be used to power infrastructure; development of technologies and techniques for the management of distributed storage/reserve capacity for power grid and private consumption ancillary services, exploiting electric and hybrid vehicle storage batteries;
- The promotion and development of end-use technologies is deemed necessary: these include fuel cell technologies, capable of operating at different temperatures and hence applicable to different sectors, from the mobility sector to stationary, industrial, residential and commercial applications, with high efficiencies.

Italy should invest in systems of this kind as they boost research excellence spanning from the laboratories of public bodies and universities to the industrial sphere. This will change the economy of whole regions, prompting the rise of new manufacturing hubs linked to new energy sources and more efficient use of energy. Moreover, a larger amount of green energy will be produced and supplied, which will probably see a scaling back of the strategic roles of some players in the supply of energy, such as the Middle East and Russia.

The expected impact of the scenario on R&D activities is predominantly linked to the necessity for investments in both structural and technological aspects, with a medium to long term impact.

This scenario should be studied from the point of view of the following action lines:

LI2: Industrial sustainability,

LI4: High-efficiency manufacturing,

LI5: Innovative production processes,

LI7: Digital platforms, modelling, AI, security.

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Strategic Action Line LI1: Personalised Production

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Abstract The objective of this chapter is to describe the action line related to Personalised production (LI1). In particular, this chapter proposes research and innovation priorities aimed at promoting industrial systems and models for the efficient manufacture of customized products that can be reconfigured with fast turnarounds to meet specific requests fielded from individual customers or small groups, and that deliver a high level of integration with the customers in order to ensure they become the main actors of the resulting solution. These design and production systems must be conceived to have the capacity to be reconfigured for the manufacture of products that can be required in certain times of emergency (such as health emergencies) or in response to events that can cause a sudden shift in system priorities and require the industrial system to transfer its focus to different categories of products to those usually made. In this action line, it is important to research new supply chain management models and local manufacturing models as well as smart materials.

Keywords Personalised production · Design · Configuration · Supply chain · Smart materials

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1　Introduction

In recent years, the capability to provide consumers and clients with personalised products that meet their specific needs on a large scale, thanks to high levels of flexibility in the production system, has emerged as one of the strategies that can enable to differentiate business offer through high value-added innovative products (Seitz et al., 2020; Aheleroff et al., 2019; Martinelli and Tunisini, 2019). With regard to consumer goods (clothing, footwear, sports items, eyewear, etc.) an approach based on a high level of customisation (i.e. personalisation) helps emphasizing the strength of *Made in Italy* since it provides consumers with a product that combines design and style, with advantages in terms of both functions and comfort (Macchion et al., 2019; He et al., 2022). Other relevant sectors such as the medical one (with personalised prostheses in the orthopaedic, dental and other fields), and production of durable goods in general (in industrial design, automotive and manufacturing sectors overall) can benefit from this approach by seizing the opportunities and challenges arising from a growing demand, both at European level and worldwide, for products that differ in value, functionality and performance (Trenfield et al., 2019; Siiskonen et al. 2020).

The objective of this strategic action line is to study and develop industrial systems and models for an efficient production of personalised products to meet the specific requirements of individual clients and ensure a high degree of integration that can make the clients themselves active players of the developed solutions.

Such design and production systems should be design and developed in a reconfigurable way in order to manufacture specific products needed at times of particular emergency (such as health emergencies) or in the aftermath of disruptive events that can suddenly change the system's priorities and require the industrial system to reposition on product ranges other than the usual (Fig. 1).

To this end, specific models and tools will need to be developed, using technologies that are versatile from both a manufacturing point of view (such as additive manufacturing, micro-processing), and digital point of view (such as artificial intelligence, IoT, Big Data), to exploit the knowledge of the specific context through an integrated approach to the design, production, validation and management of products and services (such as design tools that can promptly generate design alternatives).

Priority research and innovation topics depend on the different development aspects and include digital solutions for the acquisition of customers' requirements, product configurators, advanced measurement systems, consumer-monitoring platforms, and innovative customised-production technologies, such as additive manufacturing, micro-manufacturing, hybrid processes, etc. New flexible and agile supply chain models are also needed, to take into account product modularization, postponement and "multi decoupling-point" strategies with a view to personalisation.

Prerequisites for personalised production systems are cyber security, privacy protection and the availability of platforms for data storage and traceability of information. The digital architectures shall be designed to foster the advancement of

Fig. 1 Strategic Action Line 1—Personalised production

interoperability standards and to promote the integration of the different IT systems available in the production and distribution chain.

The solutions identified should be geared towards eco-compatibility criteria, with a view to controlling environmental impact, like in mass production (in particular, for consumer goods such as footwear, clothing, etc.), fostering production systems to reduce processing and manufacturing waste generation to a minimum.

Expected impact: increasing offer of personalised solutions in various manufacturing sectors; improvement of end product quality; improved matching of consumer needs and proposed solutions; increase in the efficiency and adaptability of customized production systems; optimization of customization processes through an improved control of waste levels and use of resources (such as set up times, production queues, scraps); management of logistics processes with control of procurement and production lead times along the entire supply chain thanks to the interoperability and transparency of processes; models and tools for decentralized production; reduction in the cost of the personalised product/service (compared to the current cost of manufacturing a personalised product).

2 PRI1.1: Advanced Tools for Configuration and Design of Personalised Solutions

Customers can be effectively integrated into the production chain through the identification and correct interpretation of their individual requirements during the design phase. The tools must be targeted at gathering customers' requirements and correctly using them to deliver an optimized concept and design for individual and specific

products (Tan et al., 2022; Hara et al., 2019). There is, therefore, a primary need for tools that enable customers to communicate their ideas and/or requirements in a simple way, without demanding specific knowledge and/or posing cultural and linguistic restrictions. The ability to orchestrate properly the innovation phase of a product or service in a multidisciplinary environment involving many players that interact in a virtual way becomes of fundamental importance (Reinhart et al., 2010). Furthermore, the growing demand for possible product variants increases the importance for companies to predict the impact of design choices on all aspects of their production cycle (e.g. product functionality, manufacturability and production costs), distribution, use and disposal/recycling. The ability to exploit the specific knowledge of the context in which a product will be used thanks to artificial intelligence technologies becomes fundamental for the creation of efficient tools, in particular for those types of products created to meet specific requirements that can impact on the functionality of the product itself (e.g. bio-medical products).

The goals of this research and innovation priority are therefore:

- Development of "multi-user" collaborative design platforms that enable the interaction of all the different players involved in the production process (designers, end users, producers, suppliers of materials and components). These platforms must be based on sharing knowledge to predict systems' behaviour and improve modelling and simulation, offering and integrating easy-to-use solutions and more efficient test and validation methods. In particular, it includes:
- Automated and creative design systems to facilitate the design of product alternatives;
- Design systems with embedded tools for the assessment of the feasibility and product-costing;
- Configuration tools that can successfully integrate the identified customer requirements;
- Geometric processing and analysis methods to integrate design and simulation in a consistent way and maximize the advantage of using specific production technologies.
- Development of "mobile" platforms that, by using artificial intelligence and big data analytics, can support the collection of both users' requirements (directly and indirectly expressed), and feedback from the field during product usage, and at the same time facilitate the identification of market trends. Specifically, it includes:
- Data Capturing systems for the acquisition and analysis of heterogeneous data from different sources (such as social media, feedback during the use phase of a product, etc.);
- Systems for storing and managing large amounts of "personal" data obtained from widely used applications, protected and made available to consumers, to be used during personalisation process.
- Development of **innovative virtual and collaborative design platforms** (based on AI, VR/AR technologies) intended for non-expert users; such platforms should not require specific knowledge or design skill but rather support the user in

expressing or detecting in a natural and easy way their specific requirements. In particular, these solutions should be based on:

- Emerging Human–Computer Interaction-HCI technologies (e.g. visual, tactile, sound) for easy and natural interaction;
- 3D modelling representations suitable to manage multidimensional heterogeneous data (i.e. images, 3D geometry);
- Systems based on the principles of the Internet of Actions (IoA) to allow the user (consumer, retailer, manufacturer) to act remotely and reproduce sensations and actions in an interactive and adaptive way. It is thus possible for expert and non-expert operators to interact remotely. The development of new sensors and actuators will be essential in creating the perception of being present when working/acting from remote, and in ensuring accurate and safe remote actions.
- Development of **tools and methods for the creation of structured product models** starting from the collected data based on context semantics and geared to overcome the limits of 3D reconstruction due to the lack of effective integration between detected data and knowledge of the reference domain (for instance, in models of anatomical parts for the construction of personalised prostheses the limit is represented by the incomplete integration of medical knowledge).Specifically, it includes::
- 3D reconstruction methods guided by semantics of the context
- Systems for managing feedback on wearable products (IOT) to test products' functionality during use.

Interaction with Other Strategic Action Lines

- LI4—Product design for customisation should be aligned with process design and efficiency
- LI6—Product design for customisation should be aligned with process design to support product reconfigurability
- LI7—The management of big data related to customisation is essential in managing inputs from products, customers and the market, just as cyber-security aspects are in the management of data.

Time Horizon

Short-term goals (2–3 years):

- Development of capturing systems for the acquisition and analysis of heterogeneous data;
- Development of systems for storing and managing large amounts of "personal" data obtained from widely used applications, protected and made available to consumers, to be used in the personalisation process.

Medium-term goals (4–6 years):

- Development of automated and creative design systems to rapidly produce design alternatives;
- Development of design tools integrated with feasibility assessment and product costing tools;
- Development of configuration optimization tools that can successfully integrate specific requirements;
- Definition of geometric processing and analysis methods to integrate design and simulation in a consistent way and maximize the advantage of using specific production technologies;
- Development of systems based on emerging Human–Computer Interaction-HCI technologies (e.g. visual, tactile, sound technologies) for easy and natural interaction;
- Definition of new representations for 3D modelling suitable to manage multidimensional heterogeneous data (i.e. images, 3D geometry);
- 3D reconstruction methods guided by semantics of the context;
- Development of systems for managing feedback on wearable products (IOT) to test products' functionality during use.

3   PRI1.2: Solutions for the Efficient Production of High Value Personalised Products

Personalised products require modular, flexible and adaptable production systems, i.e. adapting and reconfiguring themselves according to the features required from time to time by the customer, without losing efficiency and product quality, in accordance with the emerging production paradigms of "Zero-waste and Zero Defect manufacturing", focusing on product quality and efficient use of resources.

Production systems heading in this direction already exist but the amount of alternatives required by personalisation is constantly increasing and must ensure that resources can be used efficiently and adapted to such needs. A high level of customisation (personalisation) also requires production phases to be synchronized with the product design, and with the logistics for handling the parts, so that information can be moved from one phase to another in a flexible and reliable manner (Medini et al., 2019). It is therefore necessary to study new reconfigurable systems and new plug-and-produce devices capable of guaranteeing a rapid response to frequent changes in customers' requirements and unit batches as well (Plasch et al., 2012).

These new paradigms carry along a strong integration between production and logistics systems at shop floor level. New digital models, algorithms and self-adaptive autonomous technologies need to be developed to ensure real-time planning and control of reconfigurable production and logistics systems, reducing reconfiguration and downtime (Medini et al., 2019; Keiningham et al., 2020; Zhang et al., 2019).

The goals of this research and innovation priority are:

- Reconfigurable production systems dedicated to both B2B and B2C **personalisation** for the production of components and products **very often characterized by dynamic properties and behaviours, differentiated in response to the needs and requirements of the consumer**. In particular, these solutions must be supported by innovative approaches to the production process and its control, in order to transform the project into a product that has the appropriate mechanical and functional characteristics according to user needs. In this context, the hybridization of traditional technologies (i.e. hybrid/additive), that is the integration of different production processes into a single machine, is a step towards a potentially very broad diversification of technological alternatives.
- **Manufacturing technologies for products with complex geometries** and high surface finishes, combining different materials and a progressive variation of properties in the various areas of the production process.
- Solutions for **modularity** and **reconfigurability** of manufacturing lines: such solutions should be supported by **flexible "plug & produce" modules** that can be applied on machines built by different manufacturers. In particular, the development of production platforms that allow the automatic integration of production modules for customized components with those for standard components (tooling/production line set-up) in order to guarantee various functions such as: the integration of modules equipped with controllers with different degrees of intelligence; product changeover; the management of demand fluctuation and its impacts on the production system; the removal and/or integration of modules in real time. In addition, modular self-adjusting and self-adapting systems of a plug-and-produce type, based on digital models and artificial intelligence can help to promptly react to frequent changes in customer orders and to the high variability of demand.
- **Procurement/storage/handling systems that are tailored to the increased variability of shapes, sizes, weight and materials** required by the wide range of different raw materials, semi-finished and finished products necessary for the goods personalisation. The adoption of advanced sensor systems is required, for instance, for the tracking of products in batch-1, for the automatic creation of assembly kits, visual inspection systems for the assembly kits control even with customized and unitary batch.

Interaction with Other Strategic Action Lines

LI4—High efficiency integrated systems: a reconfigurable internal production and logistics system must guarantee high efficiency even in contexts of high level of product personalisation.

LI5—Innovative production processes: reconfigurability and high flexibility production systems can be achieved through intelligent machines and handling systems.

LI6 and LI7—An efficient production of personalised and high value-added products can be obtained by controlling reconfigurable production systems, Digital

Twin solutions, implementation of Human Robot Co-working and applications of AI algorithms.

Time Horizon

Short-term goals (2–3 years) that are pursued starting from existing technologies:

- Improving the surface finish in product manufacturing through additive manufacturing and increasing the productivity of hybrid machines for additive manufacturing up to the levels of mass production systems;
- Easily integrate, exchange, or remove production equipment without the need for specialized personnel to reconfigure the system, through advanced Plug and Produce technologies.

Medium-term goals (4–6 years) that involve significant development:

- Development of integrated frameworks (from end-user design to product delivery) that can ensure a time to market ranging from 24–48 h;
- Innovative technologies for handling soft and flexible materials such as gripping, moving, positioning, sorting, joining processes, in order to include these handling solutions in flexible production processes;
- Intelligent manufacturing and handling solutions that can adapt themselves to the product characteristics (in terms of size, shape, weight, colour, material composition, defects, etc.).

Long-term goals (7–10 years) that require the integration of all the technologies developed as a result of a research and innovation priority:

- Digital Twin platforms for customized and resilient productions.

4   PRI1.3: Advanced solutions for customer-driven production management

From a technological point of view, it is essential that demand-driven production is synchronized with the customer order management, with scheduling and production, through a coordinated management of material and information flows. It is also necessary to coordinate production with internal and external logistics through appropriate models for integrating information that comes from different sources.

In order to achieve these objectives, new management systems must be developed, based on technologies such as Big Data Analytics, Artificial Intelligence and decision-supporting models geared to increase the companies' ability to manage and use large amounts of data from different sources (customer, suppliers, social networks) to allow better production management, dynamic supply and distribution networks.

The use of big data technology also allows the activation of blockchain processes that guarantee the integrity of the transferred data. In addition, greater interoperability, transparency and autonomy in the product life cycle through the use of resources and value-added services is desirable.

In this context, goals of this research and innovation priority are:

- **Collaborative platforms** development: through appropriate knowledge sharing systems at different levels of the value chain these platforms can support decisions such as: dynamic network configuration, decentralized planning of activities, real-time management of independent and reconfigurable production systems, product modularization strategies, postponement strategies and "multi decoupling-point". These platforms must be able to manage key elements such as demand variability, specific personalisation characteristics within product families, economy-of-scale, service capacity, and the trade-off between the decentralization of production (global integration) and the local manufacturing of some of the components needed in personalisation. These collaboration platforms must guarantee high levels of interoperability between different information management systems.
- **Production and logistics control and monitoring tools for managing disruptive events**: tools based on the data collected in real time from different sources (machinery, products, suppliers, handling systems). These tools allow company manager the detection of critical issues and definition of response policies to any uncontrolled processes, through solutions capable of "mediating" on different products, processes or services and capable of operating with small batches, even down to one. It is necessary to be able to track the status of each resource in real time, in order to implement specific actions (process parameters, replacement and maintenance policies) and react promptly to unexpected events. Furthermore, the possibility to provide real-time data to check the resources and process status will allow the development of new approaches for the certification of the personalised product for anti-counterfeiting purposes and for the certification of production process, particularly in highly regulated sectors such as biomedical and aerospace. These tools will have to operate according to the paradigms of interoperability, transparency and autonomy.
- **Models and methods for the validation and certification of information for the design, production and distribution of personalised products**. Such systems must enable decentralized interaction in the production chain, ensuring the coordination of actions and supporting the collection and sharing of data through synchronization even in very dispersed and broad contexts from a trust-management perspective.
- **Digital Twin platforms** capable of integrating suppliers and users in a transparent and efficient manner. Such systems should also allow the real-time management of autonomous systems, which ought to be self-adapting and self-organizing in keeping with paradigms of interoperability, transparency and autonomy.

Interaction with Other Strategic Action Lines

LI4—Production planning and management require high-efficiency integrated systems, especially where considerable product personalisation is required.

LI5—The management of internal and external logistics to ensure reconfigurability and flexibility needs innovative and "smart" production processes.

LI6 and LI7—Digital Twin solutions and AI algorithm applications can ensure efficient management of the supply chain of high value-added personalised products.

Time Horizon

Short-term goals (2–3 years) that are pursued starting from existing technologies:

- Development of models to formalize and connect the design, production and distribution requirements of personalised products;
- Development of systems to share data collected from the field (e.g. distributed ledger technology) with production management systems and vice versa.

Medium-term goals (4–6 years) that entail significant development:

- Greater extension of End-to-End Engineering through the design of systems for the reconfigurability of a product's dynamic requirements.

Long-term goals (7–10 years) that require the integration of all the technologies developed as a result of the research and innovation priority:

- Design and develop Digital Twin platforms to integrae material and information flows between suppliers and users transparently and efficiently;
- Digital Twin tools that allow the real-time management of autonomous systems, which are self-adapting and self-organizing according to the following paradigms: interoperability, transparency and autonomy.

5 PRI1.4: Mini-Factories in the Production and Distribution Chain of Personalised Products

Small-scale distributed production becomes increasingly important in different sectors and in different situations (such as in a health crisis when it is necessary to quickly produce basic necessities with limitations deriving, for example, from the closure of national and regional borders) and is based on the structuring of production facilities with very fast set-up and decommissioning times and easily transferable to different locations (real mini-plants, fab-labs, production in containers).

It is thus possible to ensure that part of the production and in particular the manufacturing of personalised parts/components is postponed to the last mile and carried out near the place of delivery and use of the objects.

It is therefore necessary to define new organizational models based, in accordance with the *urban manufacturing* paradigm, on the creation of laboratories and mini-factories equipped with advanced machinery that support the production of personalized products quickly and at low cost. The new organizational model must include the use of technology highly reconfigurable and adaptable to the specific context and the revision of the collaboration model upstream with suppliers and downstream with users to redefine the flow of operations.

The possibility of operating locally (neighbourhood, municipality, region) with dedicated mini-factories, in addition to reducing logistics costs, can extend the scope of application of "customized" recycling technologies that would otherwise be too expensive and thus meet to the growing demand for customization in the repair/reuse of end-of-life products.

The mini-factory model can constitute the connection between (Do-it-yourself) makers and industrial companies and give rise to new functionalities and innovative production methods (new processes, new machines, low-cost ideas, etc.).

The goals of this research and innovation priority are therefore:

- **Simplified, easily transportable and low-cost set-up machinery for the on-site production of dedicated products,** or for the functionalization/customization of products, or for disassembly (modular factory—factory on truck, etc.) purposes. In particular, development of new production technologies that are very versatile in terms of geometries and materials in order to obtain a large set of components with multiple functions with a limited set of machinery.
- **Innovative production chain management models based on the study of decentralized production centres to bring personalisation to the last mile.** New production models integrated with distribution, that allow the delivery of raw materials and small batches of products in urban contexts (mini factories served as consumers—use of e-commerce systems) even with the use of adequate self-driving vehicles that can circulate in difficult environments with low carbon emission.
- **Multi-user collaboration platforms for the design, manufacturing and distribution of products and related components, based on open innovation principles that integrate mini-factories.** This also implies the definition of new IP sharing mechanisms, in order to guarantee rewarding systems for new types of business.
- New **service centre** models to provide temporary solutions (rental) consisting of autonomous mini-factories, in order to facilitate the access of new innovative players (makers, small businesses, etc.). These service centres should also ensure integration between different mini-factories for the production of components and products of different types by means of design and production systems that allow the sharing of resources and materials.

Interaction with Other Strategic Action Lines

This priority is closely linked to the LI5 line of intervention and in particular to the development of low cost and high productivity multimaterial additive technologies (for local "real time" production of personalised products/components).

Time Horizon

Short-term goals (2–3 years) that are pursued starting from existing technologies:

- Development of multi-user collaboration platforms for the design, production and distribution of personalised products and related components, based on open innovation principles (Distributed Design Platform);
- Development of simplified, transportable and low cost set-up machinery (integrated, ultra-fast, self-configurable and user-friendly systems).

Medium-term goals (4–6 years) that entail significant development:

- New production models integrated with distribution, which allow the delivery of raw materials and small batches of products in urban contexts (mini-factories served as consumers);
- Development of new models of service centres to provide temporary (rental) solutions of autonomous mini-factories to facilitate the access of new players (makers, small businesses, etc.).

Long-term goals (7–10 years) that require the integration of all the technologies developed as a result of the research and innovation priority:

- Integration in a single supply chain of the four previous objectives.

6 PRI1.5: Production Systems of Smart Materials for Product/service Personalisation

This research and innovation priority focuses on technologies and processes for the production of innovative and intelligent materials (e.g. sensorized fabrics, display materials, micro- and nano-materials, multifunctional fabrics, materials for biomedical use, high-performance renewable materials) that can produce in line with the specific consumer needs or can perform a function based on the adaptive capacity of the material itself (i.e. that can work as sensors by capturing changes in parameters and at the same time as actuators by performing an action). To achieve this goal, the new production systems should produce components made of homogeneous materials (to be easily recyclable and based on the intrinsic active properties of the material, such as shape memory materials, photosensitive, magnetostrictive materials, etc.) or components with engineered morphological structures (lattice structures, multiscale, with gradient, micro-kinematics, etc.) or composite structures or materials.

The ability to integrate a device with sensor capabilities that can equip it with intrinsic intelligence is also of utmost importance. Examples include Lab-on-chip with integrated biosensors for precision medicine and mechanical devices that can monitor external parameters related to the work environment or the device's internal parameters (such as fatigue, critical situations of dysfunctionality, etc.).

The goals of this research and innovation priority are therefore:

- **Production systems that aim at integrating "smart" functions directly during the manufacturing process** (on line), that is production systems that can directly manage materials with smart functions or assign functions to the components downstream the production process
- **3D printing or multi-material additive systems,** that is additive systems that can manage multiple materials at the same time, geared at producing functional devices with property gradient and additive systems that provide the product with smart functionalities during the manufacturing process (even achieving non-constant functionalities in the final device)
- **Components with engineered and "customizable" morphological structures** (latex, multiscale, gradient, micro-kinematic structures, etc.): composite structures or materials that can make use of such engineering in the manufacturing of components with high functional performance and easy personalisation.
- Innovative production technologies for the **manufacturing of intelligent micro-devices**, including devices with sensor capabilities, such as for example lab-on-chip with integrated biosensors for precision medicine or mechanical devices that can monitor external parameters and parameters related to the work environment and device's internal parameters (such as fatigue, critical situations of non-functionality, etc.).

Interaction with Other Strategic Action Lines

Connection with the PRI5.5 of action line LI5, which deals with the production and manufacturing processes of innovative materials.

Time Horizon

Short-term goals:

- Development of design tools for engineered morphological structures;

Medium-term goals:

- Development of production systems based on the use of smart materials and with high geometric flexibility (4D printing);
- Development of design tools for active structures.

Medium-long term goals:

- Development of innovative production technologies for the manufacturing of bioengineered Lab-on-chip micro-devices with integrated biosensors for precision medicine.

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Strategic Action Line LI2: Industrial Sustainability

Melissa DeMartini, Marcello Colledani, Nicoletta Picone, Grazia Barberio, and Mauro Parrini

Abstract Over the past 20 years, sustainability has become a central issue on the manufacturing and political agenda, and it has recently grown in importance in light of increasingly powerful and devastating climate events. In this chapter, a strategic action line to support companies is proposed to implement industrial sustainability (LI2) by means of strategies, methods and tools to implement sustainable production processes at an environmental, economic and social level, reducing dependence on the external supply of critical production resources or on resources penalized by the laws in force. Priority research actions proposed concern new solutions to reduce noxious or polluting emissions from production processes; methods and techniques for strategic product-process evaluation from a Life-Cycle-Thinking perspective; technologies and processes for the reuse, re-manufacturing and recycling of products, components and materials from used products or maintenance processes; systems and methods for measuring and implementing Sustainable Supply Chains and Closed-Loop Supply Chains.

Keywords Industrial sustainability · Design · Raw materials · Circular economy

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1   Introduction

Over the past 20 years, sustainability has become a central issue on the manufacturing and political agenda, and has recently grown in importance in light of increasingly powerful and devastating climate events. Against this background, industrial sustainability plays a fundamental role in responding to environmental, social, and economic challenges and transforming the Italian manufacturing sector.

Not only can the industry reduce its environmental impact, but it can also manufacture products that, on the one hand, solve various environmental problems and, on the other, have a limited impact during their life cycle.

This requires raising awareness on the need to transform industrial processes and conceive new products with a view to a circular economy to significantly reduce carbon emissions and improve energy efficiency, reduce, and rationalize water consumption, foster and promote resource recovery. In a circular economy, there are two types of material flows: biological, suitable to re-enter the biosphere, and technical, intended to be reused without entering the biosphere. In line with this vision, all the activities carried out in the industrial system, starting from extraction and production, must be organized in such a way that the waste produced by one sector can, after appropriate transformations, become a resource for others. In addition to material recovery, recovery of a product's functions is also very promising, as it makes it possible not only to recycle raw materials but also to avoid losing the value of the activities carried out to transform the material into a product. These changes require the introduction of new processes, new machines, and new systems, creating an in-depth review of the domestic production base, and laying the foundations for new capital goods markets in which Italy may assume a leadership role.

These systems should be consistent with the evolution of markets and enabling technologies, using technology as a competitive lever with respect to the three dimensions of sustainability (economic, environmental, and social). In this new perspective, the role of the manufacturing industry is fundamental towards the implementation of a circular factory concept. The manufacturer can design products that can be disassembled after use, integrating an increasingly larger fraction of secondary raw materials. In addition, it can manage product information along the value chain with a view to improving the efficiency of component and material recovery after the use phase, thus increasing value for money in reusing them.

In this context, the issue of "de-and re-remanufacturing" is gaining ground, because of the increase in the cost of raw materials and the specific laws introduced by the European Union, which require an improvement in the recovery rate of materials. Furthermore, critical raw materials and primary resources are increasingly scarce (e.g., water) or more expensive (e.g., energy), and their current use levels are no longer sustainable. The demand for critical raw materials in the manufacturing of high-tech products is constantly increasing in Europe, their procurement causing major economic and strategic problems. It is therefore necessary to study how to use electronic waste as a source of rare materials for new technologically advanced products (Fig. 1).

Fig. 1 Strategic Action Line 2 -Industrial Sustainability

The Importance of a rational use of energy and water resources that are essential for various production processes should also be emphasized, through the promotion of practices aimed at an efficient use of these resources, reduction of consumption, reuse, and optimization of residual flows with a view to closing the cycles and recovering resources, for example from thermal flows, wastewater and sludge generated from their treatment.

In Italy, this line of intervention is aimed at the study and development of strategies, methods, and tools to implement more sustainable production processes at an environmental, economic and social level, reducing dependence on the external supply of critical production resources or on resources penalized by the laws in force. Priority research actions in this sector mainly concern new solutions to reduce noxious or polluting emissions from production processes; methods and techniques for strategic product-process evaluation from a Life-Cycle-Thinking perspective; technologies and processes for the reuse, re-manufacturing and recycling of products, components and materials from used products or maintenance processes; systems and methods for measuring and implementing "Sustainable Supply Chains" or "Closed-Loop Supply Chains".

To encourage the change described above, it is therefore necessary to:

- promote the development of an industrial system that can implement circular economy solutions;
- enable better understanding of how sustainability can change the planning process in manufacturing firms;
- determine what changes are required at a firm's level, to improve sustainability performance;
- identify the system-level changes required to increase sustainability;

- activate company-level experimentation through new business models and improve the ability of the industrial sector to systematically act towards the implementation of a circular economy.

Expected impact of the strategic action line: minimization of the environmental impact of manufacturing with specific focus on increasing the efficiency of natural and energy resources; control and minimization of the environmental footprint at the level of the entire product/process/system life cycle; creation of value in cross-sectoral supply chains; improved ability to recover secondary raw materials and recover the functionality of products; improved recovery and valorisation of waste; improved ability to recover products and transform waste into inputs thanks to industrial symbiosis models.

The research and innovation priorities of the strategic action line on Industrial Sustainability are:

PRI2.1—Design and development from a life-cycle thinking perspective.

PRI2.2—Monitoring of the environmental footprint of products.

PRI2.3—Systems for secondary raw materials.

PRI2.4—Technologies, processes and tools for the reuse, re-manufacturing and recycling of products, components, and materials.

PRI2.5—Modelling and simulation for the Sustainable supply chain.

PRI2.6—Models and tools for "Circular Economy".

2 PRI2.1. Design and Development from a Life-Cycle-Thinking Perspective

Product complexity has increased in several respects, due to the expanding use of innovative materials, materials with key functions and combinations of different types of components. The technological difficulty of separating the various product components limits the development of circular economy strategies, which involve repairing, updating, and remanufacturing to prevent the waste of the precious resources contained in those products.

In this context, the design and development of products from a life-cycle-thinking perspective is one of the key issues of circular economy.

Therefore, it is of strategic importance to consider, from as early as a product's design phase, the use of recycled materials or components that can be reused after their first use phase, in line with the business alternatives offered by circular economy. The goals of this research and innovation priority are related to:

1. Tools for the analysis and design of product functions from an eco-design, design-for-environment (DFE) perspective to develop innovative products with a view to exploiting the multifunctionality of a product and its components. Applying principles of Eco-design, Design for Environment (DFE) will help design sustainable products that use fewer resources, materials, components and that can be reused or re-manufactured after their end of life;

2. Integration of advanced tools of Life Cycle Environmental Cost Analysis (LCECA), Life Cycle Cost (LCC) and Life Cycle Analysis (LCA) to enable the quantification of the potential environmental impact of designed products (in terms of resource consumption, waste and emissions) from as early as their design phase integrating these information into PLM systems;
3. Design tools with appropriate functionalities to facilitate the development of modular and repairable/upgradeable products designed for multiple use cycles and suitable to respond to evolving customer requirements, through subsequent upgrades of functions and components during the product's life; such tools should also optimize, for instance, the use of contaminants, which could be subject to limitations and prohibitions over time, support the design of product and service systems in a circularity perspective, i.e. based on production-use-repair cycles, reconfiguration, reconditioning, recycling.

Interaction with Other Strategic Action Lines

PRI2.4—Technologies, processes and tools for the reuse, de- and re-manufacturing and recycling of products, components and materials.

Time Horizon

Short-term goals (2–3 years):

- use of simplified LCA, LCECA, LCC tools to design products according to the principles of eco-design and circular economy.

Medium-term goals (4–6 years):

- definition of product design techniques to promote energy and water efficiency, the integration of recycled materials or re-generable components.
- design solutions to facilitate the development of modular and repairable/upgradeable products designed for multiple use cycles.

Long-term goals (7–10 years):

- design solutions for upgradeable products through multiple use cycles to respond to evolving market requirements.

3 PRI2.2. Monitoring of the Environmental Footprint of Products and Processes

The identification and monitoring of the environmental footprint of products and processes are fundamental in providing with a choice-evaluation element the stakeholders involved in a product life cycle (like consumers, entrepreneurs, and policy makers), especially in view of the ambitious strategies and objectives at European

level for the next few years (e.g., "Energy Roadmap 2050", "2030 EU Climate and Energy framework"). One of the problems consists in the unavailability of a complete, uniform, updated and available data set for the entire industrial sector and the complexity of modelling particular processes to monitor all its phases. The goals of this research and innovation priority can be grouped in different categories:

- **Tools and methodologies to configure sensorized systems for the monitoring and control of the environmental impact with a greenfield and brownfield perspective** (considering machine revamping). Sensor connectivity allows the operation of the Internet of Things (IoT) and the cyber-physical systems (CPS) in which objects and machines interact with each other and with the physical world. These technologies require research and development to help control carbon emissions, energy, water, and material consumption processes, by monitoring production systems and environmental conditions. This opens up new opportunities for companies to assess system production performance more effectively, including in a perspective of LCA systems application.
- **Tools and methodologies for monitoring and controlling energy and environmental consumption and emissions during the product use phase**: recent advances in digital tracking and traceability technologies, such as digital identifiers, physical markers, or sensors, offer opportunities to capture post dynamics—sales at product, component, and raw material level. New systems are to be studied to store information on product composition and disassembly instructions and track changes to product conditions on PLCs using digital formats. Furthermore, it is necessary to study data integration models through new data acquisition systems from different sources (shopfloor, machines, products etc.), and which allow the integration of such data within tools such as LCA and LCC with the aim of analysing specific sectors, products and processes that have a specific interest in tracking the energy and environmental footprint of the entire supply chain.
- **Analysis models** that, connected to plant sensors and management systems, can acquire and handle process, consumption, and emissions data to provide dynamic product and process LCAs. The goal should be to have homogeneous production batches with a certified LCA.

Interaction with Other Strategic Action Lines

- PRI2.1. Integration of design and development processes in a life-cycle-thinking perspective: identification of useful indicators for LCC and LCA analyses whose parameters (in full or in part) would be monitored within the activities dealt with in PRI2.2.
- PRI6.2 Components, sensors, and intelligent machines for adaptive and evolutionary manufacturing: The objective of PRI6.2 is to obtain greater flexibility and adaptability of the machines in the face of changes in set-up and production, to ensure process continuity and adapt to the growing need for product customization. The PRI 2.2 is largely based on the monitoring of operational parameters that are affected by production set-up and context.

- PRI7.3 Models and tools for monitoring production and managing production assets.
- PRI7.4 IioT models and tools for factory data management: With regard to priority 7.4, an important synergy can be created by integrating technologies for the generation (micro sensors and connected MEMS), collection, processing, integration and sharing of raw data from the field, to improve productivity.

Time Horizon

Short-term goals (2–3 years):

- Configuration of sensorized systems to support the monitoring and control of the environmental impact from a greenfield and brownfield perspective.

Medium-term goals (4–6 years):

- Methodologies to define the optimal configuration of integrated sensor systems.
- Integration of the automated traceability of environmental impact data with product and process parameters, in order to produce models and indicators that can always better describe the broader and more complex concept of sustainability also from an LCA perspective.

4   PRI2.3 Systems for Secondary Raw Materials

Today, Secondary Raw Materials (SRMs) are few, scarcely available and tend to be more expensive than "traditional" raw materials. This lack of choice, availability and price competitiveness is the first major obstacle to their diffusion and their use on an industrial scale. Furthermore, the properties and volumes of SRMs are often difficult to predict, poorly repeatable and not suitable for large-scale industrial applications. To date, no competition is possible on large numbers with traditional raw materials, due to their scarce availability, competitiveness, and performance repeatability. Most of the industrial efforts conducted to date have focused on scale economies and the optimization of production processes that assume an enormous availability of basic raw materials of the same quality over time.

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

- **Production systems for SRMs:** these systems should help increase production in terms of flow stability, quantity, quality, competitiveness (i.e., price/performance ratio) and their use in high value product manufacturing. There is not as much of a need to replace the raw materials' production processes currently in use as to support them with new, more flexible, robust, and controlled processes that guarantee repeatable outputs and quality levels in compliance with the specifications even if they contain SRMs, and as to use tools to promote industrial symbiosis processes for a simple and systematic exchange of resources. This challenge therefore requires thinking in terms of integration about the characteristics of the products, of the production processes that transform the mix of raw and secondary

materials into finished products, and of the systems that must implement these processes. The most advanced zero-defect manufacturing and industry 4.0 techniques can be extremely useful in providing current manufacturing systems with the soundness and flexibility required for this purpose.

- **Development of systems to facilitate the acquisition, maintenance and transfer of information relating to the quality of SRMs** with a cross-sectoral approach, to attain certification levels for the properties of these materials that are comparable with those of raw materials.
- **Innovative solutions and products based on SRMs for sustainable materials and processes**. Development of new materials or advanced solutions based on industrial waste, creation of synergies for the development of new materials created, for example, from the recycling of glass, fibres, or construction products. The goal is to develop a new model for the use of SRMs, by connecting different industries and decision makers, to track and model SRM flows, and share knowledge and information along the value chain.
- **New applications for SRMs**: almost all the process chains are "market driven", so it is essential that the markets know and appreciate products made with SRMs, to promote their diffusion. The success of products that are, even if not overtly, made entirely or partly of SRMs significantly increases recourse to SRMs in production processes. For the market to receive, evaluate and appreciate/accept products of this kind, it is essential that designers or product development managers begin to introduce this type of raw material as widely as possible.

Interaction with Other Strategic Action Lines

- LI1 Customized product systems: smart materials
- PRI2.1. Integration of design and development processes in a life-cycle-thinking perspective: integrating product-process-system modelling for eco-efficiency from a life-cycle-thinking perspective is one of the keys to encouraging the transition to circular economy and can only increase the overall impact of the roadmap
- PR2.5 Technologies and tools for intelligent re-and de-manufacturing
- PR2.7 Business models for Circular Economy

Time Horizon

Short-term goals (2–3 years):

- Integration of SRMs in high value-added products.

Medium-term goals (4–6 years):

- Ensure the acquisition and transfer of information relating to SRMs.
- Tools for the design of products based on SRMs.

Long-term goals (7–10 years):

- Study of new integrated product-process-system schemes in order to support the implementation of a large-scale manufacturer-centric and repeatable circular economy model.

5 PRI2.4 Technologies, Processes and Tools for the Reuse, De- and Re-Manufacturing and Recycling of Products, Components and Materials

Complex products, consisting of several materials significantly different from each other (for example metals and polymers) are particularly difficult to recycle through mechanical processes, unless one is prepared to forgo the properties of individual materials and significantly downgrade them. The technical difficulty of separating constituent materials or the excessive cost of doing so suggests a different approach for the management of these types of products/materials.

In metal recycling, the greatest criticalities are observed with respect to precious metals and metals defined as critical. The system for closing the processing cycle according to the principles of Circular Economy is still incomplete for these metals, unlike what happens for ferrous and non-ferrous metals, which can count on a consolidated supply chain. In fact, the infrastructures for the recovery and purification of these materials from industrial by-products and waste and from technological waste (e.g. lithium batteries, permanent magnets, WEEE, red sludge) are still very limited in Italy. The state of the art is that hydrometallurgical technologies are the most suitable to pursue these objectives, for which investments are necessary in order to open new branches of research.

The objectives of this research and innovation priority focus on de- and re-manufacturing processes for the recovery of functionality and/or intrinsic value of materials from end-of-life products, by-products, and industrial waste. To this effect, the following actions have been identified:

- **Disassembly and re-assembly solutions for functionality recovery:** the goal is to focus on innovative and complex high-value end-of-life products, for which priority must be given to functional recovery with a focus on reuse. In this context, it is necessary to develop innovative technological solutions for automated disassembly with high levels of automation, control, inspection, testing, regeneration, and reassembly. In a subsequent step, these de- and re-manufacturing solutions will have to include a combination of design and production systems, with a view to a new integrated manufacturing paradigm that can ensure greater efficiency and sustainability;
- For metal materials, it is necessary to develop processes that can improve **selectivity**, **characterization**, **sorting**, and **separation**. They are currently widespread in industrial contexts as recycling business options, but not sufficiently optimized. For example, it would be desirable to study how the synergistic use of advanced

optical multi-sensor systems, the use of robotics solutions, including collaborative ones, the use of multi-physical separation processes, in synergy with modern collection techniques, modelling, data analysis and control deriving from industry 4.0, for example the use of feed-forward control systems and cyber-physical systems, can be extremely efficient in complex context;

- For polymeric materials, on the other hand, it is necessary to **research new systems and methods for the integration of** advanced chemical (solvolysis), thermochemical (pyrolysis) and mechanical (defragmentation) **technologies** that could be a valid solution to carry out a depolymerization in such a way as to obtain polymer fractions and/or polymer chains, which would be the elementary building blocks of a new chemistry based on the formulation and reaction of these organic decomposition products. Similarly, it is possible to design polymers with chemical constituents that more easily undergo depolymerization processes by solvents (design for solvolysis) or pyrolysis (design for pyrolysis). These processes, together with mechanical ones, help us extend material recoverability to almost all the products/materials commonly in use today;

- In addition, in production processes aimed at **recovery and enhancement of industrial waste and by-products**, particular focus is to be given to biological processes for circularity. Production processes concerning, for example, agri-food/agro-industrial productions generate a large amount of waste, by-products and wastewater that can be part of new transformation processes and be fully exploited even in production sectors that are very different from those that originated them (Pharmaceuticals, Cosmetics, Construction).

Interaction with Other Strategic Action Lines

- PRI2.1—Integration of design and development processes from a life-cycle-thinking perspective. Technologies, processes and tools for the reuse, re-manufacturing and recycling of products, components and materials should be developed with support of design processes (and vice versa) in order to maximize the results of the industrial sustainability roadmap.

- PRI2.6—Business models for Circular Economy. Need to develop and test suitable business models that allow the large-scale diffusion of economically sustainable factories, including "small" size or mobile ones, and the aforementioned de- and remanufacturing techniques.

Time Horizon

Short-Term Goals (2–3 years):

- Creating appropriate infrastructures for the demonstration of scientific research applications (e.g. laboratories / workshops for the construction of prototypes, pre-industrial scale plants, networks, etc.).
- Methodologies for the optimization of de- and re-manufacturing processes.

Medium-Term Goals (4–6 years):

- Developing processes to improve selectivity, characterization, sorting, and separation, which are currently widespread, but not sufficiently optimized, in industrial recycling business contexts.
- Developing technological solutions and de- and re-manufacturing processes to recover the functionality and/or intrinsic value of materials from complex end-of-life products, by-products and industrial waste, according to an upcycling approach.
- Increasing the degree of automation of de- and re-manufacturing systems.

Long-Term Goals (7–10 years):

- Designing production and de-production systems jointly, with a view to a closed-loop reuse.

6 PRI2.5 Modelling and Simulation for the Sustainable Supply Chain

Industrial sustainability is a complex concept that requires the combination of different players (companies, institutions, governments, etc.), it impacts different sectors and presents a non-linear and non-rational behaviour. To describe these interactions at best, one needs to devise an approach that combines both the bottom-up (industrial and business dimensions) and the top-down (political) perspectives. Traditional approaches (such as the General Equilibrium Model, the Input–Output analysis) cannot fully grasp these dynamics. For this reason, the approaches developed in recent years start with the theory of Complex Adaptive Systems (CAS) and are based on a combination of different approaches, giving rise to hybrid models that allow for a responsible management, from a social, environmental, and economic point of view, of all procurement, production, and distribution processes.

Sustainable supply chains can exploit the benefits generated by hybrid modelling approaches to support decisions, achieve quality, efficiency and productivity goals and solve specific sustainability problems such as those pointed out in the Sustainable Development Goals (United Nations, 2015). When it comes to selecting or designing a sustainable supply chain, hybrid models are considered particularly appropriate for the way they manage flexibility in their analyses.

The goals of this research and Innovation priority are:

- **Methodologies and models based on hybrid approaches:** These models based on data collected from different sources along the production chain (production process, design, distribution, use, etc.) are meant to:

  o Analyse the dynamics and impacts of sustainable business models on supply chains (including the analysis of the industrial symbiosis potential);
  o Evaluate the impact of government laws and incentives that can influence the behaviour of supply chains from a sustainability point of view;
  o Provide sustainability metrics to support decision making;

o Provide cooperation patterns between companies and public bodies to enable the improvement and optimization of production flows;

o Provide indications and metrics related to the social dimension of sustainability, including information on the impact of physical-cognitive ergonomics on industrial processes' operators.

- **Models and tools for cross-sector supply-chain design:** Sustainability issues are so complex that no company can tackle them on its own. To cope with the pressures from governments and corporations, companies seek to improve the management of their supply chains from both a social and an environmental point of view. New modelling approaches are necessary to support supply chains through a cross-sector cooperation (for example, industrial symbiosis). One of the challenges is to model these networks from the point of view of the value creation process (design problems, distribution problems, types of partnerships and level of interaction between companies/supply chains).

- **Models for forecasting product and material return flows (based on use, average life of the products, consumer attitudes):** Implementing sustainability strategies in manufacturing environments gives rise to several risks, including mismatches between fluctuations in demand, supply, and value of components used, causing uncertainty about costs and return on investment. A further issue is lack of information on the condition, availability, and location of resources in service. The gradual spread of technologies based on the principles of Industry 4.0 offers the opportunity to overcome some of these obstacles to the full implementation of sustainability principles in the manufacturing sector. In fact, data driven models (based on the use of technologies such as simulation, digital twins, IoT and sensors) can handle information such as product conditions and consumer habits, facilitating the study of forecast models for the return flows of products and materials.

Interaction with Other Strategic Action Lines

LI5: Innovative production processes.
LI6: Evolutionary and resilient production.
LI7: AI, Digital Platforms, Cyber-Security.

Time Horizon

Short-term goals:

- Hybrid approaches for sustainable supply chain management.

Medium-term objectives:

- Models and tools for cross-sector supply chain design.
- Models for forecasting product and material return flows (based on use, average life of the products, consumer attitudes).

7   PRI2.6 Models and Tools for the "Circular Economy"

Circular economy is emerging as an economic rather than a purely environmental strategy that requires not only a change in production processes, but also in value creation activities, and consumption. This research and innovation priority aims to promote the development and implementation of tools and models for supporting circular economy, by reducing demand for resources and raw materials, increasing the value of scraps and waste, and arranging for their recovery and reuse. The main goals of this research and innovation priority are:

- **Models for the management of discrete products in a circular economy perspective:** Development of appropriate models for the management of return flows of materials; models for the management of reverse logistics processes; methods to handle integration between organizations, suppliers and customers which, based on the information collected by the various players involved, can manage and direct the flows to recovery, recycling and transformation centres.
- **Models for the management of industrial symbiosis:** Models for the integrated management of shared resources in continuous processes (materials, water, by-products, waste) according to a cooperative approach, in which the output of a company can be used as input by a third-party for its manufacturing process. New models are needed to support industrial symbiosis, for the diagnosis, use and management of resources at company and at system level, taking into account the various local contexts.
- **Models for the development of circular economy strategies in SMEs:** business models, strategies, and tools developed specifically for SMEs, to support them in the implementation of the circular economy paradigm and for an easy definition of a "virtuous" supply chain of raw materials and waste.
- Solutions to actively support **conscious consumption by end users**: tools that, based on the data collected during the product's use phase, encourage an approach to consumption based on circular economy models, favouring actions such as upgrades, repairs, maintenance, product/function sharing with other users.
- Actions for fostering collaborative and inclusive approach such as **networks** and **citizen engagement**: models and tools based on the territorial analysis that can encourage a co-design of circular economy solutions, dialogue and good practices exchange.
- **Circularity measurement tools:** performance assessment systems at both factory and supply-chain level to monitor and evaluate the level of implementation of circular economy and support relevant decisions, through suitable indicators to overcome the limits of current assessment systems, integrating indicators at the macroeconomic level (countries, regions), and indicators at the micro level (products, companies).

Interaction with Other Strategic Action Lines

LI15: Processi produttivi innovativi.

Time Horizon

Short-term goals:

- Circularity measurement tools.
- Solutions to actively support informed consumption by end users.

Medium-term objectives:

- Models for the management of discrete products in a circular economy perspective.

Management models for industrial symbiosis.

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Strategic Action Line LI3: Factories for Humans

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Abstract The objective of this chapter is to describe the strategic action line related to the factories for humans (LI3). In particular, this chapter proposes research and innovation priorities aimed at designing and developing new solutions to enhance the role of human resources and their skills, and contribute to their satisfaction and wellbeing; research and experimentation of new technologies for reducing physical exertion, cooperation with advanced support systems, with collaborative robots and with AI-powered technologies; mapping of knowledge generated on the job, especially implicit knowledge, in a way that is compatible with privacy requirements, introducing advantages both on the human wellbeing front—whether the individuals are users, operators or managers—and in terms of business strategies and procedures. In this regard, innovative factories will need to be increasingly inclusive, strongly geared towards the engagement and participation of individuals (users, operators and managers). These models must take a human-centric approach to look into/

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investigate new technologies and all the dimensions through which the new factory is defined.

Keywords Workers · Human–machine interaction · Skills and competences · Training · Safety and ergonomics

1   Introduction

In the coming years, exponential growth in connected IoT devices is expected. It will include consumer, industrial and healthcare applications, with a market forecast of between $4 and $11 trillion by 2025, around 1600 billion in Industrial IoT (*Source* McKinsey). Machines will be increasingly pervasive, intelligent, connected, and equipped with forms of distributed intelligence that will interface with users.

Ongoing technological changes call for the definition of socially sustainable digital innovation pathways make technology work at the service of humans (workers, citizens, students, or else) and for the development of a human-centred society. According to a 2018 study by the McKinsey Global Institute, in urban contexts, digitization has contributed to raising various quality-of-life indicators from 10 to 30%, in areas ranging from transport and healthcare to the reduction of the pollution generated by manufacturing.

In particular, according to a recent Microsoft/IDC study, about 85% of jobs are expected to undergo a transformation in the next 3 years, 33% of workers will have to engage in re-skilling, 26% will take on new roles, 27% of works will be outsourced or automated.[1] Skills will undergo essential changes accordingly. A ranking of the skills necessary to use artificial intelligence shows that technical, cognitive, process and social skills will need improvement. New future professions include, among others, data scientists, data engineers, data analysts and the like.[2]

The new document of the European Commission on Industry 5.0 focuses on the crucial role of people, in industrial contexts, on data, information and knowledge management. Industry 5.0 presents a business model based on cooperation between machines and humans, which implies rethinking and innovating models and tools for managing information, as the current ones are often inadequate to deal with the complexity of present socio-technological environments. Particularly so in fact, as the evolution of information technology has made new developments possible.

In the new scenarios, the debate on the role of people in factories is spurred by a wealth of new ideas. This makes it increasingly urgent to study new models that can enable people to improve their work and have a leading role in the evolution of production processes and in the introduction of systems for the exploitation

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[1] Microsoft (2018). Brave New World - How AI Will Impact Work and Jobs. Retrieved from https://news.microsoft.com/en-hk/2018/05/02/brave-new-world-how-ai-will-impact-work-and-jobs/

[2] Deloitte (2018). Global Human Capital Trends. Retrieved from: https://www2.deloitte.com/us/en/insights/focus/human-capital-trends/2018.html.

of artificial intelligence. All these studies have to consider the diversities of the workers' cognitive and physical skills. Artificial intelligence and future technologies will increase the workers' skills and knowledge, providing physical help in dealing with the heaviest and riskiest jobs and decision-making support.

However, knowledge generated during the job (particularly tacit knowledge) must be mapped before it can be re-used in the company in a way that meets the privacy requirements of the factory and the individuals. All this requires an intensive effort from both a technological and an organizational point of view.

The continuous introduction of new technologies and management practices calls for new skills and knowledge that should be developed through training for people wishing to enter the job market and through continuous education programs for those already in employment.

This action line aims to design and develop new solutions to enhance individuals and their skills, thus contributing to their satisfaction and well-being. Innovative factories should be increasingly inclusive and firmly focused on the involvement and participation of people (users, operators, managers). These models should be human-centric. Humans run and control technologies and, in general, all the dimensions through which the new factory is defined.

The most relevant challenges certainly include the creation of safe and comfortable workplaces capable of generating positive emotions in the people involved in the production, and workstations that reduce the workers' physical and cognitive effort and help them move on to activities with greater value added. In the new factories, the design of spaces, workstations, new facilities architectures, and new models for the safe interaction between humans and machines will become central aspects. Particular attention will be paid to improving human interaction with an environment populated by various technologies/systems such as robots, machinery, interfaces, and automation systems.

The study and experimentation of new technologies for reducing physical effort can be sparked by exploiting the potential of wearable devices and exoskeletons. The cognitive effort could be eased by intelligible and straightforward information, profiled according to the worker's needs.

Similarly, the role of workers is shifting from traditional repetitive to higher-level tasks thanks to the cooperation with advanced support systems, collaborative robots, and AI-based technologies. On the one hand, the objective will be to provide all the material and cognitive support tools that can improve workers' skills and knowledge and, on the other, generate new training procedures and tools to help workers be up-to-date and keep step with the changes in manufacturing processes.

Finally, the knowledge generated on the job, particularly tacit knowledge, will be mapped and reused within the company to be compatible with individual privacy. This will bring benefits both in terms of the well-being of people, whether users, operator or managers, and in terms of company policies and procedures.

Expected impact: increasing workplace safety and well-being; reducing psycho-physical stress; increasing qualification opportunities and promoting the personal enhancement of workers, preserving them from exclusion and downgrading; improving the transparency of the algorithms that regulate the operation of digital
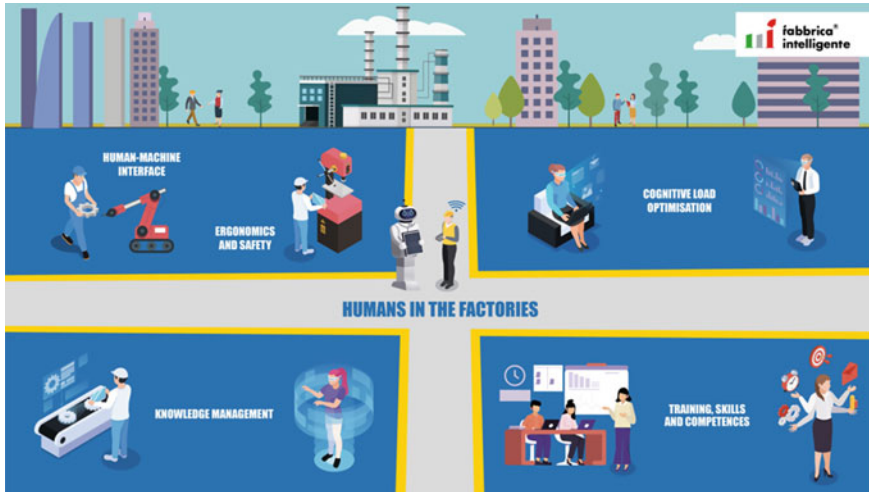
Fig. 1 Strategic Action Line 3—Factories for humans

platforms; improving the capacity of companies and workers to exploit the advantages of the data economy to ensure, in compliance with ethical-legal limitations and individual freedom, the achievement of collective goals in terms of the workers' health and well-being in the factory.

The research and innovation priorities of the strategic action line on Factories for humans are (Fig. 1):

- PRI3.1—New Technologies, Methods and Tools to optimize the work environment, human–machine interactions and cognitive load
- PRI3.2—New Technologies and Methods for the management of Knowledge, Information, Privacy and the Company's Human Capital
- PRI3.3—New Technologies and Methods for the training and certification of the skills and professionalism of persons and of the human capital in the Life Long Learning (LLL) era

2 PRI3.1 New Technologies, Methods and Tools for Optimizing the Work Environment, Human–machine Interactions and Cognitive Load

People play a central role in designing intelligent factories and, above all, in generating their flexibility and "resilience". Factories can thus adapt to new and not entirely predictable contexts and reconfigure promptly and efficient according to new work patterns and production models.

This research and innovation priority proposes to design new technologies and methods for managing human resources as a critical element in the new concept of "resilient factory". In particular, this priority proposes objectives connected with ergonomics, human–machine interaction, and the person's cognitive load, promoting new ways of working and communicating (remote work, collaboration with automation systems, and management of production re-purposing).

The proposal is to develop methods, models, and systems to support operators in their work, increase their physical and cognitive abilities, improve work quality and productivity, and reduce margins of error while ensuring the workers' general well-being. As a result, safety and well-being in the workplace will be increased by acting on numerous factors: an adequate redesign of the type and sequence of activities during work shifts, better organization of the premises, information display mode optimized according to needs and activities, natural and intuitive interactions between humans and machines). This will reduce psycho-physical stress, mental and psychological fatigue, anxiety, and overload.

One of the fundamental themes for the future will be to guarantee a continuous and rapid evolution of production systems to seize new opportunities and to face ongoing changes. Humans are at the centre of a constant redevelopment that requires analytical skills, goal identification, and creation of solutions and planning of pathways to achieve the desired results. This shift has to take place at all levels, from the local improvement of individual workstations, geared to increase efficiency and respond to new needs in terms of products and materials, seizing new opportunities in terms of tools, sensors and plants, to factory networks, supply chains and interaction with the markets. To be effective, this change must be pervasive and see the joint effort of all the people who take part in this evolution at different levels. The ability to manage this evolution, rather than the optimization of individual situations, will in all likelihood be the real competitive lever in a rapidly and radically changing context such as the current one. Humans are the critical resource, as they can use their intelligence and dedication to ensure high performance and competitiveness for their company. In this perspective, it is important to underline that people must be put in a position of dominating changes. The rapid and continuous evolution of technological products and production systems should parallel the ongoing and targeted development of the knowledge and skills of the people who cooperate to manage change at different levels.

In particular, the goals of this research and innovation priority concern:

- **New materials and tools for workstation ergonomics and safety:** development of active and passive PPE (Personal Protective Equipment) including materials that absorb high levels of thermal and mechanical energy, safety devices, wearable sensors, smart work clothes, workers' supports for repetitive tasks, intelligent exoskeletons for workers' safety, digitization of workers and work environment so that the worker's operations can be designed in a human-centred perspective and complex tasks can become more accessible.
- **New technologies for customization of work environments:** development of intelligent solutions designed to adapt workstations to the specific physical and

cognitive skills of individual workers, considering their role, duties, abilities and needs; developments of intelligent solutions designed to recognize operators and to reconfigure the working environment based on working conditions.

- **Methods and technologies for the management of the human–machine interaction: development of** natural and intuitive interaction models, new human–machine interaction paradigms, new methods and tools for the analysis of workplace interactions, new human–robot cooperation and collaboration models, natural communication languages, natural and transparent intelligent adaptive interfaces, including environmental, wearable and multi-modal types (immersive interfaces with Virtual and Augmented Reality, Brain Computer Interfaces, etc.).
- **Methodologies and technologies for optimizing the cognitive load**: development of work environment design models and advanced interfaces capable of supporting control activities and decision-making; structured approaches for the measurement of mental stress in the industrial environment, intelligent systems (based on Deep Learning, Digital Twin, Artificial Intelligence, GANs networks, etc.) to help optimizing mental load, avoiding both overload and underload.
- **Tools to bolster adaptation to continuous changes in production**: development of intelligent systems that can predict the operator's actions and provide online support on Virtual and Augmented Reality (operations to be carried out, procedures, activity tracking, etc.), Virtual Training systems and immersive, augmented or mixed Virtual Reality tools, that can help to improve staff safety by providing remote training on how to deal with risky situations.

Interaction with Other Action Lines

This research and innovation priority is transversal and will have strong interaction with action lines LI5 and LI6.

- Human–machine collaboration and integration in innovative manufacturing (LI5) will increase human capabilities rather than replace them, allowing humans to focus on higher value-added, creative and socially relevant activities.
- Human–machine interaction will be studied in close connection with Strategic action line LI6. The aim will be to provide guidelines for designing collaborative human–robot systems within evolutionary and resilient manufacturing systems geared to enhance people's work and gain by the workers' experience.

Time Horizon

Short-Term Goals (2–3 years):

- Materials and tools to improve workplace ergonomics and safety,
- Models for the management of the human–machine interaction geared to enhance the work of people in factories,
- Models for designing working environments and advanced interfaces that can provide support for control and decision-making,
- Digital models of workers to be deployed in planning their operations and designing the means to facilitate complex tasks.

Medium-Term Goals (4–6 years):

- Technologies for the customization of work environments,
- Intelligent solutions capable of adapting machines to operators, detecting the presence of DPIs and checking in real time that the correct procedures are being carried out,
- Technologies for the management of the human–machine interaction,
- Technologies for the optimization of cognitive load

Long-term goals (7–10 years):

- Tools to bolster the adaptation to continuous changes in production processes (intelligent systems capable of predicting the operator's actions and offering online support, and advanced Virtual Training systems to train operators to deal with changes)

3 PRI3.2 New Approaches to the Management of Corporate Knowledge, Privacy and Human Capital

Knowledge, creativity and the human capability to cope with unforeseen events play a fundamental role in generating innovation and managing production. Competitiveness involves acquiring awareness of these aspects and enhancing the human component and its ongoing development. As machines become increasingly intelligent and connected (Smart Machines), new business models will lead the way from a product economy to a product-service economy (Servitization) also in manufacturing. Prognostics and remote configuration of the new "connected products" will be the basis for this change. Knowledge is increasingly important and remotely available thanks to new digital tools.

Furthermore, emerging production models provide for the pervasive introduction of AI-based tools, which involves the creation of knowledge management and decision-making support tools, as well as smart machines that work together with humans. In this scenario, it is necessary to keep the focus on the central role and skills of people means promoting the trustworthiness and explainability of AI methodologies, with a view to ensuring that AI-based systems comply with the ethical principles of respect for people, prevention of damage, fairness and explicability.

The research and innovation priority must therefore address the following objectives:

- **Methods for managing information, privacy of people and factories:** Define rules and methodologies to collect, manage, harmonize and share information related to workers and factories. They should ensure an appropriate acquisition and use of data with a particular focus on sensitive data Privacy and Security. This area includes: CyberSecurity (i.e. IT equipment safety and security), anonymization of data both at data generation and data processing level, certification of data from its generation all along the management and analysis process chains. The issue of

the workers' self-sovereignty with regard to their digital identities (Self Sovreign Identity) is also very important.

- **Technologies and methodologies for the management of corporate knowledge:** It is necessary to develop new tools for the collection, integration and harmonization of knowledge generated by people and databases, with a view to ensuring that such knowledge can be reused and optimized. In particular, data should be made accessible, available and easily integrated through new methods in support of data analysis and event prediction. Specific consideration should also be given to systems for the management of information useful in carrying out the manufacturing and decision-making processes assigned to the workers. Structured and shared knowledge will help workers be more productive, sharing experiences that will help them find easier, quicker and cheaper solutions to problems, contributing to their personal development and training in the specific field. In particular, this goal requires actions to be deployed along three lines:
- **Knowledge capture:** Defining "Human Computation" methodologies and technologies to transform tacit into explicit knowledge by actively involving people in processing information, putting users back at the centre of the process (human-in-the-loop), to collect, improve and preserve the quality and reliability of knowledge. This will make it possible to create and enhance a company's living asset capable of generating systems that can be used by workers for their self-improvement, favouring a natural transition from a behavioural to a cognitivist perspective on skills. Knowledge capture systems will also make it possible to valorise intangible assets through appropriate measurement systems, also for valorising them in financial statement.
- **Knowledge Analysis & management:** Developing a new generation of methodologies and application tools capable of combining the analysis of captured and structured knowledge with the management of information, whether from human sources or machine interfaces. The aim is to support operations and decision-making processes, by defining conceptual reference models, sharing and managing assets according to FAIR (Findable, Accessible, Interoperable, Reusable) principles. Throughout this process, it is essential that formalized knowledge is communicated in understandable formats to the operators so that new knowledge can constantly be built on existing one and the operator can maintain control of this evolving situation.
- **Knowledge transfer and sharing:** Once become a corporate asset, knowledge can be shared, exploited and preserved within the company. Thus it is necessary to develop systems for sharing information and data among people and manufacturing units within the factory with the aim to create value for the workers, for instance through re-skilling and coaching sessions conducted by experienced people for recruitment of new resources and field support. There is a need for Human–Machine Knowledge Transfer mechanisms (Artificial Neural Networks, ANNs) and collaborative robots (Cobots) that operate taking into account human behaviour, using artificial intelligences based on Explainable & Trustworthy AI. As a result, ANNs and cobots will be assigned to small value added activities, and to facilitate workers in their daily actions and support them in their decisions, by

providing them with the necessary decision-making elements. It is expected that in these systems, the "human factor" will be at the centre of the decision-making process.

- **Systems for the management of Knowledge IP:** it is essential to define methods, infrastructures, guidelines and application tools to ensure that the ownership of knowledge is available and valued, as both a corporate and a personal asset, in a perspective of trust and enhancement of the ideas of those who generated them and of those who provided the tools to generate them.

Interaction with Other Strategic Action Lines

- Data protection and workers' privacy issues need to be addressed in close relation with the actions carried out in Strategic action line LI7 regarding cyber-security.
- With reference to LI6, digitization/digital twin issues will be useful in defining the tools for sharing and managing knowledge within the digital factory.

Time Horizon

Short-term goals (2–3 years):

- **Knowledge**: the digitization of the working experience of operators (mapping skills and digitizing them to create value for the company) is a key issue and will lead to the creation of a shared re-skilling knowledge base for the rapid recruitment of new resources. To date, these issues are regarded by companies as interesting and certain initiatives are underway, but no structured solutions are as yet available. For this reason, the goals in this area are defined in the short term of 2 to 3 years, to start raising awareness and promote the creation of solutions to channel these needs. More complex solutions, for instance based on Explainable and Trustworthy AI, should be set in motion promptly to avoid losing ground to competition from other markets. However, their full integration will only be achieved through medium-long term actions (1–5 years)
- **Information & Privacy**: data privacy, security and Self Sovereign Identity are certainly extremely engaging issues for both companies and workers, and should be addressed in the short term.

Medium-term goals (4–6 years):

- **Advanced Interactions:** The definition and development of IoT, AR and smart wearable technologies, for monitoring and supporting workers, can be addressed through actions in the short-medium term.

Long-Term Goals (7–10 years):

- **Advanced Interactions:** Natural multi-modal interfaces, capable of allowing intelligent and self-adaptive interaction with the industrial environment and robots, and convergence of AI, CBI and Exoskeleton systems should instead be addressed in the medium-long term, given the complexity of the context.

4 PRI3.3 New Technologies and Methods to train and certify the skills and competence of individuals and of a company's human capital in the era of Life Long Learning (LLL)

The constant introduction of new technologies and new management practices in companies is creating a lack of coordination between demand for new professional profiles, the qualification of operators active on the labour market. In Italy, the difference between supply and demand amounts to more than 150,000 jobs available within companies that are not matched on the labour market (2019 data).

In addition, the knowledge acquired by the current workforce during their educational career becomes obsolete quickly and continuous training is required to generate added value for the company. Accordingly, there is a demand for new skills and knowledge in the offer of training programs for people entering the job market, and of updating programs for those already in employment.

From a company's point of view, it becomes essential to map the workforce's competence and skills to understand proactively the impact of a new technology, the timeframe to its full exploitation as added value and the most effective training methods.

From an individual's point of view, the need is for virtual and tangible tools and environments to be constantly available, to ensure a continuous education and the certification of the skills and knowledge acquired, in a Life Long Learning (LLL) perspective. New teaching frames must be used to increase the power of attraction of the manufacturing world and the efficacy of training.

New tools should be developed also to provide user support functions, to manage knowledge and training for classes of both younger and more experienced users, to develop/improve high-profile skills in manufacturing.

Finally, it is essential to develop tools to assess the work carried out and test the skills and abilities acquired, so that the new strategies and technologies introduced can be properly validated from a corporate point of view, the effects of the training received can be assessed, and objective tools can be provided for the certification of the skills and abilities acquired on the job.

The research and innovation priority must therefore address the following objectives:

1. **New methods and tools for active training**: the availability of new hardware devices such as smartphones, tablets, smart glasses, combined with the prompt availability of protocols with enormous bitrates (5G) and the use of software such as social media and APPs pave the way to the interaction with digital twins of machinery, lines and production environments. The focus is on strengthening MOOCs (Massive Open Online Courses) and experiential tools such as Mixed, Augmented and Virtual Reality, alongside innovative methodologies and new educational models such as "serious games", to further enable training both in presence and at a distance.

2. **Physical environments for the education and training:** Development of "protected" physical environments where people can be educated and trained on new technologies, and pilot and demo work environments (Teaching & Learning Factories) which can also be used remotely. An environment of this type should facilitate training in value-added manufacturing, providing workers with interdisciplinary skills, preparing them to integrate new technologies and empowering them with the capability of combining knowledge. The goal is to design and plan "hands on" training courses, in which workers can directly experience technologies. This will guarantee an immediate return from the prompt redeployment of such technologies in the factories.

3. **Methods and tools for assessing the acquired skills and abilities:** Development of automatic systems for the assessment of the operative skills achieved and required for the performance of the various tasks assigned. Methods and tools to track the impact of education and training in terms of improving and increasing the efficiency of production systems.

4. **Methods and tools for planning staff development paths:** development of systems that make it possible to plan an evolution of products, processes and manufacturing systems in parallel with the development and acquisition of skills by the staff. This opens the way to the adoption of planning models that focus on improving knowledge and skills through exchanges between operators with different experiences. Such models need to hold into account the knowledge's evolution timing and connect it to the systems' evolution timing.

Interaction with Other Strategic Action Lines

- With reference to LI6, digitization/digital twin's issues will be useful in defining tools for sharing and managing knowledge within the digital factory.

Time Horizon

Short-term goal (2–3 years):

- New serious-game methods and tools for active training
- Physical environments for the education and training of people
- Methods and tools for planning staff growth paths

Medium-term goal (4–6 years):

- New methods and tools for active training based on virtual reality and multisensory approaches
- Methods and tools for assessing the skills and abilities acquired

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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.
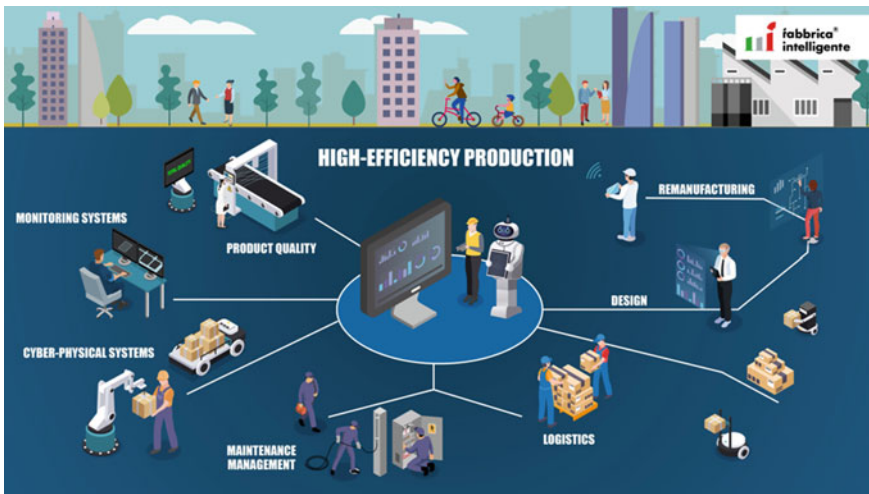

Fig. 1 Strategic Action Line—High-efficiency and zero defect

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 CO_2 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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Strategic Action Line LI5: Innovative Production Processes

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Abstract The objective of this chapter is to describe the strategic action line related to innovative production processes (LI5). In particular, this chapter proposes research and innovation priorities across various aspects both related to conventional and non-conventional processes, such as: digitization of conventional production processes in order to improve their interactions and handle different types of processing, even by means of hybrid processes; the growing role of additive manufacturing and its ensuing challenges in terms of both design and production; processing of standard and innovative materials, or materials with meso/macro geometries, including also nano- and micro-manufacturing. In addition, process innovation also needs to take the shape of innovation in support of re- and de-manufacturing processes, to start with, through to the development of bio-inspired transformation models.

Keywords Smart materials · Bio-intelligent manufacturing · Consolidated manufacturing · Micro-nano processes · Additive manufacturing

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1   Introduction

Manufacturing processes must be the focus of innovation in manufacturing, since they influence the competitiveness of the country-system and provide capital assets for the domestic market or for exportation. This improves global performance in terms of efficiency, sustainability, reconfiguration, flexibility and resilience.

In particular, Italy should become a leader in building manufacturing facilities to be able to address various types of needs, including: management of a large variety of products at different stages of the life cycle; regeneration, reuse, repair of products, components, materials; increase in process efficiency to manufacture high-value and highly complex products.

Research and innovation to promote the digitization of consolidated manufacturing processes have come to the forefront in recent years, but there is still scope for further developments, as consolidated processes continue to represent a large portion of manufacturing processes as a whole.

At the same time, it is essential to study the development of innovative processes with a view adapting them to industrial contexts and improving the interactions that make different types of processes (hybrid processes) manageable. These improvements should focus on a manufacturing system that processes both standard and innovative materials, as well as meso/macro geometries even on a nano or micro scale. Process innovation has always focused on transformation processes for production, and should now support first of all re- and de-manufacturing processes, and the development of transformation models inspired by biological systems.

Against this background, this strategic action line aims to define research and innovation priorities for the development of innovative manufacturing processes that can help the manufacturing system implement the necessary transformation to meet the social and technological challenges illustrated below (Fig. 1):

Process innovation: in order to remain competitive, conventional processes will need to implement digital transformation in combination with technological improvement. This involves adopting systems that can develop solutions to improve productivity, flexibility and sustainability, including through real time process control solutions and process management by way of adaptive control systems. In the short term, these technologies will be just marginally replaced by alternative technologies, as they achieve high surface finishes and geometric accuracy. However, the growing demand for increasingly complex products with lower production volumes is leading to the development of unconventional technologies such as Additive Manufacturing, laser, micromachining, electro -physical and chemical processes and innovative assembly processes, as well as hybrid processes consisting in a combination with traditional technologies, which needs to overcome lead times, volume and cost limits in order to compete in terms of efficiency with traditional processes.

Materials innovation: innovation in materials should be geared towards greater durability, environmental sustainability, possible reuse/recycling, zero/low CO_2 emissions. Manufacturing processes should produce and use these innovative materials in typically industrial volumes and time. The concept of generative design is
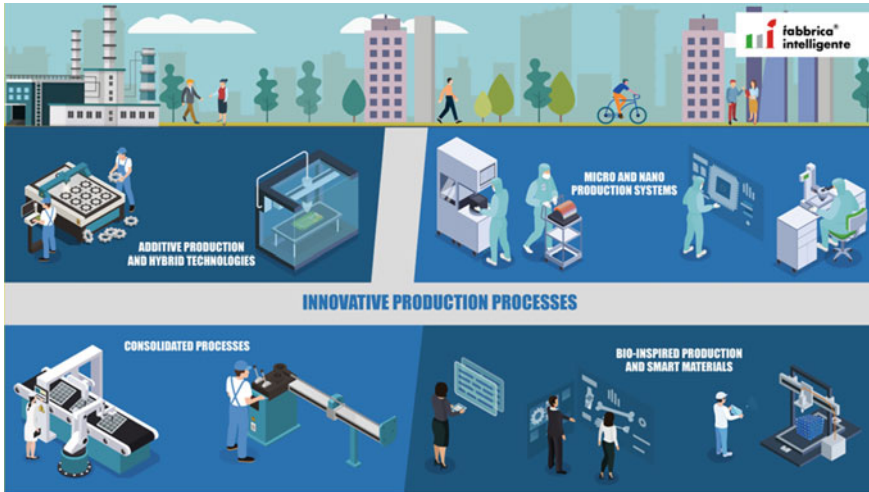
Fig. 1 Strategic Action Line 5—Innovative production processses

also important. Generative design involves the integration of the properties of these materials in the manufacturing cycle of a component right from the design stage, by developing databases and software tools that include material, process, product performance and life cycle modifications to enhance the advanced modeling and characterization tools of the manufacturing process.

New production paradigms such as biological transformation: a new concept of manufacturing inspired by biological systems found in nature is currently spreading at European level (Byrne et al., 2018). Biological and bio-inspired principles, materials, functions, structures and resources are expected to be increasingly used and integrated in manufacturing, in order to obtain intelligent and sustainable technologies and manufacturing systems (Cainelli et al., 2020).

Four research priorities have been dedicated to the first paradigm. They focus on the innovation of consolidated processes, processes for additive manufacturing, hybrid processes and micro processes. Distinct research priorities have been dedicated to the second and third paradigms, which are in fact cross-topical.

Expected impact: innovation of conventional and non-conventional processes; reduction and reuse of waste materials through innovative processes; increased flexibility and resilience of manufacturing processes; increased performance in terms of volume of work and productivity of innovative processes; reduction of energy consumption; redesign of the manufacturing cycle of a component based on the choice of new materials, new geometries and new manufacturing processes; integration between consolidated and innovative manufacturing processes, improvement of the tools necessary for the simulation of manufacturing processes; reduction of set up and cycle times with shorter time-to-market; improvement of manufacturing processes' sustainability.

The research and innovation priorities of the strategic action line on Innnovation Production Processes are:

PRI5.1.—Technologies, processes and materials for additive manufacturing
PRI5.2.—Bio-inspired technologies and manufacturing processes
PRI5.3.—Innovation of consolidated manufacturing processes
PRI5.4.—Manufacturing processes through hybrid technologies
PRI5.5.—Manufacturing and processing of innovative materials
PRI5.6.—Processes, products and functionalities on a micro scale

2 PRI5.1 Technologies, Processes and Materials for Additive Manufacturing

On a domestic front, Additive Manufacturing (AM) has been recognized as one of the enabling technologies of the Industry 4.0 plan defined by the Minister of Economic Development, because of the benefits it offers in terms of strategic aspects such as design digitalization, supply chain transformation and high flexibility and freedom in the manufacturing of high-value innovative products. In addition, there is a growing interest on the part of domestic, European and international industry for the development of AM technologies to manufacture metal components and components reinforced with polymeric matrix fibers. In these areas there has been a rapid and important technological development from systems limited to rapid prototyping, to systems that can support small series manufacturing of functional components and final parts.

Despite its robust growth (SmarTech Analysis estimated in 2019 a global additive manufacturing market grow over 10.4 billion dollars) AM is still not fully mature to be implemented in a manufacturing system due to its yet limited manufacturing times and volumes. In particular, the most consolidated processes for manufacturing metal parts (PBF—Powder Bed Fusion and DED—Direct Energy Deposition) are still showing considerable limits in terms of time, printable materials, high defect rate and eecomplex post process operations for the removal of supports, as mentioned by Gartner Hype Cycle 2019, which places these processes in the "Sliding into the Trough" phase. As it is mainly achieved through Material Extrusion processes, also the manufacturing of reinforced components experiences high lead times and the deposition of customizable fibers only on the plane orthogonal to the printing direction. Finally, it should be stressed that, out of habit, the geometry of a component is still currently designed in accordance with traditional processes' rules, without a full exploitation of AM's intrinsic ability to manage complex geometric shapes.

For AM to become an industrially viable technology, the research and innovation priority should set the following goals:

- **New design rules**: make the most of the AM design potential by combining the concepts of generative design, topological optimization, conformal geometries,

meta and multi materials, hierarchical and functional complexity using numerical modeling software to test their performance.

- **Simulation of AM processes**: develop software to predict, correct and manage printed parts. The creation of digital twins using exceptional software tools will play an important role in reducing risks when printing parts from prototype to manufacturing. This software should make it possible to simulate the individual manufacturing process of a component and the MES (Manufacturing Execution System) that is essential to control and rationalize the AM workflows of medium/large manufacturing batches.
- **Innovative systems for AM**: new AM solutions to increase work volume and/or productivity, thus ensuring the manufacturing of at least 10,000 pieces/year. Development of innovative post-process treatments. Development of innovative solutions for in-process monitoring and control and for post-process inspection and quality control.
- **Solutions for metal AM**: new solutions for the manufacturing of complex shape metal components. These solutions should not be constrained by the geometric limits and available materials that typically affect powder bed processes.
- **Solutions for Multi-material AM**: new materials, solutions, software and machining strategies for the creation of components built according to criteria of continuous and discontinuous functionally graded materials.
- **Solutions for composite AM**: exploit the potential of AM composite materials, solutions to make manipulation of fiber alignments possible at unprecedented levels.
- **AM solutions for new industrial sectors**: based on the capacity of AM technology, study and develop solutions for entry into new industrial sectors such as clothing and footwear, oil & gas, pharmaceuticals etc.
- **Sustainable AM**: new solutions to improve process sustainability, recover and optimize specific materials such as plastic and in general all materials resulting from other manufacturing processes (second life material).

The expected benefits will be considerable: reducing waste materials and energy consumption compared to traditional technologies will improve the environmental impact of manufacturing; furthermore, new, more sustainable products can be introduced on the market if existing components and assemblies are redesigned with a view to reducing their weight and keeping the same performance. The reduction in set-up and cycle times will lead to a reduction in the time-to-market of small series, allowing Italian companies to be competitive on the global market.

Interaction with Other Action Lines

- This research and innovation priority will certainly support LI1 thanks to the economic advantages of AM in the production of highly customized geometries with minimum manufacturing volumes.
- In view of the research priorities expressed by LI2 to date, AM techniques look with interest to the issue of the recycling of materials and zero-waste AM processes, especially in the manufacturing of polymeric parts.

- Once again, exploiting improved capability to handle high product complexity in the generation of ad hoc solutions can be of support to LI3.
- Finally, as already explained in the goals, issues such as zero defect or the high-volume production that characterize LI4 can find in the AM a challenge to make this technology mature for the industrial world.

Time Horizon

Short-term goals (2–3 years):

- **New design rules**: the knowledge of design rules should be consolidated according to the different additive processes available, highlighting the current limits of technologies in the generation of complex geometries. Completing the knowledge and potential use of the design techniques available to date (topological optimization, conformal cooling, multi-material, etc.) is essential. They have certainly been extensively studied at a basic research level but they are not yet mature for concrete applications on an industrial scale.
- **Simulation of AM processes**: available multifunctional software already allows users to perform print quality checks (deformations, residual stress, etc.), orient the parts on a print area/volume, optimize the structure of the parts to take-off weight, add supports and perform what-if analyzes. However, this software is not yet mature to simulate objects that have been designed by extending the geometry of the component as far as possible, for instance for the simulation of the behavior of latex structures, multimaterials such as fiber-loaded polymers and complex materials (for example with combined mechanical and electronic properties).
- **Solutions for composites AM**: given the expiry of several patents and the degree of maturity of the technological processes that can manufacture these materials, in recent years a large proliferation of reinforced components has led to a rapid evolution of the knowledge and potential of these solutions. The near future will have to focus on the real applications of these materials in making complex components and on their real alternative to metal components.

Medium-term goals (4–6 years):

- **Innovative systems for AM**: today many companies are increasing production volumes as well as the range of printable materials, but few are the pilot projects that support process control. The new AM systems, and in particular those used in manufacturing metal components, should be fitted with integrated monitoring systems for a real-time control of the machining process in order to modify process parameters and correct any machining mistakes as well as stop the process altogether in order to reduce waste of material, time and energy for increasingly sustainable processes.
- **AM solutions for new industrial sectors**: to date, the sectors that principally use AM technology are aerospace, automotive, the medical\dental and electronics sectors. Several sectoral studies are forecasting applications in sectors such as clothing, oil & gas, pharmaceutical and architecture in the next few years.

- **Sustainable AM**: this issue is closely linked to the creation of innovative systems for AM. Both have therefore, the same time horizon.
- **Solutions for metal AM**: in many cases the consolidated PBF and DED processes for these technologies are not yet industrially sustainable. However, other more mature technologies such as Binder Jetting and Material Extrusion are being tested for their performance in manufacturing metal components. These technologies require further improvements in order to be exploitable in manufacturing real components]. At the time being they are not yet totally reliable especially from the point of view of the scale as well as of the real mechanical properties that can be obtained and exploited in the manufacturing of real components.

Long-term goals (7–10 years):

- **Solutions for Multi-material AM**: at present, this topic is strongly growing in terms of scientific research but it is not yet ready for an effective fallout in the industrial world as the main AM process (DED) is being developed as reported by Gartner's Hype Cycle. In the coming years it will be necessary to analyze and optimize the aspects related to dimensional accuracy, thermal stress, the chemical and physical affinity obtainable by mixing different materials.

3   PRI5.2 Bio-Inspired Technologies and Manufacturing Processes

Biological transformation, i.e. the systematic application of biological knowledge in improving manufacturing, is expected to be one of the next technological leaps in manufacturing processes. From a manufacturing point of view, an increase is expected in the use and integration of biological and bio-inspired principles, materials, functions, structures and resources to obtain intelligent and sustainable technologies and manufacturing systems. Biological transformation processes can develop in three separate steps: inspiration, integration, interaction.

In the first step, inspiration, biological phenomena will be translated in the design of products (for instance lighter structures), in their functionality (for instance biomechanics), in the organizational solutions (for instance swarm intelligence, neural networks). In the second step, knowledge of biology will be applied to obtain a real integration of biological systems into manufacturing systems (e.g. replacement of chemical processes with biological processes such as the use of microorganisms for the extraction of rare-earth elements from magnets). The third step will finally see a global interaction between manufacturing, information and biological systems, leading to the creation of completely new and self-sufficient technologies and production structures or the so-called bio intelligent production systems.

The impact of biological transformation in manufacturing will lead in the long term to a continuous improvement in innovation and sustainability for manufacturing processes. A systematic two-way approach would lead to new manufacturing developments, innovations and new products. It would be driven (top down) by technology

and industry or (bottom up) by biology. This systematic approach should be based on the various manufacturing processes and on the different biological elements. Full potential can only be reached by combining the various strategies with data collection, digitization and the development of new processes such as additive manufacturing technologies.

However, these paradigms are still at basic research levels to date. Therefore, with a view to their integration into the manufacturing world, this research and innovation priority has the following goals:

- **New structures and surfaces for bio-inspired materials**: The major developments in biology-inspired material solutions can be related to a material's micro/meso structure or to the characteristics of its surface. If the function of a biological material is related to the structure rather than its properties, it is possible to replace the biological material with an artificial one without losing the key aspects of the function concerned (e.g. the structure of a bone). Conversely, it is possible to analyze a material at nano metric level by taking inspiration from the characteristics of its surface rather than its internal structure (e.g. hydrophobicity of leaves).
- **Bio-inspired design**: Nature offers examples of highly coupled solutions for complex movements, force and power distribution, controlled degradation, self-healing and regeneration. It is necessary to develop design tools that make it possible to conceive products designed to satisfy the mentioned multi-functionalities, for example by integrating mechanical and electronic parts.
- **Biological interaction and integration in manufacturing processes:** The potential for biologization in manufacturing processes, machine tools, robots, assembly systems and sensors is vast and should include environmentally friendly and anti-pollution technologies. The direct use of biological magnitudes and material in manufacturing processes (e.g. use of microbes as a lubricant in cutting operations, use of enzymes for the extraction of raw materials from waste or to carry out transformations, for example in microelectronics, microsystems and polymeric electronics) will be aimed at the optimization of processes and parameters, integration of the biological function in structures, integration of biomimetic sensors in processes as well as in robots' body mimicry.
- **Manufacturing of bio-intelligent devices:** in order to achieve the ultimate goal of bio-intelligent manufacturing, it is necessary to boost the potential of correctly applied concepts in the fields of synthetic biology, bio electrochemistry, microfluidics, bioreactors and artificial intelligence to allow the development of intelligent devices.

Interaction with Other Action Lines

- Interaction with LI1 with regard to the creation of bio-intelligent devices.
- This will pave the way towards the realization of new sustainability benchmarks in line with LI2
- Regarding LI3, study of new human–machine interfaces based on components that integrate biological structures.

- The concept of biological inspiration will be applied at various levels in current business situations, from process innovation to system innovation (LI 4, LI 6) and it will finally change the rules of next generation manufacturing management systems (LI 7).

Time Horizon

Medium-term goals (4–6 years):

- **New structures and surfaces for bio-inspired materials**: to date there are different prototypes of products or surfaces of bio-inspired parts. However they present certain critical issues that must be investigated, such as: scalability—since certain biological functions that work on a micro- or nanoscale fail on a macro scale (e.g. geckoes' adhesive property); constraints in materials—since for certain biological materials no artificial substitute is available (e.g. no man-made material can mimic a spider's web and retain its unique properties, even if its molecular structure is well known); constraints related to manufacturing processes.
- **Bio-inspired design**: the advantages drawn to date from bio-inspired product design include the possibility of changing the products' design in order to increase their performance, even if this means increasing their manufacturing complexity. It will therefore be necessary to increase both the level of knowledge and the limits of this new design concept as well as the level of digitization of the manufacturing chain, in order to be able to manage the higher levels of complexity given by the new designs.
- **Enzymatic processes**: they are mature for some specific sectors (e.g. food) and in the medium term it will be necessary to understand which ones can find their application in manufacturing (e.g. use of microbes as refrigerants in cutting operations).
- **Manufacturing of bio-intelligent devices**: promising technology in the field of micro fluidics and micro electronics in general. Future scenarios will show a development through integration of the biological with the artificial component and manufacturing processes that can achieve such integration.

Long-term goals (7–10 years):

- **Biological interaction and integration in manufacturing processes**: the transition to the design of bio-inspired processes should take place incrementally by adopting various biological solutions in the medium-long term.

4   PRI5.3 Innovation of Consolidated Manufacturing Processes

The increasing demand for customized products, with lower environmental impact and prompt and quick response to customer needs, is radically changing the organization of manufacturing systems (A graphical method for performance mapping

of machines & milling tools). Despite the current evolution of innovative technologies such as additive manufacturing, chip removal will for years to come retain its role as primary technology (Agubra et al., 2016) in the higher value sectors of the Italian supply chains, together with foundry, plastic deformation and sheet metal processing (cutting, welding and bending) because they can obtain excellent surface finishes and high geometric accuracy. For example, it is expected that some sectors, such as e-mobility, will push towards an ever greater use of machine tools, given that powertrain components require high levels of precision (AMFG—The Additive Manufacturing Landscape, 2020).

In order to remain competitive, consolidated processes will have to undergo a digital transformation associated with technological growth through the adoption of systems capable of developing solutions that can improve productivity, flexibility and sustainability, also by adopting solutions for real-time process control and its management by adaptive control systems (Arias-Rosales; Armendia et al., 2019; Ii & La Bioeconomia in Italia).

The goals associated with this research and innovation priority are listed below:

- **Development of Digital Twin models for tools, processes and manufacturing machines** with the aim of creating libraries and digital models to capture the physical phenomena underlying the processes and predict their behavior so as to support both their design and their execution phase. Furthermore, it is also necessary to develop adequate architectures that promote the integration of different digital models of different process components.
- **Design and development of manufacturing processes** to take into account the evolving features of machines and tools to the production needs. In particular, it is necessary to design jointly both the process and the machine that carries out production.
- **Innovative solutions for manufacturing technologies:** manufacturing processes need to be transformed to allow the processing of difficult materials (e.g. fragile, elastic materials), processing in critical environments (e.g. explosive environments, biohazard environments), increase in production rates (e.g. cutting speed), improvement of quality and reduction of set-up times. These innovations include technological machine modules (e.g. spindle, sources), tools (e.g. materials, geometries) and equipment (e.g. zero-point clamping, adaptive equipment).
- **Solutions for real-time optimization of productivity and process quality,** easy to use and install on machines with different characteristics and numerical controls. Namely, the development of adaptive control methodologies, including those based on artificial intelligence, model-based process control systems and control systems based on artificial intelligence, to improve the performance of a manufacturing system, optimize performance in terms of productivity, quality and efficiency and a use of the machines to optimize their life cycle.
- **Methods and models for process planning and product re-design**: it is necessary to develop joint product-process design models that make the most of the materials' potential (whether from a catalog or purpose designed) both to smooth work during manufacturing and to monitor performance during use. There is also a

need for process planning models designed to meet several goals, such as the cost-effectiveness and low environmental impact of machining processes, and that can produce alternative machining sequences one can choose from during the manufacturing of products, depending on the conditions of each specific manufacturing plant.

- **Solutions to reduce the environmental impact of processing,** by developing new strategies to reduce the impact of consumables (lubrication) and energy consumption of the process (modifications to machine components and choice of working parameters) and for the reduction of scraps. A second line of industrial research will address the reduction of the chemical footprint through the adoption of substances and primary materials and accessories that have higher recyclability.

- **Multi-material and multifunctional joining techniques** to ensure the coexistence of different functional responses, such as for example (homogeneous or non-homogeneous) welds with different mechanical properties (elastic and stainless), electrical properties (excellent conductivity, low contact potential) and thermal properties (good conductivity). The improvement of the features of joints should address balanced goals and respond to needs that might even be conflicting such as mechanical properties during operation and the ease of disassembly, in a circular economy perspective.

- **Innovative solutions for assembly:** development of new solutions to ensure a product's performance when precision limits are set on the components' production through solutions for tolerance compensation that may ensure high quality products through selective assembling strategies.

- **Adaptive and resilient processes**, i.e. processes that can continue production even where there are significant supply change disruptions, as it happened with SARS Covid 19 (resilience), or quickly adapt to changing market demands.

Interaction with Other Action Lines

- Technological integration, endorsed through LI4, especially for the strong level of automation already existing in companies operating in sectors such as the automotive industry, combined with the new opportunities offered by electric mobility.

- The solutions based on generative design and multifunctional joints will be related to the customization and rapid adaptation goals set out in LI1.

- With regard to strategic action line LI3, it will be necessary to study and adapt the human–machine interaction systems that incorporate new functions and new digital process models,

- The issues addressed in LI2 are obviously important for LI5, a goal of which is sustainable evolution of consolidated processes by improving their energy efficiency and environmental footprint.

Time Horizon

Short-term goals (2–3 years):

- **Autonomous solutions for real-time optimization of productivity and process quality**—These solutions should not be considered only at individual machining process level. Instead, it is necessary to develop rules and logics at machine and manufacturing cell level.

Medium-term goals (4–6 years):

- **Solutions to reduce the environmental impact of manufacturing**—These solutions must be meant to act both on the process side and on the automation side, at machine level and at cell level.
- **Generative design**—Aimed to develop approaches that may turn the design of physical chemical properties into methods available in CAD CAM for the mechanical designer and establish specifications that can be transferred to the manufacturing process.
- **Digital Twin models of tools, machining processes and processing machines**— In the medium term, new models must be studied and developed for CAD, CAM and simulation platforms, to ensure the formalization of knowledge and calculation speed.

Medium-long term objectives (5–10 years).

- **Multifunctional joining techniques**—The improvement of the characteristics of multifunctional joints is being researched and, in order to be truly applicable in the industrial field, it requires the development and fine-tuning of new processes that can guarantee an optimal balance of the priorities of the various materials.
- **Process control through artificial intelligence systems**—selection and optimized control of process parameters during AI-supported machining.
- **Adaptive and resilient processes** to comply with this definition, processes must be able to adapt the manufacturing cycle of products based on the deviations of the characteristics of materials and incoming parts. Furthermore, tools and methodologies must be developed to quickly adapt processes to the new productions.

5 PRI5.4 Manufacturing Processes Using Hybrid Technologies

Developing production systems to support customization is a goal of the transition to Industry 4.0 at national and international level (A graphical method for performance mapping of machines & milling tools; Agubra et al., 2016). This goal can be achieved by developing flexible, productive solutions that can process the new materials available on the market. Thanks to research and technological development, many conventional and unconventional manufacturing processes are now

available for a highly efficient machining of traditional and innovative materials. The combination and integration of these processes to create a hybrid production system is a fundamental step to drive further improvements in process efficiency and greater flexibility. Hybrid manufacturing processes are based on a controlled interaction of several processes during the same machining procedure. These processes have different energy sources, tools and process parameters (AMFG—The Additive Manufacturing Landscape, 2020). This integration can help obtain improved performance, i.e. better machining of materials and less friction, and achieve high levels of flexibility by promptly alternating multiple technologies within the same manufacturing process. This can already be seen in the additive-subtractive hybrid machines recently launched on the market (Arias-Rosales).

The integration of different technologies poses challenges at design and process management level. It will be necessary not only to identify the optimal solutions for hybridization, pinpointing groups of technologies that can lead to concrete benefits thanks to a thorough integration, but also to develop solutions and approaches for an efficient use of hybrid technologies, whether in terms of guidelines for redesigning components and work cycles or in terms of software for constant exchange of information between integrated processes (Manufuture 2030; Armendia et al., 2019).

These systems should allow companies to reduce manufacturing cycle times and manufacturing cycle setup times, significantly increasing production flexibility. The introduction of new multi-materials makes it possible to obtain products with better physical–mechanical characteristics than current solutions. Furthermore, an increase in productivity is expected thanks to the support of multiple technologies/energy sources. Processes will be faster and cheaper and material waste will be contained by adopting technologies that can reduce the geometric constraints of current solutions (e.g.: additive–subtractive hybrid solutions).

The goal of this research and innovation priority is to study and develop advanced hybrid solutions and in particular:

- **Hybrid machines** that can use different technologies both sequentially and simultaneously and improve the performance of a manufacturing process and its manufacturing flexibility. Furthermore, new solutions should be developed, introducing multisensory approaches to control materials and product in line.
- **Hybrid solutions for AM:** Integration of additive technologies and conventional technologies, for a greater flexibility in production planning by containing lead times, and in the definition of a component's geometries. These technologies also promote the creation of multi-material and/or fiber-reinforced hybrid components.
- **Design of hybrid processes/tools** to improve machining yield and increase process capacity, by exploiting multiple technologies at the same time (for example drilling and ultrasound, laser and plastic deformation, forming and joining processes, differentiated functionalization of the different materials in a product).
- **Hybridization strategies through the use of mechanical and thermal processes** or conditioning technologies (lubrication, refrigeration) for the material being processed and the tools.

- **Combination of traditional and micro-scale machining** in an integrated machine that guarantees an improvement in cycle times (i.e. time required to move the component from one station to another) and component quality (no repositioning).

Interaction with Other Action Lines

- Interaction with LI1 (Systems for customized production) since the integration of multiple processes in a single manufacturing system will make it possible to develop machines that can support Mass Customization, not only because of an increase in flexibility, but also because of the introduction of new (multi) materials that can more easily meet the customer's needs.
- Interaction with LI4 (Systems for high efficiency manufacturing) since the integration of technologies will aim to improve the efficiency of the process thanks to the development of new approaches that increase a material's workability, lubrication and machining rate.

Time Horizon

Short-term goals (2–3 years):

- **Hybrid solutions for AM**: improvements regarding process monitoring, development of guidelines for their efficient use and greater flexibility in changing materials.
- **Hybridization strategies through the use of mechanical and thermal processes** (2–3 years): improvement of processing efficiency to increase the number of possible applications (e.g.: Laser Assisted Machining).

Medium-term goals (4–6 years):

- **Hybrid process/tool design** (4–6 years): the development of highly integrated manufacturing systems consisting of 2 or more technologies requires the design of new machines and the development of control systems and guidelines for its efficient use.
- **Combination of traditional and micro scale machining** (4–6 years): the application of hybrid technologies to the micro world will reduce the components' manufacturing times in rapidly growing sectors such as medical devices.

6 PRI5.5. Manufacturing and Machining Processes for Innovative Materials

The European strategy towards circular economy (waste elimination) implies that materials for 500 Mt/year could be re-injected into the economic system. Therefore, materials innovation will be oriented towards greater sustainability in terms of durability, environmental sustainability, the reusing/recycling possibility, zero/low CO_2 emissions. The replacement of metals with polymers is already a reality thanks

to injection processes for the manufacturing of gears, levers, pulleys, for example in food packaging. Innovative design is already proposing materials obtained from completely natural raw materials (bio-based and biodegradable packaging), such as "plastics" from algae. Organic alternatives such as bamboo, mushrooms and wheat straw are already being used in place of traditional oil and plastic-based packaging.

Innovation in materials requires guaranteed performance, to be implemented in terms of multifunctionality and diversification of application areas, because of the improved performance (for example of composites) with respect to the new geometries/architectures resulting from the application of lightening, miniaturization and hybridization.

The use of materials can be improved from as early as the combined product/material design phase, by developing databases and software tools that include material, process, product performance and life cycle changes, by enhancing modeling tools and advanced characterization (generative design). (Arias-Rosales; Armendia et al., 2019) The development of new materials (light, high-performance, secondary materials) requires the study and development of many technologies, processes and capital assets.

The objectives of this priority for the coming years refer to:

- **Technologies for manufacturing based on innovative materials**, with high mechanical and functional characteristics such as CO2 capture materials, membranes and filter systems, catalysts, NOx depletion coatings, waste materials, for the water and gas effluents treatment materials, new polymers and composites including from organic waste, biocompatible materials, lighter materials, recycled materials from other machining processes (second life materials);
- **Technologies for manufacturing energy products based on high performance materials** such as metal alloys, ceramics and coatings for high temperatures, structural materials for advanced wind technologies, functional materials for photovoltaic and solar thermal systems, of energy accumulation materials, thermal insulation and electricity/heat storage materials (Bourell et al., 2005; Byrne et al., 2018; Cainelli et al., 2020; BIT II – La Bioeconomia in Italia).
- **Technologies for manufacturing products based on the use of nano-materials** that allow the functionalization/nano-structuring of surfaces to give, for example, antimicrobial, antiviral, "anti-fouling", self-cleaning properties, especially focusing on manufacturing safety and the use of nano-powders.
- **Innovation of processes** for manufacturing complex high-value materials increasing their efficiency (in terms of energy consumption, waste reduction, reduction of the use of non-renewable raw materials)
- **Technologies for manufacturing materials for high-risk applications**, such as materials to operate in specific environmental conditions, explosive atmospheres, biological and chemical risks.
- **New processes for manufacturing composite materials on a large scale** as well as tools to process them (wear resistance, low cost, flexibility).

Interaction with Other Intervention Lines

- Integration with LI3 and LI4 with regard to the improvement of monitoring/diagnostic tools, which is possible thanks to materials for new sensors, actuators, wireless systems,
- Integration with LI3 also with regard to the impact of the processing of new materials on the workers' health risks;
- Generative design is a topic shared with LI7, for a greater integration of the materials' data in computing systems' libraries.
- Integration with LI4 with regard to the technologies for the production of energy materials. The aim is to achieve a large mass production that is competitive on the global scene and yet meets the safety and environmental sustainability standards of EU regulations.

Time Horizon

Short-term goals (2–3 years):

- Manufacturing of structural and functional materials: this goal, which is currently consolidated at laboratory level, will be effectively introduced into the manufacturing system in the coming years.

Medium-term goals (4–6 years):

- Technologies for the use of nano-materials: the technologies that will allow industrial production in the next five years will have to be developed in the short and medium term.

Long-term goals (7–10 years).

- Production of energy materials with particular reference to the segments of the battery value chain, to achieve the set goals by 2030.
- Development of new processes for the manufacturing of composite materials on a large scale: this goal is strongly correlated to the evolution of technological production processes (from traditional to innovative ones such as additive manufacturing) and is currently in a mature phase as regards manufacturing of composite materials, but still ongoing for large-scale production.

7   PRI5.6. Micro-Scale Processes, Products and Functionalities

In recent decades, a strong trend has emerged towards the miniaturization of devices, to extend their use to contexts with space and weight limitations. The electronic field, with MEMS, was the pioneer of this breakthrough towards miniaturization, first with laptops and then with smartphones. The coming of microengineering, in addition to microelectronics, has generated new product and process strategies that are becoming significantly widespread in the aerospace, automotive and, above all, biomedical

industries. The latter, in particular, represents the real next frontier of micro devices development. In fact, applications such as lab-on-chips and microfluidic devices in general, for home care and self-diagnosis, have become attractive development areas for the scientific community and the industrial world.

In the field of micromachining, two different approaches can be identified, namely one that specifically focuses on the creation of micro components and one that deals with developing micro functionalities on macro products. These two approaches often involve, in different ways, main micro-processing techniques such as micro EDM, laser micro-processing, micro-milling, injection micro-molding, surface micro structuring. In other cases, however, they all contribute, thanks to an interdisciplinary approach, to the development of very complex devices with a massive impact in terms of diffusion.

The "micro factory" has become the new manufacturing standard, and it focuses on the realization of micro components and micro devices. The production of micro parts often requires special manufacturing, handling and assembly environments, such as clean rooms or vacuum chambers. A prerequisite for both the micro-factory and the (macro) factory, is the achievement of complete process integration. The manufacturing of micro parts can, in fact, be facilitated if different processes (or process phases) are performed with only one positioning, in order to contain machining tolerances, with micrometric or even sub-micrometric precision. A new concept of factory is being defined, as a result of the high cost of the devices and equipment used in microfabrication, and the high technological competence required, namely the concept of a widespread (micro) factory, in which the various parts of the equipment are available in different places, towns or even regions. This approach distributes the costs of purchasing and operating equipment, but it also requires planning to optimize the transfer of components or semi-finished products (sometimes in considerable volumes) from one place to another. Thus, "design for micro-manufacturing" and "design for micro-assembly" are no longer alternative, but strongly interconnected approaches. An aspect that is positively affected by this miniaturization process is certainly logistics. Indeed, moving these micro parts is very simple and very economical as their small size makes them considerably easier to be packed and transported safely, while also ensuring the management of large volumes.

Therefore, the essential goals for the next few years, in order to bring the micro manufacturing sector to an important level of feasibility, are:

- **New approaches focused on the reliability of micromachining processes**: a topic in great demand by the European Community is "reliability", since the medium-term goal is to reach industrial production level for micro-base devices and/or components, through the study and development of new approaches that improve the reliability of micromachining and surface functionalization and structuring;
- **New approaches for the geometric characterization of products and functionalities at micro level**: this is one of the most critical aspects of micro manufacturing because the typical "macro" approaches do not work when it comes to the characterization of a micro product or functionality due to technical limitations,

because of its small size and the risk of damaging micro components. It is therefore necessary to study and develop new inspection technologies, new approaches and methodologies to support the geometric and surface characterization of micro products.

- **Methodologies and approaches for simulating micro processes:** simulation is fundamental for virtualization of processes in order to minimize errors and reduce manufacturing costs. Several efforts have been put in recent years in the simulation of micro processes. This has highlighted the need for new approaches to support processes such as micro injection molding and laser-material iteration, with high-brightness sources as well as ultra-short pulses, micro electro-erosion and micro milling.
- **New micro factory models**: the current approach to micromachining as dedicated to individual independent processes need to be overcome. In particular, the migration to "micro factories" needs to be supported by integrating the different micromachining processes and minimizing mistakes, ensuring high production quality also through the distributed micro factory concept.
- **Technologies and systems for assembly at a micro geometric level**: this is an aspect of great scientific interest which, however, still has a very low TRL. The handling of micro components presents several criticalities. This involves the need to study new technologies and systems for assembly operations such as the gripping of a micro component, its correct orientation and its release.

Interaction with Other Action Lines

- In view of the research priorities expressed by LI2, micro technologies, especially in the manufacturing of parts made with innovative materials, can be considered highly sustainable given the small size of the devices and the consequent lower use of materials.
- The concept of micro factory requires interaction at a macro level with LI4, LI6.

Time Horizon

Medium-term goals (4–6 years):

- **Reliability of micromachining processes.**
- **Geometric characterization of products and functionalities at micro level:** reaching a level of geometric characterization for micro components, as is already available for macro components, is still an open challenge. Eventually, however some light begins to be shed on the goal. The great scientific efforts made over the last few years to identify characterization criteria for the micro sector are moving in the right direction. The real challenge is implementing vision systems also for the control of micro components during the manufacturing phase
- **Simulation of micromachining processes:** the simulation of micro processes is very complex since it often presupposes the use of software developed for conventional processes, the reference models of which must therefore be adapted. The main difficulty lies in the fact that anything considered negligible at macro

level takes on considerable importance in the micro field. Let us think, for example, of the Van der Walls forces, the surface tension rather than the adhesion coefficient.

Long-term goals (7–10 years).

- **Technologies and systems for handling and assembly at micro geometric level:** The handling of micro-components, their correct orientation and release are very complex issues, and they still require a lot of research efforts combined with the need to rethink the devices' design with a view to minimizing as much as possible both handling and assembly phases.
- **Integration of micro processes towards the concept of micro-factories**: this is the real challenge for the future, i.e. the integration of various micro-machining processes, at present still often used independently.

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Strategic Action Line LI6: Evolving and Resilient Production

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Abstract The objective of this chapter is to describe the strategic action line related to evolving and resilient production (LI6). In particular, this chapter proposes research and innovation priorities aimed at exploiting a high degree of machine automation and self-learning, with levels of autonomy and adaptive intelligence designed to facilitate the operators' job. From the work with cluster members, it emerged in particular that the following topics need to be studied and developed in the coming years: modelling and simulation for the design and management of production systems as well as hardware and software technologies for production system reconfigurability. The technology enablers are linked to the availability of smart modular devices that can be integrated wireless in a transparent, autonomous way, capable of monitoring and controlling manufacturing assets and products, and supporting decision-making, ensuring ready access to all necessary operational, configuration, fault and maintenance data.

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1 Introduction

The use of sensors, automated controllers and embedded systems has become an essential part of production systems. However, many industrial companies have rather chosen to develop a proprietary Intranet of Objects, focused on local, restricted and closed-loop scenarios. Yet, the changes that are required of companies depend on a greater and deeper interaction between the various parts of the factory, based on collaborative machine-machine and human–machine behaviours. The analysis of the information collected and exchanged will allow to evaluate the occurrence of modifications and adapt the behaviour of machines, ensuring optimization of efficiency even in variable contexts. This will in turn encourage the implementation of manufacturing intelligence, i.e. a self-aware production system, capable of evolving and resilient enough to defy the uncertainties of the context.

Collaboration and connectivity will result in large amounts of data that will need to be analysed in real-time or near-real time and to be converted for the mobile devices of the decision makers at both central management and plant levels. Manufacturing firms will have a competitive advantage over their competitors if they can perform real-time analytics on a large volume of data from business processes, products and management systems.

The objective of this strategic action line is studying a new generation of production systems that can evolve over time to adapt dynamically to the changing conditions of the context, which are determined by the turbulence of demand, the speed of technological cycles, the dynamics of the competitive situation, and also by the dynamics resulting from sudden changes, such as catastrophic events like pandemics. The new production systems should, therefore, be conceived like evolving and resilient ones thanks to a high degree of machine automation and self-learning, with levels of autonomy and adaptive intelligence to facilitate operators to a large extent. Priority research topics regard: modelling and simulation for the design and management of reconfigurable production systems with related hardware and software technologies. Technological enablers will be dependent on the availability of modular and intelligent devices integrated wireless in a transparent and independent way, capable of monitoring and controlling production assets and products, and of supporting decisions based on data related to the entire operational, configuration, failure and maintenance processes (Fig. 1).

This objective will be implemented through research activities on the following areas:

- **Reconfigurability:** Design and control of reconfigurable and modular production systems;
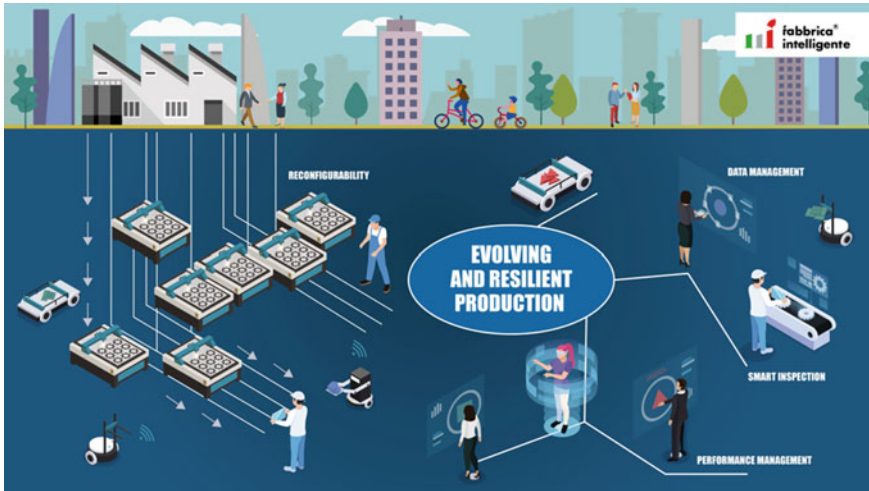
Fig. 1 Strategic Action Line 6—Evolving and resilient production

- **Components:** Components, sensors and intelligent machines for adaptive and evolving production;
- **Performance:** Systems for the prediction of manufacturing and logistics operations management and performance;
- **Inspections and data analysis:** Smart Inspection & Machine Learning;
- **Robot-human collaboration:** Human–Robot Co-working.

Artificial intelligence and related techniques will also have a significant influence in the development of each research and innovation priority.

Expected impact: improvement of the manufacturing sector's capacity to adapt to the continuous evolution of technological, economic and market scenarios; improvement of the sector's ability to respond to endogenous and exogenous shocks (from natural disasters to the temporary unavailability of critical infrastructures, from epidemics and health emergencies to contingent situations with a high impact on performance and continuity of operations); decrease in time to market; improvement of production factors' efficiency; improvement of production control in real time/near-real time; improvement of system performance prediction capacity and greater human–robot collaboration.

The research and innovation priorities of the strategic action line on Industrial Sustainability are:

- **PRI6.1**—Design and control of reconfigurable production systems
- **PRI6.2**—Components, sensors and intelligent machines for adaptive and evolutionary production
- **PRI6.3**—Digital Twins for performance prediction and operational management of highly flexible production and logistics systems
- **PRI6.4**—Smart Inspection & Machine Learning

- **PRI6.5**—Human—Robot Co-working

2   PRI6.1 Design and Control of Reconfigurable Production Systems

The evolution of market and the speed of change in consumer needs are shifting mass production in favour of new products that can quickly meet immediate needs even when caused by disruptive events and trends related to product customization.

The new paradigm of competitive manufacturing will be redesigning assets adapting as promptly as possible to market changes, relying on an adaptive and resilient production system. The goal of this research and innovation priority is the study and development of technologies and algorithms for the design and control of highly reconfigurable manufacturing systems (i.e. easily integrated, adaptable and scalable).

Compared to the state of the art, the problem of reconfigurability must be considered at both machine and production line level, which involves the necessary development of advanced design, control and simulation systems and techniques that can adapt and optimize production models according to the product or the product mix.

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

- **Modelling and simulation.** To make the most of each factory's peculiarities, it is necessary to study and develop suitable software to speed up and improve the definition of the digital factory model and develop corresponding simulation environments, through procedures based on techniques of identification and adaptive recognition of the resources used in the production system—machinery, people, and materials. In particular, it is necessary to study new systems for the (semi-) automatic generation of simulation models (e.g. discrete-event simulation) starting from a digital model ("model-driven generation"), the use of simulation to support Artificial Intelligence generating synthetic data that can be used as training datasets. In every case, simulation draws the major benefits from the creation of accurate and constantly updated digital twins.
- **Methodologies for the design of evolving production systems.** In terms of design methodologies for production systems, it appears necessary to develop design techniques for production systems, such as, for instance, design for reconfigurability, design for maintenance, design for fast set-up and ramp-up, with particular attention to the design of systems for the production of unit batches and evolutionary systems.
- **Configuration of communication and data exchange architectures.** System configuration involves not only configuring the system's components but also the data architecture and data exchange systems among the different modules, which should be based on automatic transfer activity, such as to enable the configuration of the production system's data-model part.

- **Configuration of monitoring and control.** The reconfigurability of a production system requires adequate methodologies for configuration of a monitoring and control system that should adapt to the variability of applications and operating conditions. In particular, It is necessary to study and develop new methodologies for safe and remote commissioning of production lines when technicians can't be on site with the support of systems for the modelling, simulation, control and monitoring of the systems.

Interaction with Other Lines of Action

LI1—Personalised production: reconfigurability affords the necessary adaptability for personalised production systems.

LI4—High efficiency production & zero-defect production: a reconfigurable production system can adapt to varying operating conditions to achieve maximum efficiency at all times.

LI5—Innovative production processes: reconfigurability is frequently the key element for the development of new highly flexible production processes.

Time Horizon

Short-term goals of 2–3 years (starting from existing technologies):

- Solutions to simplify the definition of the digital factory model and corresponding simulation environments, through procedures based on techniques of identification and adaptive recognition of the resources used in the production system—machinery, people, materials, also aimed at remote set-up and control;

Mid-term goals of 4–6 years (significant development required):

- Advanced design and simulation technologies to translate product customization specifications into the design, production and development of the necessary machines and plants for those products;
- Configuration of appropriate communication architectures to integrate different control and data analysis functions;

Long-term goals of 7–10 years (requiring the integration of all the technologies developed by the research and innovation priority):

- Configuration of advanced monitoring systems for production plants, generation of dynamic digital twins with extensive use of machine learning and deep learning techniques.

3 PRI6.2 Components, Sensors and Intelligent Machines for Adaptive and Resilient Production

An adaptive and resilient production system requires new components that can detect and exchange data in an effective and intelligent way as well as new methodologies for managing collected and exchanged data which need to be integrated into the machines operating in the production plant.

Adaptive and resilient production systems will be characterized by multisensory networks for the supervision of processes and environments and for data collection. Increasingly sensitive and cost-effective sensors will facilitate the measurement of various process-influencing parameters, including on site measurements for process monitoring.

Sensor networks collect data that can be stored and processed near processes (edge computing) or uploaded to a private or public cloud network. Data must be available anytime and anywhere within the production system so that they can be processed through artificial intelligence systems, improving knowledge of a process at a systemic and detailed level.

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

- **Intelligent embedded sensors.** In order to improve the flexibility of the sensors used in machines, it will be necessary to develop techniques for miniaturization, which should lead to the generation of low cost sensors, with adequate energy autonomy and implementation of protocols for data communication. These innovations will be implemented on on-board sensors, equipment sensors, sensors on transport and handling systems and on the materials being processed. It is also necessary to research and develop sensors that can pre-process data on board data collection stations so that the processed data can be communicated to the control units and databases for the collection of the factory's big data, thus avoiding a redundant transfer of data.
- **Sensors and components for the Internet of Actions.** Development of sensors that can support remote actions, to avoid any loss of sensorial aspects, by enabling interactive and adaptive actions. Expert operators can thus operate remotely, getting around any limits to the mobility of individuals. In particular, the development of new sensors and actuators will be essential in creating a sense of presence when working remotely, as well as accurate and safe remote actions. In particular, new sensors and actuators that receive and reproduce tactile, visual, sound and olfactory signals are necessary. The devices used in IoA architectures must be designed to appropriately manage the interaction between the environment and humans and ensure the connection of devices present in the shopfloor to provide data on the status of ongoing processes. In particular, these devices should be suitable to handle a large amount of heterogeneous multi-source data, with adequate solutions to process the data streams with a view to extracting relevant information.
- **Universal intelligent gateways.** To increase the flexibility of machines and production lines, universal intelligent gateways need to be studied and developed and they should be vendor-neutral both in terms of transmission protocols

and in terms of the provided data formats. It will also be necessary to study new decoupling systems between the data measurement and collection part and the machines and plants control system.

- **Intelligent processing methods and tools.** To optimize the use of data generated by sensors, it is necessary to study and develop an adequate data collection and exchange infrastructure that can ensure data consistency and comparability. In addition, new protocols for accessing and recording data are needed, to implement large databases (i.e. big data) that are secure, persistent, resilient, modular and scalable.
- **In-process monitoring of sensors.** Precise and stable models for sensors and components need to be researched and developed, to ensure resilience and adaptability during the working cycle, with a view to approaching the process in a precise and deterministic way, to avoid deviation in the behaviour of the sensor or component from their model. Furthermore, using these models, and advanced machine learning and deep learning techniques, it will be possible to develop self-diagnostic strategies for the machine and, in the case of known and repetitive processes, predictive maintenance strategies.

Interaction with Other Strategic Action Lines

LI5—Innovative production processes: the new components and materials and the most effective sensors will forge intelligent machines to be deployed towards the design of innovative production processes.

LI1—Personalized production & LI4—High efficiency production: the new components will improve production systems, increasing both their adherence to individual needs (LI1) and their production efficiency, by reducing waste and defects (LI4).

Time Horizon

Short term of 2–3 years (starting from existing technologies).

- Methods and tools based on "Data Fusion", "Machine Learning" and Artificial Intelligence logics for centralized data collection and processing;
- Tools based on innovative HMI and augmented reality able to simplify the corrective intervention by the operator.

Medium-term of 4–6 years (significant development required).

- New design methods for embedded sensors;
- Intelligent universal gateways that interface with sensor networks both at machine and at production system level;
- Integration of sensors that operate as distributed autonomous systems for the acquisition of data on the context, the machine and the production process;
- Methods and actuators for the implementation of adaptive and evolutionary behaviours at component/machine level.

Long term of 7–10 years (requires the integration of all the technologies developed by the research and innovation priority).

- Integration, at machine and process level, of "in-process" monitoring techniques for a closed-loop control of semi-finished/finished products' quality and for the implementation of self-diagnostic and predictive maintenance logics.

4   PRI6.3 Digital Twins for Performance Prediction and Operational Management in Highly Flexible Production and Logistics Systems

The introduction of Cyber Physical System (CPS) allows the development of advanced and highly flexible production and logistics systems. With CPSs in the factory, shop floor control architecture for supervision in real/near-real time becomes feasible. This development is required by the current high product-variety trends, which result in a resource management complexity that has to be synchronized to the production-logistics system.

The "traditional" ability to manage and control the system in real time is supported by a new ability to predict performance in short-term decision-making (i.e., a few hours, several work shifts, a few weeks of planning) and supervision of decisions regarding operations. The use of Digital Twins (DTs) is a help in this context, for the processing of real-time/near-real time information from the field to support production control, in coordination with related activities such as maintenance, factory logistics, quality and others.

The potential of DTs in this area promises benefits in terms of enhancing system performance prediction capacities starting from constant monitoring of activities, in terms of ensuring the robustness of production programs in the face of process variability and frequent changes in workload conditions, and in terms of enabling a high response capacity to market needs while respecting production efficiency and costs. These features support the decision makers in the prompt evaluation of the various alternatives involved, so that they can select the best option in consideration of the system's operating conditions.

The general goal of this research and innovation priority is the study and development of methodologies and tools geared to improve the use of DTs in real time/near-real time, for the ultimate purpose of exploiting their high potential for performance prediction and operational management of production and logistics systems with high flexibility.

In particular, the introduction of this type of DT is intended to complement existing architectures for the control and coordination of production, based on systems classed as Manufacturing Execution Systems (MES), and on advanced systems built with Internet of Things (IoT) infrastructures, introduced in order to integrate information on the state of the process, machinery and other resources involved in factory production and logistics also by applying Artificial Intelligence technologies for the

classification and prediction of the state of the processes, technical assets (such as machines, handling systems, equipment, …) and the activities of the operators in the operating stations.

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

Integration of DTs with IoT platforms for monitoring the real state of the production-logistics system, and in general with standard connections and protocols to ensure communication with sensors and local controllers from the field, to improve the identification of the critical factors that emerge from the shop floor in relation to the status of the process, the machinery and other resources involved in factory production and logistics. In particular, these DTs must be able to generate a feedback on the system-control process and the related machinery and equipment in progress, and facilitate the synchronization of material flows in the Digital Twin's real time near-real time simulation.

Development of DT's advanced functionalities for the monitoring and analysis of material flows, starting from the logical and physical traceability of specific elements (the marking, labelling of products or, in general, from information collected through tracking devices).

Integration of DT with Artificial Intelligence (AI) techniques for the classification and prediction of operating conditions, state of health and future degradation of machines and other technical assets (with machine learning algorithms to support classification and prediction with a view to integrating the simulation capabilities of the DT).

Development of advanced functions in the DT for monitoring purposes and use of augmented intelligence in the execution of operators' tasks, to improve, including through AI techniques, a human–machine interaction in an increasingly close collaboration scenario, to optimize coordination and efficiency in the execution of operational tasks and facilitate operator productivity by mitigating the complexity due to the variety of products.

Integration of the DT with methods and tools to monitor and supervise production, to adapt the production program depending on the status of the process, machinery and activities in the various operating stations, to increase the robustness of performance in the face of process variability and frequent changes in workload conditions.

Development of advanced functions in the DT to monitor and analyse the sustainability of production technologies, to analyse consumption and limit waste of resources employed as part of a process of continuous performance improvement that combines DT simulation with "traditional" analysis techniques.

Eventually, the production-logistics system will draw overall benefits from the prediction, adaptability and resilience driven by a supervisory control in real time/ near-real time, supported by the DT and by the systems backing operational decisions that are connected to it. In particular, real time/near-real time DTs for production-logistics systems will guarantee:

– Reduction of delivery lead times and reliability of production programs. Prediction, combined with optimization and verification of the variability impacts on system performance will allow greater confidence in achieving the objectives required by the supply chain in which the factory operates;
– Productivity and production costs, thanks to the optimization of the use of resources and of the execution of service activities (such as equipment preparation, material logistics, maintenance), while operating in conditions of variability;
– Higher product quality, thanks to the advance assessment of any process and machinery decay, in relation to current conditions and system prediction;
– Sustainability of production technologies, with the continuous improvement of performance and prediction of it;
– Operator productivity, taking into account its impact on system performance in ever tighter man–machine collaboration scenarios;
– Effectiveness of the decision maker's task, thanks to the possibility of evaluating the trade-offs of different decision-making alternatives generated through the supervisory control of the system.

Interaction with Other Lines of Action

LI5—Innovative production processes: DTs should be developed in a way that is functional to technologies.
LI7—Digital platforms, modelling, AI, security: The technologies developed in the research and innovation priority can be applied to develop the platforms under LI7 and vice versa.

Time Horizon

Short-term goals of 2–3 years (starting from existing technologies).

- Integration of DT with IoT platforms for monitoring the real status of the production-logistics system
- Development of the DT's advanced functionalities, to monitor and analyse material flows
- Integration of DTs with Artificial Intelligence (AI) techniques for the classification and prediction of operating conditions, state of health and future degradation of machines and other technical assets

Mid-term goals of 4–6 years (significant development required).

- Development of advanced functionalities in the DT for the monitoring and analysis of operators' tasks
- Integration of the DTs with the methods and tools for monitoring and supervising production

Long-term goals of 7–10 years (requiring the integration of all the technologies developed by the research and innovation priority).

- Development of advanced functionalities in the DT for the monitoring and analysis of the sustainability of manufacturing technologies

5   PRI6.4 Smart Inspection & Machine Learning

Competition on global markets is determined by the possibility of ensuring, on the one hand, the quality of finished products and, on the other, the perfect efficiency of production systems, in a dual relationship in which the production system determines the quality of the product, while the quality of the product is evidence of the efficiency of the system. In an adaptive and resilient production system, the ability to verify production quality in a simple and intuitive way is essential, and smart inspection systems based on image analysis are the most attuned to this need. At the same time, the complexity of relations between system and product, in a context of continuous changes in products and operating conditions, can be managed through continuously adapting artificial intelligence systems that do not need reprogramming.

The goal of this research and innovation priority is the study and development of smart inspection systems and algorithms constantly connected to the production system. Compared to the state of the art, it is necessary to develop new smart inspection systems that can be intuitively programmed and that exploit the data exchanged in the factory to obtain a prediction of the quality of production while, on the other hand, helping to generate reliable information for the maintenance of the production system. This activity will have to allow a "Zero"-defects oriented strategy, with a production quality management that leverages the capabilities useful to other company areas, such as product design and machine design.

The main gap in state of the art systems is the lack of availability of smart inspection systems that are at the same time representative of a large number of product characteristics and that can be interpreted for decision-making purposes. For example, the development of supervised Machine Learning techniques, both predictive and classifying, should support the collection of information that comes from products and should automatically adapt to ever different products, without the need to be reprogrammed. Finally, it is necessary to develop advanced predictive maintenance systems that are related to production quality as well as to a machine's sensor system.

The availability of reliable smart inspection systems will allow operators to enter controls online, increase production reliability and reduce costs and time to market at the same time.

The objectives of this research and innovation priority are:

- **Teach by demonstration.** Teach-by-Demonstration algorithms to programme collaborative and industrial robots, define sequences in an intuitive and yet robust way, in line with any constraints regarding system, product and interaction with the operator. Programming must ease high operational flexibility and avoid learning fatigue, through the implementation of human in the loop adaptation phases. The sequences have to be generalizable to adapt to different contexts. Efficient sequences should be implemented over a wide range of operational skills, including high-dexterity ones.
- **Machine learning for smart inspection.** Research and development of Machine Learning/Deep Learning algorithms is essential to ensure predictive quality to Smart Inspection systems. They would not only allow the correct classification of

product quality, but also the prediction of future events connected to the quality of the product, with a view to anticipating their occurrence. These algorithms must be able to optimize their parameters, adapting to different products and contexts, with no need to be reprogrammed. They should also allow an evaluation of the vision system while it is being designed and implemented, so that it produces as accurate a rating as possible.

- **Smart inspection systems.** Research and development of Smart Inspection and Machine Learning systems that can communicate with other interconnected machines, receiving information on format, material, operating conditions, or environmental changes, and automatically adapt their rating parameters to the changed production context and generate appropriate optimizations of the internal parameters. At the same time, the predictive capacity regarding specific product quality drifts must be used to activate predictive maintenance systems, to tackle the causes of subsequent defects.
- **Predictive maintenance.** Research and develop of advanced predictive maintenance systems that can collect data and signals, whether through passive systems based on embedded sensors, active systems based on the activation of specific components, or systems and analyses of the generated response. Such systems must be able to interpret the variability of the working conditions of the controlled organs according to the processes in progress, including by using environmental information (e.g. temperature, vibration), and information from Smart Inspection systems, for the determination of an optimal action time. The evaluation of the maintenance state of a complete machine system must be provided independently in terms of the estimate of the residual life of its elements, breakage likelihood, estimate of maintenance costs and potential obsolescence. It must be part of a general maintenance policy for the plant that allows to group individual actions and schedule them correctly for system management purposes.
- **Design of self-repairing machines.** In a medium-long term perspective, the integration of all the above techniques should lead to the creation of machines and systems with a capacity for self-diagnosis, remodelling and dynamic adaptation of process conditions, identification of maintenance interventions, choice of optimal strategies for intervention, automatic acquisition of replacement components, generation of detailed maintenance sequences, integration with augmented reality systems for operator or robot assisted intervention, self-checking, self-programming.

Interaction with Other Strategic Action Lines

LI4—High efficiency integrated systems & zero-defect production: Smart inspection systems can be exploited to implement high efficiency systems.

LI5—Innovative production processes: Smart inspection systems can be integrated into the development of innovative production processes.

Time Horizon

Short-term goals of 2–3 years (starting from existing technologies).

- *Teach by Demonstration* algorithms for collaborative and industrial robots that can program sequences in an intuitive and yet robust way, respecting the system, product and operator interaction constraints.
- Advanced predictive maintenance systems that can collect data and signals through passive systems, based on embedded sensors, or active ones, based on the activation of specific components and analyses of the generated response.

Mid-term goals of 4–6 years (significant development required).

- Machine Learning/Deep Learning algorithms for the predictive quality of Smart Inspection systems
- Smart Inspection and Machine Learning systems that can communicate with other interconnected machines.

Long-term goals of 7–10 years (requiring the integration of all the technologies developed by the research and innovation priority).

- Design of self-repairing machines, with self-diagnosis, reshaping and dynamic adaptation of process conditions, identification of maintenance actions, choice of optimal intervention strategies.

6   PRI6.5 Human Robot Co-Working

Today, collaborative robots are available on the market and provide safe interaction between humans and robots. However, the performance that can be achieved with collaborative robots is still limited.

Compared to the state of the art, this research and innovation priority is based on the fact that human–robot collaboration aims to optimize production and improve work quality to obtain robotic systems that make the work of operators easier and efficient.

The goal of this research and innovation priority is to promote the study and development of algorithms for human–robot collaboration in the context of production systems. The interaction between the operator and the robot must be efficient, natural and intuitive. Furthermore, robots should contribute to the improvement of working conditions, improving posture and relieving users of the heaviest tasks (e.g. lifting loads in excess of 10 kg).

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

- **Awareness.** Robots should be designed to be aware of the logistics and nature of its surroundings to optimise performance in human–robot interaction. It is therefore essential that robots process the data collected by on-board and off-board sensors to gain awareness of the surrounding environment and of the operator with whom it is collaborating. In particular, it is necessary to research and develop new sensors

and data processing algorithms to provide robots with a kinematic and semantic representation of the surrounding environment and of the operator. Robots and their control systems will thus be aware of the nature of and movement in their surroundings.

- **Task assignment.** To succeed in achieving optimal human–robot collaboration, it is essential to segregate as best as possible the tasks that each of them is expected to carry out during execution of a collaborative work. Task assignment and dynamic scheduling algorithms are required, in order to assign work to man and robot in an optimal way, depending on existing constraints (e.g. constraints related to the quality of work), required performance (e.g. minimizing execution time) and monitoring operations.
- **Rescheduling.** Collaborative robots work in a very dynamic environment and it is highly unusual that a movement planned at the beginning of a task can be completed without the robot having to stop for safety reasons. This behaviour leads to a decrease in performance, which in turn calls for dynamic rescheduling algorithms that can induce the robot to dynamically choose the best path to perform a task, thus avoiding unnecessary downtime, by relying on sensors' data and making a prediction of the behaviour of the operator (by means of AI algorithms).
- **Communication.** A user-friendly and intuitive human–robot communication needs to be studied to establish a natural and efficient collaboration. The operator would thus be able to adapt the behaviour of the robot to her/his specifications, optimizing the collaboration thanks to new multi-modal communication techniques between human and robot and create a gestural, vocal and physical interaction that maximizes the synergy between the two.
- **Quality of work.** Human–robot collaboration should be based on robots to improve the quality of the human operator's work, and new solutions for trajectory generation should take into account not only process performance, but should optimize the quality of the human operator's work (e.g. posture).
- **Collaborative Automation.** Building a collaborative robot is not enough if the cell that surrounds it consists of non-collaborative automation. Therefore, the concept of collaborative automation must be studied, and the automation needed for a safe interaction between man and technology must be developed. Only by using collaborative automation together with an intelligent collaborative robot will a collaborative work cell be possible.

Interaction with Other Lines of Action

LI5—Innovative production processes: the human–robot collaboration techniques developed in this research and innovation priority can be exploited for the development of innovative production processes.

Time Horizon

Short-term objectives (2–3 years) start from existing technologies to optimize:

- Robot's awareness of the surrounding environment;
- Rescheduling of the robot for unplanned program changes.

Medium-term objectives (4–6 years) require a significant development as regards:

- Separation of tasks between robot and operator to perform a work in a collaborative way;
- Systems to optimize the quality of work for the operator.

Long-term objectives (7–10 years) require the integration of all the technologies developed by the research and innovation priority in the short and medium term in order to improve:

- Communication to improve human–robot collaboration;
- Collaborative Automation to ensure that not only robots but also all the technologies within the factory interfacing with humans and robots are collaborative.

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Strategic Action Line LI7: Digital Platforms, Modelling, AI, Cybersecurity

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Abstract The objective of this chapter is to describe the strategic action line related to digital technologies for production processes and systems (LI7). In particular, this chapter proposes research and innovation priorities aimed at innovative digital architectures for the monitoring, control and management of manufacturing activities and related assets, modelling new products/services and production processes, use of AI, Big data and adequate Cybersecurity systems. More specifically, the research and innovation priorities are based on the assumption that criteria need to be defined for the management and transformation of raw production data into strategic information for decision makers, identifying the information to be collected from each digital access point by means of suitable enabling technologies and then delivered as appropriate. Digital platforms and cybersecurity also play a significant role in the definition of dynamic supply chain models.

Keywords Digital platforms · Industrial IoT · Business analytics · Cybersecurity · Supply chain

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1 Introduction

The different organizational and technological maturity levels of companies, especially of SMEs, call for a reference framework that is sustainable and feasible over time and that can adapt to each company's specific capabilities and the peculiarities of the Italian context. The following aspects should be considered:

1. The high number of SMEs that are part of the Italian subcontracting supply chains. A considerable portion of them has yet to adopt effective digital solutions to be integrated and compete also on the international scene.
2. The wide spectrum of digital solutions available in Italy where there are no dominant players with the capacity to set standards for the adoption and use of digital solutions.
3. The ability of the Italian producers of machines, lines and plants to integrate them with digital and automated solutions.

The digitalization of Italian manufacturing focuses on the development of flexible, reconfigurable, easily integrated digital architectures at sustainable costs, enhancing the professional profiles connected to the digitalization of companies.

In particular, cloud-based approaches should be integrated with edge computing solutions, to make the most of the benefits associated with technologies such as AI, digital twin, Industrial IoT. The various enabling technologies are chosen and adopted by the products available on the market, and combined with each other on the basis of actual needs and of the advantages they can guarantee in the short, medium and long term.

Investment in research and innovation activities that go beyond business solutions is necessary. The use of platforms can profoundly change operation methods in the manufacturing sector, opening up scenarios that can be promising for companies, allowing companies to federate and increase their critical mass. There is however an element of risk, as platform managers may gain a dominant position and limit the freedom of movement of the companies that use the platform.

This set of challenges prompts the vision of Industry 5.0, which expands the typical technological aspects of Industry 4.0 to include in the new technological developments the role of humans and add emphasis on sustainability.

Strategic action line LI7 aims to define research and innovation priorities for the development of innovative digital architectures for the monitoring, control and management of the progress of production and its assets, the modelling of new products/services and production processes, the use of AI solutions, Big data and adequate cybersecurity systems (Fig. 1).

In particular, the research and innovation priorities of the LI7 line must take into account that it is becoming increasingly necessary to define criteria for the management of raw data in production and to transform them into strategic information for decision makers, identifying the information to be collected from each digital access point through suitable enabling technologies that need to be appropriately conveyed.

Fig. 1 Strategic Action Line 7—Digital platforms, modelling, AI and cyber security

The new systems to be developed must ensure that each digital access point provides adequate information at the appropriate organizational level, growing in complexity and granularity depending on the size of the company.

Particular attention must be paid to the advantages offered by solutions that are:

- Open, to allow interoperability between systems through open-source software products used in compliance with the Copyleft granted by the author.
- Flexible and reconfigurable, even remotely, to support the resilience of companies in the face of unexpected and unplanned events.
- Based on models that can interpret the meaning of the collected data.

LI7 aims to formulate its goals taking into account that:

(1) Manufacturing companies must integrate their processes and flows into their upstream and downstream supply chains, especially if they are SMEs working through subcontracting arrangements. Dynamic Supply Chain models based on collaboration platforms make it possible to manage networks to increase their efficiency, productivity and resilience.

(2) The new consumption dynamics are gradually shifting from purchase of durable equipment to their use in terms of services (servitization), therefore the entire design and production process must be based on new models and tools, to improve the offer of product-service solutions.

(3) The integration between design, production and business management forces companies to remove the existing barriers between digital systems for product and process design (CAD, CAE, CAPE, CAM, CAPP), process and system supervision and control (MES, CMMS, QA) and management systems (ERP, Logistics, CRM, BI). Such integration can be implemented by adopting new

systems/products, and promoting their functional interoperability. At factory level, it is necessary to integrate production, logistics, quality and maintenance to increase efficiency and effectiveness of production systems.

(4) Given the heterogeneity of machinery, there is a need for infrastructures and production processes, field architecture for the interconnection of machines, data collection, processing and integration with IT systems, to ensure evolution and scalability over time, as well as the possibility to use and integrate the various technologies available, and provide advanced digital services to users at various levels of the organization.

(5) Advanced business and industrial analytics methodologies will have to support the time-consuming operations typical of off-line simulation and Deep-Learning in order to feed on-board edge systems with predictive models.

(6) Digital twins based on constantly updated and reliable "single sources of truth" should support decisions in all phases of the process and product life cycle, and produce a single and synchronized information flow.

(7) The integration between the physical and the digital world (combined with the growing proliferation of vulnerabilities at all levels, persistent cyber threats due to synergy of different attack vectors, from the physical, to the digital and social worlds) exposes industrial realities to new types of risk and to potentially negative impacts in terms of interruption of manufacturing services, quality and integrity of products, damage to tangible production plants, up to physical damage to the people involved in the production cycle.

Because of the value-added services it has introduced—such as predictive maintenance and, more generally, connectivity to IoT platforms inside and outside company networks—digital transformation increases exposure to cybersecurity risks. Developing a series of architectures, platforms and services that guarantee resilience in a manufacturing plant's activity is therefore an essential business and regulatory compliance requirement.

Expected impact: pervasive use of digital platforms, technological infrastructures, advanced services for production chain management and distribution of product/ service systems targeted to the end customer, to increase efficiency and productivity and achieve an adequate connection between supply and demand; improvement of trust creation processes in business networks; greater interconnection between the players in the supply chain; faster delivery of advanced digital services; full integration and normalization of data; interoperability and scalability of the deployed systems; greater effectiveness and efficiency of technologies thanks to cybersecurity; increased safety of production systems.

The research and innovation priorities of the strategic action line on Digital Platforms, Modelling, AI and Cybersecurity are:

PRI7.1. Models and tools for the management of collaborative companies and dynamic supply chains
PRI7.2. Design of integrated product-service solutions
PRI7.3. Models and tools for production monitoring and asset management
PRI7.4. IIoT models and tools for factory data collection

PRI7.5. Business and industrial analytics methodologies

PRI7.6. Tools for modelling and management of information based on digital twins

PRI7.7. Models and tools to support Information and Cybersecurity.

2   PRI7.1. Models and Tools for the Management of Collaborative Businesses and Dynamic Supply Chains

The strategic scenario that Italian manufacturing is facing is characterized by high international competition, both in terms of cost and technological innovation, turbulence and uncertainty in the upstream and downstream markets (recently emphasized by the tensions on trade regulations). Moreover, there is a need to manage complex and dynamic business networks where reconfigurations can be associated with political events, such as custom duties or Brexit, and environmental, or health care events, such as the Covid 19 pandemic.

The scenario shows comparatively higher stresses in Italy, due to typical aspects like the well-known small scale of companies and the heavy dependence on foreign countries in both upstream raw material procurement markets and downstream final product markets.

With regard to raw material procurement, approaches based on circular economy have considerable importance. They show advantages not only in terms of environmental sustainability, but also in terms of reduction of procurement risk (both in relation to resource availability and cost).

As described above, it is essential for companies to operate effectively and efficiently within their global Supply Chains (SC). They should also aim to enter new SCs dynamically, and with similar efficiency, based on specific business opportunities.

Integration should be increased, in the first place, by improving machine connectivity within the various supply chain plants, and the capability for monitoring and controlling work-in-progress in real time, keeping track of both products and operating conditions, at different production sites. Integration, however, relies on data and information that are often available in different formats, and are a key prerequisite for collaborative integration in global SCs.

The full exploitation of this data is based on collaborative management within the SC and ensures integration of processes and flows that go beyond the corporate scope of each SC member. For these opportunities to become operational, it is necessary to develop methods and approaches that encourage trust among the participant, extract value from information and share the benefits among them.

The aim of this research and innovation priority is to study and develop new technological and organisational solutions and foster the creation and adoption of digital platforms according to an open model, based on interoperability of the various systems adopted by the different SC actors, and characterized by specific vertical process applications mapped onto mobile (e.g. 5G) or fixed (fibre) network architectures. These infrastructures are a key prerequisite for implementing approaches based

on big data analytics and AI algorithms in support of decision-making processes. In this sense, the distributed ledger paradigm offers features consistent with the distributed nature of the organizational processes and supply-chain flows.

The solutions developed should be geared to overcome trust problems between the various SC actors and increase transparency in the exchange of information all along the supply chain, possibly in a selective and suitably manageable way, and overcome the fragmentation of information thanks to an ontology-based vision of data.

Digital platforms become a key asset for the collaborative management of dynamic supply chains and are based on the following specific research goals:

- **Models and systems for the configuration of the SC**: these models should support the design and configuration decisions of the supply chain (e.g., selection of a new supplier, location of a production or logistics centre) through the following developments:

  o Systems for expanding the physical traceability of each product and component: ensuring tracking systems so that the causes of a problem can be easily identified throughout the supply chain. Such systems would have a useful application also in terms of managing counterfeiting issues;

  o Information-certification systems related, for example, to the processes carried out by suppliers, subcontractors, and distributors to extract reliable data through suitable mechanisms, making such data selectively accessible through distributed ledger and blockchain mechanisms.

  o Big Data analytics and Artificial Intelligence systems to support supplier analysis and selection based on specific performance not only in terms of operations (costs, time, and quality) but also of sustainability.

  o Definition of trust improvement mechanisms in collaborative contexts. In order to improve coordination within the SC, especially when decision-making is distributed, approaches to design and develop mechanisms for the definition of smart contracts also by means of blockchain as enabling technology;

  o Methods and tools to evaluate and optimize supply-chain robustness and to design supply chains to ensure the expected performances in different reference scenarios.

- **Models and systems to support the SC's operational management:** these models should be based on a system transparency level that ensures the necessary sharing of information for the management of manufacturing progress and general operations, extending to all the players in the SC. In addition, these models should help decision-making even during disruptive events, to ensure target performance thanks to techniques such as machine learning, simulation and artificial intelligence, and to guarantee data security and privacy. Particular attention should be paid to the study of innovative models for the management of dynamic and collaborative SC that enable the management of a products' end of life and support circular economy in general.

- **Digital twin for the SC**: study and development of a digital twin for the SC, based on methods to connect different digital models of the products, machines, lines of the SC's actors, ensuring the overall consistency and the modelling of complex interactions that generate emerging, hard-to-predict behaviours.

Interaction with Other Strategic Action Lines

Possible interactions with other Strategic Action Lines are as follows:

- LI1—Personalised production: the support in the definition of mechanisms that ensure the transparency of processes, the streamlining of the decision-making process and the facilitated collaboration along the SC can be synergic with the theme of modular factories.
- LI2—Industrial sustainability: SCs consisting of dynamic and collaborative companies make sustainable production processes easier and, particularly, consistent with circular economy. They also facilitate the management of flows between different SC players who exchange by-products as secondary raw materials. The objectives mentioned above can be linked to some general issues such as circular economy. For instance, transparency along the supply chain (in terms, for example, of time, quantity, quality) is essential to enable the use of by-products as secondary raw materials in a supply chain (indeed, the availability of this information is critical because by-products flows have lower continuity and predictability than conventional raw materials); smart contracts can foster such exchanges making them profitable and safe for the parties involved.
- LI5—Innovative production processes & LI6—Evolving and resilient production systems: both these LIs pursue actions related to "internal requirements" as defined above (one for all, process digital twin for LI5 and machine digital twin for LI6). These "internal requirements" are enablers of the PR at issue.

Time Horizon

Short-medium term goals (2–3 years).

- Models and systems for the configuration of the SC, to speed decisions at project level (e.g. selection of a new supplier) by using suitable indicators for company profiling.

Medium-term goals (4–6 years):

- Development of models and systems for the operational management of the SC, and development of distributed digital twins that allow the evaluation of emerging behaviours, thus supporting decisions concerning the configuration of the SC itself and operations management.

3   PRI7.2. Models and Tools for Designing Integrated Product/service Solutions

Durable equipment is increasingly being managed through a service-based model while until recently durable assets were mainly purchased in ownership. The commercial transaction is thus valorised not so much on an ownership basis but through the use of the asset itself. This trend is already established in both the B2B and B2C segments, for example in the aeronautical sector, where engines are supplied to aircraft manufacturers as a cost-per-flight-hour service, or in the automotive sector where vehicles or construction equipment are rented long term and paid per mile or working hour.

Also in the sector of capital goods for manufacturing, servitization makes it possible to integrate the sale of assets with services that ensure a machine's operating availability through on-condition and predictive monitoring and maintenance services.

This model also includes manufacturing processes supplied as a service (manufacturing as a service) by specialised companies that provide a machine's pay-per-use service to other manufacturing companies for particular processes that cannot be carried out on site.

The goals of this research and innovation priority are:

- **Platforms and solutions for advanced digital services** that enable traceability of a product's use to improve its configurability and support remote assistance through, for example:

  o Innovative APP and HMI for end users in SaaS (Software as a Service) mode and development of new interfaces between products and service to facilitate exchange of information between one component and another of an integrated solution and to enable appropriate support services.
  o Digital platforms for the management of multi-tenant cloud digital services.

- **Digital solutions for revamping** the existing product range, extending product life and improving product use, providing new interconnective functions to corporate systems or digital service platforms. In particular, it is necessary to focus on the study and development of:

  o Solutions involving the sensorization of machines to connect them to factory systems, in a safe and minimally invasive way;
  o Generation of interfaces that automatically and/or semi-automatically integrate existing solutions and ensure communication with a machine;
  o Automatic and/or semi-automatic systems interconnecting to company's MIS software or low-cost digital cloud service platforms that can be easily integrated to control work-in-progress and the improvement of predictive maintenance and factory automation;

    o Vision systems designed to interpret and reconstruct the system's appearance in order to rebuild and interpret the appearance of the shop floor even when only partial information is received from the sensors.

- **New multidisciplinary models and new PLMs** for the joint design of a product/service. They must integrate different knowledge and technologies necessary at the various design levels (Mechanics, Electronics, Automation, System software, Application software, remote and proximity connectivity, etc.). These tools can help design new products, redesign existing products and design services as an integral part of the life cycle of the new product/service, through design software that can assess the impact of design choices on the use of a product, to estimate for example the Total Cost of Ownership, and related services. Cybersecurity-by-design systems are necessary to design a new product/service from a PLM perspective.

Interaction with Other Strategic Action Lines

- LI1: Personalised production systems: personalisation of the solution through the supply of integrated digital services to support the product
- LI2: Industrial sustainability: development of services to support the monitoring and control of the sustainability of products and plants.
- LI3: People in the factory: development of digital services to support workers online.

Time Horizon

Short-term goals (2–3 years):

- Digital solutions to revamp existing products by providing new interconnection capacities to company systems or digital service platforms.

Medium-term goals (4–6 years):

- Advanced digital services that enable traceability of the use of a product by integrating it with company systems or new digital services managed in the cloud to improve configurability and remote assistance.

Long-term goals (7–10 years):

- PLM design tools for products and services with a view to cybersecurity-by-design and to planning solutions that consider their impact throughout a product's life cycle.

4 PRI7.3. Models and Tools for Production Monitoring and Production Asset Management

It is increasingly urgent that production processes be managed in synchrony with other business processes so that useful information is exchanged in real time and in a reliable way at different levels in the organization. By way of example, real-time management of information could be applied to the monitoring of product availability when the order has been placed, to plan the handling of semi-finished products within the factory, or to optimize transport times and costs, internal and external logistics, and the maintenance and data exchange with management systems.

A production process should generate objective and certified data, to facilitate analysis of the areas in which production should be improved, consolidate budgeting capacity and ensure availability of production resources for an efficient planning.

Industrial implementation of these solutions is at present almost entirely the prerogative of large companies, and that poses an additional limitation to their implementation. Furthermore, the focus is on individual and specific assets that tend to be complex and expensive. It is therefore necessary to make this production process accessible to full production systems at different complexity levels (even distributed and remote), and small and medium-sized companies, which cannot manage to exploit effectively the data they generate despite investing in I4.0-compliant machinery.

More and more frequently, operations technology (machines, automations, controls, SCADA, etc.) produce data that must be transformed into ready-to-use information for MIS (ERP, BI, logistics, etc.), including other production-related systems with which they can interface, such as MES, CMMS, PLM etc.

The objectives of this research and innovation priority concern:

- **Modular solutions for dynamic asset management** that can solve resource management and monitoring problems by appropriately combining specific modules. These solutions should be designed in such a way as to: a) be sufficiently generic (avoiding ad hoc solutions), but at the same time take into account the specific production structure where they are intended to be implemented (set up times, type of production, etc.); b) ensure that monitoring and scheduling can be adapted according to the configuration of constantly evolving assets, also in consideration of any changes related to resilience or circular economy. These infrastructures should be designed based on a weakly coupled architecture, providing SMEs with the ability to build their own scalable and modifiable solution at any time according to criteria of:

  o Interoperability in the horizontal and vertical integration of their systems
  o Flexibility in the reconfiguration of their processes and information flows
  o Data control and certification for the consolidation of decision-making systems
  o Integration with digital supply chain platforms.

- **Solutions for factory communication based on 5G:** infrastructures for the dynamic management of assets must be able to convey diverse data in real time and in a massive manner by exploiting the URLLC (Ultra Reliable Low Latency Communication) operating modes of the 5G network. In addition, the development of a process' specific vertical applications (Verticals) will have to ensure reliability and security of communication and, at the same time, minimize latency. In particular, certain features of industrial 5G are inextricably linked to the typical requirements of operation technologies, and should be based on the creation of "connectivity bubbles" that connect the elements found within the corporate campus by integrating 5G and WLAN as required by the standards and ensure an adequate performance of reliability, availability, data-rate and latency. It will also be necessary to study the issues related to Beyong5G which involve the joint use of sensing and communication techniques.

Interaction with Other Strategic Action Lines

- LI5: Innovative Production Processes
- LI6: Evolving and Resilient Production Systems

Time Horizon

Short-term goals (2–3 years):

- Development of Connectivity solutions based on 5G Private Industrial and 4G Public connectivity over WAN. Creation of PoCs and extension of coverage to the entire supply chain. Introduction and integration of standardized wired/wireless connectivity platforms to ensure the necessary connectivity for Industry 5.0 processes and solutions.

Medium-term goals (4–6 years):

- Study and development of modular solutions that can solve resource management and monitoring problems. These solutions must be designed in such a way as to be sufficiently generic (avoiding ad hoc solutions), but at the same time they must take into account the specific production structure where they are supposed to be implemented (set up times, type of production, etc.).
- Study and development of factory communication solutions based on 5G.

Medium-term goals (7–10 years).

- Study of Beyong5G communication systems that involve the joint use of sensing and communication techniques.

5 PRI7.4. IIoT Models and Tools for Factory Data Management

A fundamental infrastructural element in the field of digital solutions concerns architectures and technologies for the generation (such as microsensors and connected MEMS), collection, processing, integration and sharing of raw data from the field which, transformed into appropriate information, can lead to an improvement in productivity and a reduction in environmental impact through the smart management of plant assets.

The paradigm of Industrial IoT, borrowed from the Internet of Things (more oriented to the interaction between user and smart object in the home or smart city) and based on the adoption of mission-critical technologies (for timing and QoS, reliability, security and privacy purposes) for M2M interaction, opens the way to a deeper understanding of the manufacturing process, thus enabling efficient and sustainable production, and process innovation (Xu et al., 2018; Sisinni et al., 2018).

The main objectives of this research and innovation priority include:

- **Vertical systems and applications** that enable on the basis of **edge computing architectures** the management of signals from the field in near-real or real time and transform them into easily usable information,. In particular, the approaches required should allow also the local use of artificial intelligence, such as the use of neural networks to interpret information at an appropriate level before it is transmitted to the highest decision-making level. In addition to appropriate sensors that cover different types of signals such as vision sensors (infrared, x-ray, hyperspectral, etc.), sound sensors, electromagnetic sensors with very sophisticated local processing capacity, it will be necessary to develop new types of local processors that take into account the different sources from which data is collected (both from objects and from workers through wearable sensors).
- **Systems to support the transformation of data** (in most cases massive, unstructured and heterogeneous) into **information** and to facilitate its transfer to decision-making systems also through 5G-enabled wireless communication systems. In the case of plant data, these systems must ensure that the transmitted information has high reliability, high security and low latency.
- **Communication systems (wired or wireless)** that ensure real-time and low-latency dialogue between sensors located in different data collection points, so that they can convey a stereoscopic view and ensure the interaction of edge computing even at a local level. It is thus possible to have a local distributed intelligence, which dialogues and appropriately transmits data and/or artificial intelligence or machine learning models, to limit the amount of information transmitted without introducing too many penalties on the accuracy of the inference results.
- **Mission critical technologies and platforms** of smart M2M interaction at different stack levels, from communication and middleware to distributed processing between local systems, Edge and Cloud with different latency and capacity features that can work together to best meet application requirements.

Such systems must also be designed to ensure the reconfiguration of the network itself.

- **Wearable hardware devices that ensure**, for example, interaction with gesture language, or non-wearable devices to visualise 3D objects locally and manage, for example, the maintenance of machinery and the training of operators. Such technologies can improve workflow and productivity through the convergence of physical and digital elements. Furthermore, the availability of computational resources that can be accessed with very low latency enables the creation of innovative convergent services, including proximity AR, to support on-board maintenance and 3D HMI for remote diagnostics of the machines, avoiding otherwise complex navigation between traditional HMI data (lists, diagrams, alarms).
- There is also a close relationship between pervasive connectivity in production lines and cybersecurity, which must protect it without limiting operations. Therefore, new methods, architectures and algorithms must be sought, on the basis of unified and standardized approaches that also take into account the great diversity of equipment and technologies, both in terms of technological generation (in particular legacy systems) and for suppliers, typically present in production factories.

The identified goals can be summed up as the full achievement of data integration and normalization, including in real-time, and the improvement of security, interoperability and scalability of the systems in the field, at project and implementation level, also considering the large installed base of legacy systems.

Interaction with Other Strategic Action Lines

There is no doubt that the research and innovation priority has strong interactions with strategic action lines:

- LI5—Innovative production processes and LI6—Evolving and resilient production, for which it is one of the main enabling technologies.
- PR7.5 Business Industrial Analytics and PR7 Information and Cybersecurity, as synergistic and complementary to the achievement of the goals of efficiency, resilience and innovation of production processes.

Time Horizon

Short-term goals (2–3 years):

- Interaction and communication systems between sensors, even of different types
- Wearable hardware devices

Medium-term goals (4–6 years):

- Design of interaction methods and data fusion systems to obtain information from the set of data collected by sensors useful for an industrial context.

6　PRI7.5. Advanced Business and Industrial Analytics Methodologies

Digital transition opens significant opportunities in the management of systems, components and industrial plants. These opportunities improve efficiency and reduce environmental impact, but they also present significant new challenges.

The possibility to improve machinery and tools with sensors, the increase of communication speed, and the spread of computing capacity both locally (Edge) and remotely (Cloud) make available large volumes of data (including images) that through Artificial Intelligence algorithms can be used, for instance, for predictive maintenance and problem diagnostics, to optimize plant configuration and production strategies, to collaborate in real time during the production phases with customers (B2B). Furthermore, the new methodologies enable a direct feedback to the plant from sales and products usage data, to generate new solutions with an integrated B2B2C approach. In order to get value from industrial data, it is necessary to resolve the constraints posed by the collection of data in a plant environment, and precisely:

- The large amount of raw data, often showing lack of uniformity (sampling frequencies, semantics, structure, format) and lack of historical data and data in systems regimes different from normal operation, in particular for complex plants
- The differences in the treatment of micro-stops (more frequent and resolvable with on-site intervention) or critical stops (rare and typically related to components to be replaced);
- The difficulty of exploiting non-empirical information, such as knowledge of the plant structure (or component) (because of the lack of plant and component models)

In light of the above, the objectives of this research and innovation priority concern:

- Data Analytics, Machine Learning and Image Recognition method and tools for the system automatic monitoring with the following features:
  o Ability to manage data applying ontological and reasoning approaches and to evaluate cause-effect relationships from information derived from heterogeneous sources such as tools, machinery and systems.
  o Ability to combine input information from operators and machines and obtain information that would otherwise escape observation.
  o Ability to re-train the non-deterministic models within times compatible with production plants.

- Self-awareness solutions for production systems, with reference models that use digital twin representation taking into account interaction between the different lines and cells that make up the system.

- Virtual sensors: solutions that link system model to existing sensors. This approach is based on the development of models that allow the combination of information gathered from reality and overcome the difficulties of exploiting non-empirical information, such as plant knowledge.

- Systems to integrate data analytics methods on hybrid infrastructures (Edge and Cloud type): new solutions should integrate Cloud systems overseeing time-consuming operations typical of off-line simulation and re-training of the models and Edge systems on board of the plant to run real time predictive models.

Interaction with Other Strategic Action Lines

Interactions with almost all the research priorities of this action line, namely:

- PRI7.3 Models and tools for monitoring production and managing production assets,
- PRI7.4 Stack IIoT for factory data management and
- PRI7.7 Information and Cybersecurity, as synergistic and complementary to achieve the objectives of efficiency, resilience and innovation of production processes.

This research and innovation priority has strong relations also with LI5 and LI6 as regards the development of technologies at the various factory levels and with LI1-4 as regards the support it can give in defining solutions that can reinforce data management in relation to personalised products, sustainability, staff development and high efficiency.

Time Horizon

Short-term goals (2–3 years):

- Virtual sensors

Medium-term objectives (4–6 years):

- Ensure data fusion to give meaning to the various data collected from the field
- Methods and tools for automatic monitoring of the system status

Long-term goals (7–10 years):

- Self-awareness solutions to support the management of production systems
- Systems to integrate data analytics methods on hybrid infrastructures

7   PRI7.6 Tools for Modelling and Management of Information Based on Digital Twin

The progressive implementation of digital technologies (IoT, Advanced Sensors, Connectivity, Cloud and Edge Computing, Big and Small Data, AI) in companies makes it desirable and necessary to study and develop software tools and methodologies that exploit the advantages that can (and must) be obtained from these technologies.

At the moment, especially for PMEs, advantages mainly consist of an improvement of production efficiency. Clearly, that cannot be all. Further advantages will be the exploration and identification of new production paradigms aimed both at a better use of resources (e.g. circular economy, zero-defect manufacturing, reuse, remanufacturing and recycling), and at increasing business potential through greater efficiency in responding to market needs (e.g. mass customization, lot-size one production, reconfigurability of production systems) or new positioning in the value chain (e.g. servitization).

The development and use of dynamic digital models of all the physical entities composing the factory, i.e. digital twins, is desirable and necessary. In fact, a digital twin can be made for a product, machinery, plant, factory, system and should interact with its real twin (in a cyber-physical production system) in operation through a single, continuous, bidirectional and synchronized flow of data. Data coming both from the simulation models used mainly in the design phase, and directly from the field (embedded sensors, artificial vision, etc.) are sent, through IoT systems, both to proximity computers (edge computing), and to remote ones (cloud computing).

The objective of the research and innovation priority is the development of methodologies and calculation tools to improve the use of the data flow generated by the digital twins, with a view to exploit their enormous potential for increasing performance (economic and business, environmental and social sustainability) over the entire life cycle of the product. To do so, the virtualization of production systems (local or distributed) should be accompanied by:

- **Hybrid simulation systems of complex production systems** containing models based both on simulation (CAE, Analytics, DES, Agent Commissioning), and on data from the field, more and more finely honed to reality through the input of continuously synchronized data, coming from digital twins.
- **Decision-support systems and tools (DSS),** based on simulation models of complex production systems, optimization and forecasting, focused on different scenarios (e.g. optimization of maintenance, production, supply chain, etc.). These systems must be scalable (by complexity and costs) and have customizable HMIs (Human–Machine Interface) of contents and hierarchies for the individual tasks and for the different players interacting in the process of designing and managing product and production systems (product design and production systems, process planning, process commissioning, maintenance, quality control, procurement management, plant and/or production site management, HR, commercial area and top management).

- **Algorithms and methodologies for simulating human behaviour in flexible automation production systems.**
- These multi-agent distributed control algorithms based on cognitive sciences are expected to model and implement digital twins including for the human components that act in a production system. That is particularly relevant in flexible automation production systems, where operators are required to "collaborate" with robots.

Interaction with Other Strategic Action Lines

This priority is complementary to all research and innovation priorities of this research line.

Strong interaction with all the other Strategic Action Lines and, in particular, with the lines focusing on the various "Production Systems": LI1, LI4, LI5, LI6.

In fact, the development of this research and innovation priority would impact all types of production systems, which could even represent test cases for the development of this research and innovation priority.

Time Horizon

Medium-term goals (4–6 years):

- Hybrid solutions for simulation of complex production systems and decision-support systems and tools (DSS), as developments are essentially methodological and need to be translated into IT tools, which should be based on technologies already present on the market. This is an essential requirement for their use in businesses, especially in SMEs.

Medium-long term goals (4–10 years):

- Algorithms and methodologies simulating human behaviour in production systems with flexible automation currently involve pioneering research activities.

8 PRI7.7 Models and Tools to Support Information and Cybersecurity

The risks associated with cyber-attacks, rated in the last years in the top ten risks of any business and government, must be assessed and managed at all levels (from governments to industries, to individuals).

Recent scientific literature confirms a growing attention to cyber risk and to research and innovation priority due to:

1. **An essential connection between industry 4.0 and cybersecurity, where heterogeneous models can become an obstacle to the prompt and secure adaptation of business to the new requirements**, particularly where there are interconnected technologies with different cyber resilience and people (internal technicians and/or suppliers) who work with different approaches to security;

2. **The binding link between the digital and physical world,** which has created cyber-physical environments where data breaks can **create direct critical impacts in the real/physical elements,** both in terms of security (e.g. breaking of components) and safety (e.g. fraudulent handling of cranes/robots), whether in **environmental** terms (e.g. manipulation of water reclamation processes) or **indirect social impact** (e.g. on the internal workforce or on allied industries in the event of production interruptions);

3. **The continuous evolution of threat scenarios and 4.0 industrial processes** which requires a continuous process of identification and monitoring of the effectiveness of the protection measures;

4. **The partial effectiveness of available technological solutions taken individually;**

5. The potential high costs of available cyber technologies, in the purchase, implementation and management phases.

The security processes that companies must implement to effectively counter growing risks cannot be separated from ongoing research, development and adoption of suitable process solutions and cyber security technologies. Research must necessarily be an iterative process, following both the continuous evolution of threats and the technologies/systems that must be protected.

Research and development in cybersecurity technical solutions should take into account:

- The enabling technologies such as artificial intelligence, from machine learning to predictive models, Big Data Analytics, Blockchain.
- The data from heterogeneous sources, so that hostile behaviour can be identified effectively (i.e. with a low number of false positives).
- Usability throughout the life cycle of the product, both during production and safety management.
- The right compromise in terms of costs/benefits.

In light of all this, the following goals are identified for this research and innovation priority:

- **Innovative systems for the governance of cybersecurity** for: a) the management of risk throughout the production chain for the protection, reliability and integrity of data (from suppliers to customers), allowing the comparison of risks related to different production contexts and supply chains; b) a safe and sustainable progressive integration of new technologies into the industrial network, to support the design, analysis and enforcement of Industry 4.0, ensuring the resilience of industrial systems and production processes against a variety of possible threats; c) the definition of contents for an effective training on cybersecurity, also *using enabling technologies of Augmented reality and Simulation (e.g. digital twin of production chains)* to obtain realistic simulated cyber-physical attack/impact scenarios.
- **Solutions to support the resilience of systems** to a) **increase the protection capacity of industrial systems (OT and IoT)**, to reduce the possibility that external threats could compromise the normal functioning of the system or the

recovery of information, if necessary. The main objectives of research on industrial control systems (ICS) are the analysis of vulnerabilities and frameworks for the detection of the safety and security properties of ICS/SCADA systems; b) **enabling micro-segmentation** in isolated cells of industrial systems, and allowing granular isolation in order to prevent lateral propagation of threats on other manufacturing systems; c) **increasing the security of the maintenance processes** of industrial systems, to prevent the propagation of threats from the systems used by the maintenance service to the industrial systems.

- **Protection of communication flows** to: a) ensure the secure definition of the unilateral nature of network flows (by devising "data diode" solutions), and collect operational data from critical industrial networks (for example in *data lakes*), effectively mitigating the possibility of introducing threats into critical industrial networks; b) avoid the transmission of unauthorized industrial commands (industrial firewalls with deep packet inspection); c) decouple industrial system data flows and protocols from business processes, to prevent areas with different security levels from having a direct need to communicate with each other; d) using standardized encryption protocols for wireless connectivity as well as SIM-based authentication systems for network access.

- **Security monitoring of the Cyber-Physical world** for: a) a non-intrusive monitoring of networks and systems for the detection of anomalies; b) the identification and analysis of threats in the Cyber-Physical world in real time, thanks to an executive abstraction layer that allows to understand the possible risks, threats and problems related to manufacturing operational processes, facilitating the interpretation and synergy of groups with heterogeneous skills; c) development of a Cyber Risk Governance approach integrated with Enterprise Risk Management. This approach must be conceived with a holistic vision of risk management not only in terms of cybersecurity but also of safety, physical security and environmental risks. Furthermore, it is necessary to bring to the attention of the highest corporate level the topic of cybersecurity, to avoid the risk that the topic might be confined to a purely technical area (IT /OT).

The evolution of cybersecurity technologies is based on the creation of ad hoc public libraries to be adopted from time to time as part of the technologies, in order to ensure effectiveness and efficiency. In particular, in terms of effectiveness, the continuous development of increasingly refined algorithms by exploiting the enabling technologies will make it possible to identify/counteract promptly the ever-evolving threats. In terms of efficiency, the development of agile representation and maintenance models throughout the life cycle will allow the management of cybersecurity technologies, avoiding dissipation of value and effort.

Interaction with Other Strategic Action Lines

Strong integration with the other action lines, in particular:

- LI4-LI5: continuous technological evolution as a result of the other strategic action lines requires new processes, new interconnections and the attribution of

ever greater value to data, and a continuous reassessment of risks and necessary mitigating actions;

- LI4-LI6: sustainability (in terms of efficiency and effectiveness) in the development and adoption of protection systems is strictly correlated with the other research priorities in the OT/IoT area;
- LI4- PRI7.6: the results obtained from other lines of intervention and from other priorities (e.g. digital twin) can be adapted and used to further refine and evolve the objectives of this priority.

Time Horizon

The short-term goals (2–3 years):

- The development of systems for the governance of cybersecurity to support risk management throughout the production chain, ensuring the gradual integration of new technologies into the industrial network
- Systems for the protection of communication flows that can guarantee the secure definition of network flows and control the transmission of unauthorized industrial data

The medium-term objectives (4–6 years):

- System resilience to be improved by implementing actions on the protection capacity of industrial systems (OT and IT) and the study of solutions for industrial systems' micro-segmentation that can help overcome segregation in homogenous groups.
- Security monitoring systems in the cyber-physical world and in real-time threat analysis require medium-term actions since it is necessary to study and develop advanced, non-intrusive monitoring systems for networks, which should be supported by advanced AI and machine learning technologies.

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