

Chapter 20

Key Research Priorities for Factories of the Future—Part I: Missions



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Abstract This chapter investigates research priorities for factories of the future by adopting an approach based on mission-oriented policies to support manufacturing innovation. Missions are challenging from a scientific and technological point of view and, at the same time, are addressing problems and providing results that are understandable by common people. Missions are based on clear targets that can help mitigating grand challenges. Based on the results of the Italian Flagship Project *Factories of the Future*, this chapter proposes seven missions while identifying the societal impact, the technological and industrial challenges, and the barriers to be overcome. These missions cover topics such as circular economy, rapid and sustainable industrialisation, robotic assistant, factories for personalised medicine, internet of actions, factories close to the people, and turning ideas into products. The accomplishment of missions asks for the support of a proper research environment in terms of infrastructures to test and demonstrate the results to a wide public. Research infrastructures together with funding mechanisms will be better addressed in the next chapter of this book.

20.1 Mission-Oriented Research and Innovation Policies

The importance of the manufacturing industry both for developed and developing countries has been assessed in several works [1–4], which highlight the need of continuous innovation to cope with societal grand challenges [5]. The results of inno-

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vation actions strictly depend on the policies that are designed and implemented, mainly at public level. Cantner and Pyka [6] proposed a framework to classify technology policies by considering two axes: (a) *vicinity to the market* and (b) *specificity of a policy measure*. The first axis differentiates between basic and applied research, whereas the second axis specifies how the policy is precise in describing the research goal. High vicinity to the market leads to mission- or diffusion-oriented policies in case of precise or broad goals, respectively. *Diffusion-oriented policies* tackle a wide range of heterogeneous technologies to be further developed and applied in no specific economy sector. *Mission-oriented policies* are characterised by a relatively high degree of specificity in terms of both target technologies and economic application [6].

A mission-oriented policy for research and innovation shares common traits with Public Procurement for Innovation (PPI) [7], i.e. when a public organisation places an order for the fulfilment of certain functions within a defined time horizon. Therefore, the goal of PPI is not primarily to support the development of new products, but to provide solutions for human needs or societal problems. This kind of demand-side policy can be considered as a mission-oriented innovation policy that mitigates grand challenges, since a grand challenge is too broad to be tackled as a whole. Moreover, PPI facilitates the interactions among organisations (e.g. the procurer and supplying companies) and this is particularly relevant because companies almost never innovate in isolation. These interactions can be further enhanced by means of *focus groups* or *task forces* [7]. PPI however cannot be applied in all the sectors and tends to blur in the same step the creation of innovative solutions with the creation of a market for it and with its application in a real day by day operating context, thus putting some additional constraints that are not strictly required to achieve a mission.

It must be stressed that, in any case, the realisation of mission-oriented policies requires public sector organisations to set the *direction of change*, thus assuming a leading role in the economy that goes beyond fixing problems related to market failures [8]. The goal of a mission-oriented policy is to pave the way for new ambitious approaches and to demonstrate their feasibility instead of introducing new products or services to the market. Typically, only public sector organisations can afford high-risk investments and pursue goals like satisfying human needs and solving societal problems.

A mission-oriented approach is currently under discussion within the Directorate-General for Research and Innovation of the European Commission in view of the 9th EU Framework Programme for Research and Innovation [9]. Such approach is thought to be a solution to make the European economy sustainable and competitive. The involvement of civil society is needed to identify the main challenges and also to assess the impact of the mission results. The final objectives of the mission-oriented policy include the re-industrialisation of Europe, the creation of new jobs, the solution of societal problems, the attainment of goals that project Europe into the future, the enhancement of the European knowledge base, and the improvement of skills. This type of mission must be [9]:

- Bold, inspirational with wide societal relevance, e.g. improving health, environment, nutrition, welfare, etc. for a large share of the population.
- Defining a clear direction that is targeted, measurable and time-bound. Clear goals should be understood by the civil society.
- Ambitious but realistic. Possible (theoretical) solutions should be identified.
- Cross-disciplinary, cross-sectoral and cross-actor innovation.
- Requiring multiple, bottom-up solutions.

In this scope, the Directorate-General for Research and Innovation identified 14 examples of missions, ranging from industry renewal to bio-manufacturing, from energy independence to clean and safe mobility [10].

This chapter, on the basis of the results attained within the Flagship Project *Factories of the Future* [5], takes into consideration the mission-oriented approach in order to identify, among the others, seven missions for future manufacturing research (Sect. 20.2). These missions will foster the role of manufacturing as a backbone for the employment and wealth of European economies.

For the accomplishment of missions, a fundamental role is played by research and innovation infrastructures, as well as by effective and sustainable research and innovation funding mechanisms. These topics are anticipated in the conclusions (Sect. 20.3) and better discussed in the next chapter of this book [11].

20.2 Missions for Manufacturing Industry

The growth and sustainability of European economy requires a change from competition based on cost reduction towards high value added activities by adopting a competitive sustainable manufacturing (CSM) paradigm [12]. Indeed, European countries need continuous innovation to keep their position in a global market place while creating value in a sustainable society [13, 14]. The development of the sustainability paradigm has translated over the years into a series of global initiatives with broad objectives but without precise quantitative targets. For example, in 2015 the General Assembly of the United Nations (UN) adopted the 2030 Agenda for Sustainable Development that includes the definition of 17 Sustainable Development Goals (SDGs) [15]. The SDGs aim at promoting prosperity for all countries while protecting the planet; indeed, also the European Union is committed to monitor and improve the performance with respect to the SDGs [16]. While the agreement on the 17 goals is a big step forward, more defined actions and goals are needed in order to attain them. Missions are one of the possible ways to better specify the goals.

Adopting a mission-oriented approach (Sect. 20.1) and elaborating on the results emerged from the Flagship Project *Factories of the Future* [5], this section proposes seven missions for future manufacturing industry, while making references to the SDGs. The proposed missions are:

- Circular Economy (Sect. 20.2.1)
- Rapid and Sustainable Industrialisation (Sect. 20.2.2)

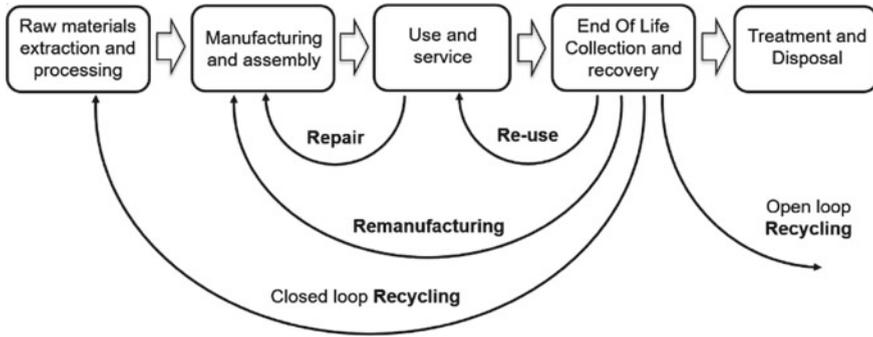


Fig. 20.1 Circular economy cycles (adapted from [19])

- Robotic Assistant (Sect. 20.2.3)
- Factories for Personalised Medicine (Sect. 20.2.4)
- Internet of Actions (Sect. 20.2.5)
- Factories close to the People (Sect. 20.2.6)
- Turning Ideas into Products (Sect. 20.2.7).

For each mission, a general description, the societal impact, the industrial and technological challenges, and the barriers to be overcome are presented. The need to face industrial and technological challenges will presumably lead to a set of projects and bottom-up experimentations, i.e. *mission projects* as defined in [9]. Barriers are meant as contextual aspects (e.g. regulations, standardization, market demand and supply, business organizations and relationships, change management) that typically are not addressed by specific mission projects.

20.2.1 Circular Economy

20.2.1.1 Definition

Circular Economy is a new paradigm fostering sustainable growth and progress while taking in due consideration limited natural resources and environment degradation [17, 18]. Circular Economy aims at overcoming the traditional linear production and consumption model that entails production, use and disposal with consequent need of large quantity of natural resources for new products, high generation of waste and negative impacts on the environment due to disposal processes. A set of *restorative* processes and practices must be put in place with reference to the traditional linear manufacturing chain (Fig. 20.1) [19].

Processes enabling Circular Economy include:

- *Re-use*, when product or components functionalities allow additional use cycles without performing any restorative operation.

- *Repair*, when ordinary or extraordinary repair operations can restore initial products functionalities.
- *Remanufacturing*, when product has to be re-built to bring it at initial specifications (using a combination of new, reused and repaired parts) [20]. Recently, the concept of *remanufacturing with upgrade* has also been proposed in addition to traditional remanufacturing [21], as well as the option to use in other products the functions provided by some components of the de-manufactured product.
- *Recycling*, when the state of the product is not anymore compatible with restore of functionalities and its materials are used to produce secondary raw materials that can be re-used in the same production process (closed loop recycling) or in other processes (open loop recycling).

Based on products characteristics and conditions of End-of-Life products, the process able to retrieve maximum value should be selected every time in a hierarchical approach [19, 22] in which re-use, remanufacturing and recycling are in a decreasing order of priority.

These processes are carried out by *Circular Factories* [17, 23] that should work in alignment (or being integrated) with the existing production factories to maximise the benefits of Circular Economy. Thus, the implementation of Circular Economy requires a systemic perspective of manufacturing, de-manufacturing, and remanufacturing networked factories that collaborate from the product design phase up to the End-of-Life.

The proposed mission for the effective implementation of Circular Economy in manufacturing is to *Design factories and industrial networks for the management of a new class of fully circular products according to innovative circular business models*.

Circular product service systems (CPSS) are totally conceived and managed during their whole life cycle according to the Circular Economy paradigm. These CPSS will be designed and used to be efficiently re-used, remanufactured and recycled, according to new processes and technologies that will make it possible. CPSS will embed smart sensors that will collect information on the use conditions and on their state, so that the optimal circular strategies can be planned and implemented after each use phase. The de-manufacturing network will include companies specialised in the various End-of-Life processes adopting new smart de-manufacturing technologies. Companies in the network can be seen as the entities providing the “energy” that allows to continually circulate the materials and restore the functions carried by the CPSS. Therefore the factories of the future will be part of a Circular Factory Network (CFN).

New circular business models will be based on offering service levels rather than products. Manufacturers will turn into service providers (or will establish strategic partnerships with them) and will develop innovative product-service bundles where product ownership will not be necessarily transferred to customers. The latter will have the guarantee of product performance and will have the option of pay per use or per result according to innovative financial mechanisms. Service suppliers will also provide continuous performance upgrade that will be obtained through

remanufacturing with upgrade enabled by a careful product design. Circular business models will revolutionise consumption behaviours and will improve quality of life of people, increasing manufacturing sustainability at the same time [24].

20.2.1.2 Societal Impact

Circular Economy has the potential of generating significant societal impacts. In the circular model, products and materials are kept in the use cycle as long as possible, thus maximising their possible exploitation and value that is generated through initial production processes. With this concept, the need for new resources, new production processes and the recourse to landfilling is reduced (cf. SDG 12.5 [15]). In 2015, the generation of waste was 1716 kg per capita in Europe and recycling of municipal waste was only 45% of total waste [25]. Indeed, it is estimated that in the consumers' goods sector, nearly 80% of the value of materials used in the production is lost globally every year [26]. Circular Economy will reduce the need for material input for production processes. It is estimated that a reduction between 17% and 24% of virgin material consumption can be achieved in European manufacturing industry through resources optimisation by 2030 [27] (cf. SDG 12.2 [15]). The reduced need of virgin materials, together with lower energy needs and emissions of manufacturing processes will strongly contribute to reduce CO₂ emissions and to positively affect climate change (cf. SDG 12.4 [15]).

Circular Economy is also an enormous opportunity for European economy and welfare. European companies will become more competitive in the global market because of the reduction of production costs due to lower cost of raw materials, energy and disposal. It is estimated that Circular Economy will provide a saving of production resources expenditure amounting at 600 billion euro per year in EU [27]. In addition, Circular Economy offers companies the opportunity to innovate their business model in the direction of *servitisation* [28], thus increasing the added value—and profitability—of their offering while limiting environmental impact at the same time [21] (cf. SDG 8.4 [15]).

From a strategic point of view, circular economy will make Europe less dependent from countries extracting raw materials and will offer the opportunity to develop a new leadership on advanced technologies for the implementation of circular economy processes, leveraging on the already recognised leadership on production technologies. Overall, increased company competitiveness and future potential leadership in Circular Economy will generate new jobs for people in Europe, both in advanced and converging regions [29–31] (cf. SDG 8.5 [15]).

In societal terms, circular economy will establish production and consumption models that will make modern products affordable for a wider class of world population, thus improving quality of life of people and stimulating global progress (cf. SDG 10.2 [15]). For example, according to the concept of *Frugal Innovation*, manufacturers can offer affordable high-quality products in emerging global markets [32]. Remanufacturing with upgrade, through which new advanced functionalities can be added to products during remanufacturing operations, coupled with advanced non-

ownership based services, can offer customers products with frequently upgraded performance avoiding the need to buy new expensive products [21].

20.2.1.3 Industrial and Technological Challenges

The development of Circular Factories involves heterogeneous sources of information and asks for distributed data gathering and cyber-physical systems to increase availability and traceability of information. Decision support tools will be based on advanced techniques such as data analytics. These smart manufacturing and Industry 4.0 topics are already commonly applied to manufacturing systems, but in case of de- and remanufacturing they have been investigated in a less structured approach. Specific challenges to be addressed include [18]:

- *Circular Economy engineering* shall be developed combining strategies for recovering the highest residual value from post-use products [33], e.g. via disassembly [34, 35]. A new set of manufacturing system engineering methods will be needed to design circular factories.
- *Zero-defect de- and remanufacturing*. The profitability of Circular Economy businesses and product acceptance by customers strictly depends on the quality of recovered materials and remanufactured products. Therefore new systemic zero-defect solutions for remanufacturing and recycling processes should be developed.
- *Flexible automated technologies for adaptable de- and remanufacturing systems*. Automated technologies of circular factories should be flexible enough to be adapted to various applications that will change unexpectedly over time due to technology trends and product conditions [36].
- *Digital factory for circular factories*. The integrated design and management of de- and remanufacturing processes and systems will need the support of digital platforms. Simulation of process capabilities will help to set process parameters. A digital twin of the real plant will support tactical and operational decisions.
- *New circular business models and value-chains*. Systematic methodologies to identify optimal circular strategies, to design circular business models and to quantitatively assess business performances and risks for the various actors of the supply chain should be developed. Also, organisational guidelines and best practices to shift towards circular service-based business models should be made available to companies.
- *Full tracing of products components and materials during multiple lives*. Products will become the means to bring functionalities where needed. Their characteristics and interaction with the environments (manufacturing, de- and remanufacturing, transport, storage, usage, reconditioning, etc.) during their multiple lives should be continuously traced and analysed in order to guarantee the desired performance and to plan the following phases of their multiple lives.

20.2.1.4 Barriers

On top of technological challenges and opportunities, there are several non-technical systemic pre-conditions and barriers that need to be addressed in favour of a large-scale implementation of new circular business models.

Circular Economy requires a systemic perspective and high cooperation among actors at all levels of the manufacturing and de-manufacturing supply chain [37]. In case of industrial symbiosis, where waste generated by an industrial ecosystem can be used as source of materials and energy for other industrial and non-industrial ecosystems [38], there is also the need for cooperation among different supply chains. Compared to current practices, one of the most relevant barriers is thus the establishment of trustful conditions among all supply chain actors enabling such an effective cooperation. Multilateral information systems for life-cycle management will enable to manage the whole product life-cycle from supplier to end-user, while adding value and maximizing the resource utilization.

Circular Economy is becoming relevant in the worldwide political and research agendas, e.g. the *Alliance on Resource Efficiency* launched by in 2015, the initiative *Closing the loop—An EU action plan for the Circular Economy* launched by the European Commission in December 2015, initiatives promoted in the Chinese *Five Year Plan* since 2006, and similar initiatives in the US, Japan, and Australia.

Legislation constitutes an additional barrier to the implementation of Circular Economy businesses. Currently, a sector-oriented approach for recycling has been adopted by the European Union. The directive on end-of-life-vehicles (2000/53/EC) and the directive on reusability, recyclability and recoverability of waste vehicles (2005/64/EC) define standards for the quality of reused parts and materials in automotive industry. Similarly, directives were issued for electrical and electronic equipment (2002/95/EC and 2011/65/EU). However, remanufacturing is still legally undefined in most countries, even though ongoing initiatives are addressing *end-of-waste* regulation [39]. At European level, specific actions were started to identify potential legislative barriers for the development of new Circular Economy businesses [40].

The lack of understanding on how to manage the uncertainties associated with Intellectual Property is another significant barrier for companies wishing to adopt a remanufacturing approach [41].

Finally, profitable circular businesses can be developed only if also cultural aspects are properly addressed. Indeed, the market acceptance of reconditioned products and the collection of post-use products are crucial factors for the transition towards use-oriented businesses. While the focus of research is mainly on technical enablers, more attention should be paid to social mechanisms of value creation in circular economy, e.g. network externality, public goods, social dilemma, and lifestyles aspects [13].

20.2.2 *Rapid and Sustainable Industrialisation*

20.2.2.1 Definition

A sustainable manufacturing industry [1–5] is fundamental to support the societal and economic growth of any country [42]. Industry allows the transformation of materials and energy into products with useful functions; therefore, the absence of industry prevents the full development especially of highly populated regions and creates enormous societal problems leading to low quality of life and frequently a sense of impotence and desperation. At the same time, the industrialization should not come at the expenses of safety and environment otherwise an immediate advantage may turn into a long term problem. Therefore, guaranteeing in each region the opportunity of sustainable industrial development is one of the ultimate challenges of humanity. This is critical in regions that did not develop an industrial system or in regions that due to catastrophic events lost, at least partially, their industrial base. The rapid installation of production capacity is particularly important in these cases since it prevents hopeless situations that in turn trigger emigration. An effective industrialization should be extremely rapid in order to revert the trend and restore hope.

Therefore, the proposed mission is *Rapid and Sustainable Industrialisation*. One possible declination of the described mission could be *to establish factories and connect them to industrial networks in a six-month period and make the newly installed production capacity sustainable in a three-year horizon*.

The availability of technologies, methodologies, and tools for the novel establishment of manufacturing capacity will provide a key instrument of foreign policy that developed countries in the European Union can exploit to build strong economic relations with *low income* countries around the world. Moreover, similar considerations apply also to regions that are not yet characterized by a significant manufacturing output in some parts of the European Union periphery, thus failing to reach an effective economic convergence. Consequently, this mission will contribute to create wider inter-regional value chains for the economic and societal progress of the whole Europe.

The technologies for rapid industrialisation can be exploited also to make already existing industries more resilient in case of natural disasters (e.g. earthquakes, flooding, eruption of volcano, major fire) that can cause serious damages to factories and infrastructures (e.g. roads, railways, airports) with consequent interruption of the production. Indeed, the economic relevance of manufacturing (Sect. 20.1) [1–5] leads to high social and private costs whenever industrial capacity and industrial networks are damaged or even destroyed in a specific region.

20.2.2.2 Societal Impact

The proposed mission will contribute to reach SDG 9 [15], and in particular Goal 9.2 (*Promote inclusive and sustainable industrialization*) while creating positive international collaborations (cf. SDG 10 [15]). In case of a region or a whole country without (sufficient) manufacturing industry, the establishment of production capacity in a short time horizon represents a boost that can have a large multiplier effect. Agriculture, mining and services risk to collapse or to be significantly depreciated if a manufacturing industry is missing. Indeed, manufacturing transformations add value to raw materials and agricultural products, whereas interactions with services take place along the whole manufacturing value chain.

The impact of fast industrialization in depressed areas is potentially huge, because the societal and economic development would be enhanced; also skilled labour force would be required and the vicious circle related to the human capital flight could be mitigated [43].

Similarly, the loss of production capacity is linked with a direct and indirect loss of employment. Whenever a relevant natural disaster happens, after the fundamental *search and rescue* operations, the restoration of the production capacity (primary, secondary, and tertiary sectors) of the region should be one of the first actions to be scheduled. This is needed so that the resident population can have a future in the stricken area thanks to economic activities that are not exclusively based on government subsidy. Otherwise, the mid- and long-term effect will be a forced mass emigration and the actual economic desertification of the region, thus creating a hardly reversible void in the emigration area and potential societal problems in the immigration area. Typically, the immigration converges to large cities, thus making the urbanization process hardly sustainable (cf. SDG 11.3 [15]).

Production capacity can be established (or restored) only if factories are built (or repaired) together with temporary infrastructures that are necessary for any trade. These tasks generate high public costs, even though also the demand-side stimulus to the economy should be considered. This type of actions can be supported only by strong government policies and international organizations. A country with the ability to quickly install production capacity would have a relevant competitive advantage that can be exploited in international negotiations as a valuable alternative to traditional policies based mainly on subsidies or military intervention.

20.2.2.3 Industrial and Technological Challenges

The fast realization of manufacturing capacity poses serious and multi-faceted technological and organisational problems. Factories implementing rapid industrialisation evolve in a short time period and need to be highly reconfigurable [44], changeable [45], and scalable [46].

If new factories must be built in a short time, then inspiration can be taken from the building and construction domain where prefabricated elements have been used for a long time [47, 48], thus leading to the novel concept of *prefabricated factory*. In this

case, a critical issue is related to the high number of functional elements composing a factory. Rapid prototyping techniques are already employed in manufacturing, but they could be scaled up for applications in factory construction as recently done with 3D printing of buildings and building components [49, 50]. In addition, a whole factory or a part of it could be transported to the destination site as a *motorfactory* (i.e. the factory version of a motorhome [51]). Much research and innovation is needed to realize a working *motorfactory* with very short ramp-up times.

Logistics and supply chain are fundamental to establish an effective manufacturing capacity. At the beginning, a rapid industrialisation will be necessarily missing most elements of a self-sustaining industrial environment, therefore just one or few industrial plants in a region need to be connected to a larger supply and distribution chain that can be far away. Initial high transportation costs will be gradually reduced as soon as missing or damaged transport infrastructures are built together with the addition of further industrial plants as close nodes of the supply chain. However, in the short-term period it will be necessary to find quick solutions to (re)activate transport channels, even if with above-market costs; for instance, autonomous vehicles (e.g. Unmanned Aerial Vehicles) could be employed in case of critical demand [52].

Rapid industrialisation must gradually evolve also from an organisational perspective. The use of advanced technologies in new factories requires skilled employees that could be missing in a region with limited manufacturing tradition. Therefore, at the beginning only a subset of the functional areas will be covered in the new plant (e.g. production, basic maintenance), whereas others (e.g. design, planning, advanced maintenance) will be initially provided remotely. This transition and extension of on-site functions will be supported by enabling technologies such as:

- Formalization, sharing and transfer of production knowledge. Semantic Web and ontologies are candidate technologies [53].
- Remote assistance for the configuration and maintenance of devices, machines and systems. Augmented and Virtual Reality (AR/VR) represent promising technologies that can be further enhanced for industrial applications (see also Sect. 20.2.5) [54, 55].
- Evolutionary planning and control that does not take the production facilities as a fixed asset but as an evolving tissue connecting several sites [56].

A new evolving mix of high-tech and low-tech [57] components needs to be designed to continuously guarantee a good fit with the improving conditions of the target area.

Energy supply is highly critical in a place without power plants and possibly without a working distribution network. Future research will address mobile power plants that can be scaled up and upgraded, while making use of renewable sources [58] (see also SDG 7 [15]).

In the particular case of natural disasters, methodologies and tools are needed to assess the performance of a damaged manufacturing plant and then support its repair.

20.2.2.4 Barriers

Initiatives of local and international governments are needed to develop the proposed mission, because of the large investment costs and the strategic trigger that normally involves political decisions.

The availability of natural resources depends on the characteristics of the country (e.g. geology and climate), but in case of manufacturing it is possible to take political decisions to enhance the capacity and thus the independence of a region, even if taking in due consideration the characteristics of every region.

The fast realization of manufacturing capacity has to deal with problems related to its long-term sustainability. New manufacturing plants will be initially supported by dedicated policies, but they must be gradually turned into self-sustaining sites by adopting appropriate business models.

The connection to a global supply chain is a decisive step for newly installed manufacturing capacity because an economically depressed area may cause problems to find proper suppliers and customers.

International organizations formally support cooperation among countries but an effective cooperation promoting a higher independence of low income countries is much more difficult to be implemented.

20.2.3 *Robotic Assistant*

20.2.3.1 Definition

Robotics technology is becoming ubiquitous in a wide range of applications including manufacturing, healthcare, agriculture, civil, commercial and consumer, transport and logistics.

The proposed long-term mission is to *Provide Robotic Assistants to everybody that can take advantage of their services in workplace and home environments*. More specifically, a declination of this mission for a mid-term horizon is to *provide a Robotic Assistant to human operators involved in manufacturing operations, logistics or in maintenance activities of machine tools and production systems*. Indeed, manufacturing systems (e.g. assembly lines [59]) offer key advantages for the development of robotic assistants because they are characterized by structured environments, clear applications, well-defined safety regulations, and continuous monitoring of performance indicators. Moreover, industrial companies can afford high investments in capital goods that will be needed to provide robotic assistants. The use of robotic assistants will be extended to other domains as soon as it is successful in manufacturing.

Independently from the application domain or technology cluster, the overall robot system performance can be characterised in terms of *abilities*: perception ability, configurability, adaptability, manipulation ability, motion ability, cognitive ability, decisional autonomy, interaction ability, dependability [60].

The interaction between humans and robots (*interaction ability*) constitutes an important aspect in current robotic applications aimed at assisting people, instead of replacing them [59]. A fruitful collaboration can be achieved only if the robot has a full understanding of the human behaviour also in unstructured contexts, including intentions, emotions, and desiderata (*cognitive ability*).

The use of a robot in real environments (e.g. advanced manufacturing, surgical room, outdoor or indoor applications in agriculture) implies the control of the operation field and of the surrounding environment (*perception ability*).

Decisional autonomy is a key feature to make robots useful in real applications to fruitfully collaborate with people also in dangerous and unstructured environments.

20.2.3.2 Societal Impact

In the future, various artificial embodied agents will populate human living and working environments. The smooth integration of these intelligent agents generates a wide range of societal and technological issues to be addressed.

The regulatory and technological evolution of robotics will bring relevant benefits for our society, because people will be supported in repetitive, unhealthy and dangerous tasks. Indeed, empowering humans is highly demanded in industry because several onerous tasks (e.g. lifting and installation of heavy components) are still manually performed, causing musculoskeletal disorders due to non-ergonomic postures (cf. SDG 8.5 [15]). Cooperative robots (e.g. wearable robotics and collaborative manipulators) will empower human operators in industrial tasks by improving ergonomics and reducing musculoskeletal stress [61]. However, it is also necessary to carefully analyse the societal impact of a co-working robot in an industrial environment [62]. The concept of *robotic assistant* implies that humans will keep a central role as orchestrators; the more skilled is the human operator, the more numerous and sophisticated will be the orchestrated robots. Empowered humans will be able to focus on tasks that can be hardly automated (e.g. reaction to unforeseen events and search of new solutions), while being free to orchestrate the robots within certain limits to better reach the production goals. Accurate and reliable robotic assistants will further improve human skills, such as in precision manufacturing, surgery, etc. (cf. SDG 4.4 [15]).

Robots acting and interacting in human contexts will have a new specific social role that will take into account different aspects such as safety, wellbeing, health, and productivity related to human companions and collaborators.

Beyond manufacturing, robotic assistants will empower humans in innovative health applications both in medical and home environments. Also the fruition and protection of public and commercial spaces (e.g. cultural heritage sites, cf. SDG 11.4 [15]) will benefit from the support of cognitive and social robots.

20.2.3.3 Industrial and Technological Challenges

The development of advanced perception systems also using alternative sensing modalities is fundamental to enhance the autonomy and safety level of robotic platforms operating in dynamic semi-structured and unstructured environments like in manufacturing (e.g. process control, surveillance, assembly and disassembly [30]) and transport (e.g. autonomous vehicles and advanced driver-assistance systems). Main challenges include the design and development of multi-sensor platforms and multi-sensor processing algorithms to be integrated on-board unmanned ground vehicles for tasks, such as multi-modal map building, situation awareness, and traversability estimation [63, 64]. Alternative sensing modalities like radar, depth-sensors, and cameras sensing outside of the visible spectrum (e.g. hyperspectral cameras or thermal cameras) and their intelligent combination and fusion, need to be further investigated for autonomous navigation under field conditions [65].

Research challenges also deal with the design and development of novel estimation and cooperative perception strategies for robotic networks to perform tasks, such as cooperative mapping, cooperative manipulation, target tracking, and environmental monitoring [66, 67].

Autonomous vehicles and cooperative robots need improved fast and safety-critical compliant communication networks and protocols, both on the intra- and inter-machine levels, for effective and safe task execution. The presence of human bystanders/co-operators also requires new conceptual frameworks and practical standardized procedures for a high-level safety validation [68]. Joint design approaches have been proposed to combine safety and security requirements in communication networks, in the typical modern scenario of ubiquitous connectivity [69]. Already existing and upcoming standards will be key enablers for the application of the Internet of Things (IoT) paradigm in a wider context [70].

Control algorithms will play a key role to enhance high-performance and high-precision human-robot cooperation, while guaranteeing safety, in particular in industrial environments (e.g. assembly tasks [71]). Learning-from-demonstration algorithms can be employed to directly teach a task to a robot. Impedance-based algorithms can improve the physical guidance of manipulators, while involving the human dynamics estimation/measurement in the control loop [72]. Machine Learning techniques allow to deal with uncertain interactions due to the robot itself or to the surrounding environment (such as in assembly tasks), thus enabling the auto-tuning of the robot control parameters [73].

The analysis and evaluation at the various levels of abstraction of the human-robot interaction through cognitive models and architectures will enable complex social interactions and effective task cooperation. The cognitive architecture of the robotic assistant will enable its *human orchestrator* to teach and activate complex tasks and behaviours by means of verbal and non-verbal (e.g. human gesture) interactions, thus creating effective and continuously evolving work teams.

Further challenges are related to the design and development of robotic systems able to mimic biological systems (e.g. bio-mimetic robotic vehicles, robotic arms

capable of mimicking the soft-behaviour of human arms) in unstructured environments so that robots can cooperate in a flexible way without rigid constraints.

Automated planning and scheduling constitute a research challenge to address intertwined task planning and execution in robotics. Timeline-based planning, dynamic task planning and coordination issues constitute key enabling technologies for the development of decisional autonomy solutions for robotics in human-robot collaborative scenarios [74]. The integration of such technology with Verification and Validation solutions [75] will foster also robust control solutions for guaranteeing effectiveness and safety of autonomous robots [76].

Multi-robot systems (MRS) under the guidance of a *human orchestrator* can improve the effectiveness of a robotic system both in terms of performance while accomplishing a given task, and of robustness and reliability of the system thanks to modularization. Current multi-robot systems research focuses on the coordination of actions and task execution by groups of robots, which can possibly be relatively large (e.g. swarms) [77, 78]. The main challenge is related to the design of robust and scalable decentralized systems with predictable dynamics, so that tasks can be effectively allocated [79] and coordinated by the *human orchestrator*.

20.2.3.4 Barriers

One of the main barriers to the diffusion of robotic assistants depends on how the presence of robots is acceptable and useful for human purposes in real scenarios (e.g. factories, workplaces, houses, schools, hospitals, museums, shops). Long-term interactions need to be carefully assessed in any robotic application, starting from manufacturing and then moving to other applications like robotic-assisted surgery [80] and healthcare for older or disabled population [81, 82].

Effective human-robot interactions will depend on how people physically and psychologically distance themselves from robots [83]. Fear and suspicion towards robots (so-called *Frankenstein complex*) has been long addressed in several science-fiction novels [84]. Safety has as large impact also on the acceptance of robotic technologies. In several cases, the physical contact can be established mitigating the risks associated with exceeding energy exchanged in the human-robot interaction. Protective safety functions are needed to immediately stop unexpected movements by controlling via software the motion, mechanical parameter limitations, and overall power supply.

The increasing complexity and flexibility of robotic cells, characterized by a large number of sensors and robots working together, require standardization and modularity. The main activities in this field are related to the development of industrial-oriented packages and to guarantee uniform support via industrial platforms (e.g. Robotic Operating System—ROS,¹ and in particular the ROS-Industrial² consortium).

¹<http://www.ros.org/>.

²<https://rosindustrial.org/>.

20.2.4 *Factories for Personalised Medicine*

20.2.4.1 Definition

The continuous advances in microelectronics and biotechnology open a wide range of innovation opportunities. In particular, microfluidics is an emerging technology dealing with the manipulation of fluids in microchannels for application in biology, chemistry, and other engineering fields to implement detection and separation procedures [85]. A lab-on-chip (LoC) is a microfluidic device integrating functions of a test laboratory (e.g. transfer of samples, use of a precise quantity of a chemical product, titration, mixing with reagents, heating) on a system with a size of a few square centimetres [86].

LoCs for biomedical applications typically include biosensors, i.e. analytical devices that couple *biology* and *human-made artefacts*. Indeed, biological sensing molecules interact with the analyte and are interfaced with a transducer device to convert a biochemical signal into digital signals. The biological material can be composed of enzymes, microorganisms, tissues, cell receptors, organelles, nucleic acids, antibodies or whole cells, whereas the transducer can be electrochemical, thermometric, optical, piezoelectric or magnetic [87]. In addition, more advanced biosensors contain also a series of interconnected zones that enable sophisticated interactions between components [88].

LoCs have the potential to drastically improve people's health through constant fast detection and prevention of diseases, but at the moment they have diffusion only at laboratory scale, since current technologies and factories do not allow sustainable mass production. Herein, the proposed mission aims to *develop factories and technologies for mass production of LoC biodevices that will provide everybody with personalised medicine solutions at affordable costs for better and inclusive healthcare systems*.

Rapid, portable and easy-to-use LoC systems will be used by anyone to provide fast qualitative or quantitative analysis by means of automatic self-testing procedures [89] that will reduce diagnosis time. Individuals will be more responsible for their own health and it will be possible to mitigate treatment delays. Such procedures are named as point-of-care (PoC) testing if they can be performed at the site of patient care [90].

Fully personalised medicine can be boosted by the availability of bioengineered microdevices if the technology of these devices is adequately improved in terms of parallelization, robustness, and throughput. There is still ongoing research on the development of LoCs, but commercial devices using microfluidics and molecular assays already exist [89]. Wider applications will be possible thanks to the identification of disease-specific critical biomarkers and the development of rapid and portable detection schemes [90]. In this direction a developing strategy consists in

combining LoC devices with mobile phones [91] to greatly reduce the cost of the system and extend its application. Furthermore, the success of PoC devices largely depends on the development of process technologies for mass production of reliable and accurate LoCs.

20.2.4.2 Societal Impact

The growing demand for personalised care services asks for new technological solutions and business models [92]. PoC devices will provide a cost-effective alternative to time-consuming and expensive laboratory tests, thus speeding up disease diagnosis and treatment decisions. Therefore, the use of PoC devices will potentially improve quality of life and treatment outcomes for all patients [90] (cf. SDG 3.8 [15]); indeed, it must be noted that the unmet need for medical care involved 3.2% of population aged 16 and over in Europe during 2015 [25]. A limited share of hospital budget is earmarked for *in vitro* diagnostics, but it has an impact on several decisions related to admittance, medication, and discharge. PoC testing enables to decentralize diagnostic testing, thus leading to faster treatment decisions and improved quality of care. Testing can be performed at doctor's office or at home to remotely monitor the progress of patients. Therefore, the number of visits needed to the hospital can be reduced, while personalising and limiting the invasiveness of treatments [94], and minimizing any adverse side effects of drugs [90].

The use of biological material in LoCs [93] may replace complex electronic devices that are characterized by a high cost and environmental impact during their life cycle (i.e. extraction of rare and expansive raw materials, energy and resource consuming production processes, polluting material recovery and disposal processes), thus leading to a positive net environmental contribution (cf. SDGs 12.2 and 12.5 [15]).

The inclusion of mammalian or human cells into biodevices will allow the realization of microfluidic Organ-on-Chips (OoC), i.e. a micro-device that enables to perform *in vitro* co-culture and perfusion of cells in conditions resembling the physiological environment and to recapitulate cell functions that are not present in conventional culture systems [95]. OoCs will allow scientists to model human physiology so that it is possible to quickly, cheaply and accurately identify chemical hazards, at the cellular and molecular level, as well as potential new medicines [96]. Possible applications with a relevant societal impact include toxicity studies, drug testing, cosmetics industry, cancer research, pharmacology, and testing of materials for implants [97] (cf. SDG 3.3 [15]). OoCs will represent an alternative to animal testing [98] and will enable the development of a personalised human model on chip that can be used to prevent and cure personal diseases [96].

In addition to biological procedures used in clinical and industrial chemistry, biosensor are promising for applications with relevant societal impact in environmental monitoring (cf. SDGs 3.9 and 6.3 [15]), food analysis, and bioterrorism [99]. For instance, applications can be focused on water analysis and air analysis, since contaminants or toxic substances have a strong impact on the environment and on

human health. Measurements can be performed in situ and in real time thanks to portable analysis devices, so that it is possible to immediately take action as soon as the problem is detected, thus drastically minimizing the consequences [100].

20.2.4.3 Industrial and Technological Challenges

Even though promising, several industrial and technological challenges must be faced to realize factories that are able to produce large quantities of the most interesting healthcare products, including LoC solutions [101]. The expertise needed for the design and manufacturing of LoC devices includes electronics, advanced materials, photonics, chemistry and microfluidics [90]. LoC devices for PoC applications are needed to meet clinical requirements while being simple to use, reliable, portable, sensitive, self-calibrating, inexpensive, and safe in storage, use and disposal [90].

The manipulation of small quantities of fluids requires a network of microchannels with dimensions ranging from 10 to 100 μm . Depending on the application, a LoC includes other functions such as pumps, valves, sensors, electronics, etc. [86], thus making the fabrication of the device even more challenging [102]. The production of LoCs is more difficult than conventional microelectronic chips because, instead of making only electrical connections, other challenges must be faced [103], e.g.:

- Guaranteeing accurate temperature control (± 1 °C).
- Significantly different pressures (± 1 atm) must be managed across the chip.
- Storage of harsh reagents and solvents.
- Biocompatibility issues (e.g. denaturation, toxicity and adhesion).
- Fluidic manipulations for purification.
- Manipulation of sub- μL volumes of extremely expensive reagents.
- A wide range of electrical signals to be applied and detected.
- Fluidic control by means of valves, pumps, etc.
- Optical probing small quantities of optically-thin materials.

The production of LoCs with biosensors is particularly challenging because the selection of manufacturing technologies needs to take into consideration also the intrinsic molecular properties of the biological material. The stability of biomolecules must be preserved in terms of temperature, with maximum values ranging between 40 and 80 °C. In addition to the thermal stress, also the shear rate and the compression rate must be monitored [88]. Moreover, in case of cells, an adequate perfusion must be guaranteed throughout the production process.

The miniaturization on a single LoC of all steps needed for a portable PoC device can be challenging [102]. The parallelization of testing on a LoC requires the design of separate droplet storage and manipulation sites on the chip [102].

Regardless of the transduction mechanism, the sensing surface of biosensors must be functionalized with selective bio-receptors as biological recognition elements [102]. The functionalized surface is close to the transducer that converts the sensing event into an output signal [90].

A key challenge related to the reuse (or disposal) of biosensors is the biological regeneration (or removal) of the receptors integrated in the biosensors [102].

The enhancement of LoCs with biosensors poses challenges related to the improvement of their sensitivity, small molecule detection, non-toxicity, specificity, and cost-effectiveness [99]. Most of LoCs with biosensors are currently fabricated at laboratory level, therefore new manufacturing techniques have to be developed for large-scale production with affordable costs so that these devices can be readily available for high-throughput biological investigations [95]. Micro/nano replication processes enabled by precision tooling technologies are expected to meet application requirements, such as low cost and high volume production, 3D features/surface properties, high quality, reproducibility and reliability [104]. Recognized as one of the strategic priorities for European industry competitiveness, the scientific and industrial research in the fields of micromanufacturing and microtooling is rapidly growing [105]. Micro- and nano-manufacturing technologies [106, 107] required to produce LoCs are both promising and challenging to enable future batch and mass production [108, 109]. Fabrication methods for LoC devices include soft lithography, hot embossing, (micro) injection moulding, ultrasonic welding, photolithography, three-dimensional (3D) printing techniques, and laser micromachining [85]. Photolithography has high costs and requires cleanrooms that increase the fabrication cost, therefore strong enhancements are needed to make it a viable solution for high volume production. Soft lithography with organic and polymeric materials is a popular method for the fabrication of 2D and 3D structures at high resolution, but is not appropriate for mass production [110]. 3D printing is a promising option and has been increasingly used for microfluidic devices construction thanks to a relatively high resolution, low cost, rapid prototyping, and wide range of materials that can be used [111]. However, the applicability of 3D printing is partially limited because it is not yet possible to reliably print microfluidic channels with dimensions less than several hundred microns [112]. Inkjet printing is a potential technology for mass production of biosensors because it is simple, flexible, rapid, low cost, high resolution, and efficient [88]. Micro injection moulding (μ IM) can be employed for the mass production of a polymeric micro-component (e.g. LoC devices) thanks to the high dosing precision and injection speed, while managing a very small amount of material. Recently, higher flexibility has been achieved by introducing tailored changeable inserts in the same master mould plates, so that different part geometries (e.g. removable cavities) can be tested for the injection of specific micro-components [113]. The fabrication of reconfigurable moulds for μ IM is still challenging because high accuracy is needed for manufacturing the small features of the whole master mould and tailored inserts.

20.2.4.4 Barriers

Personalised together with *Participatory*, *Preventive* and *Predictive* are the four key characteristics of the future medicine and healthcare. Personalised medicine (PM) can help to radically change patient management and big pharmaceutical companies

are already taking actions in this direction. The success of PM will depend on the technological progress and on the market demand for personalisation [90]. Public investments will be fundamental for a democratic development of PM.

LoCs for biomedical applications require a multi-disciplinary approach since biological, engineering and technological research and innovation are needed to create new devices, new materials, new processes, and new production systems that fully exploit the potential of the integration between the biological and artificial world.

LoCs and biosensors will be accepted for routine medical applications only if they are able to meet the requirements of the clinicians [114] and if the devices can be properly calibrated according to standardized procedures as already in place for traditional devices. In addition, it is necessary to address the regulations related to the LoCs market [85].

Diffusion of PoC devices will benefit from cost effective disposable solutions for biosensors that integrate all the needed instrumentation in a portable format [114].

OoCs have a high potential to support drug screen and tissue cure, but effective regulatory mechanisms must be established to deal with ethical issue and security risks [111].

20.2.5 *Internet of Actions*

20.2.5.1 **Definition**

The fast and the pervasive diffusion of internet, Information and Communication Technologies (ICT), electronics, and Cyber Physical Systems (CPS) paves the way for a new technology shift after *Internet of Things* [115].

The proposed mission is to *develop a novel Internet of Actions that enables everybody to share sensations and actions thanks to the ubiquitous presence of sensors and actuators.*

A specific mission for the manufacturing domain is to *develop by 2030 Internet of Actions solutions to enable a fully remote assistance and maintenance for a class of production plants (e.g. powertrain assembly lines, flexible manufacturing systems).*

Highly controlled and automated factories represent an ideal place where a mission for Internet of Actions (IoA) can be set and later extended to other domains. IoA will enable operators in a distributed set of industrial plants located also at considerable distances from each other to share data, information and actions while guaranteeing that all operators have the same view and perception at the same time. A completely remote assistance and maintenance can be beneficial both if skilled personnel is missing (cf. Sect. 20.2.2) and if intrinsically unhealthy and unsafe environments are involved.

20.2.5.2 Societal Impact

The societal impact of IoA is potentially huge in industry since it can be exploited also to protect labour rights and promote safety in working environments (cf. SDG 8.8 [15]). In 2014 the number of people killed in accidents at work was still 1.83 per 100,000 employees in Europe [25].

Digital technology may become an effective companion for humans to make an impact on the real world with actions generated in a mixed-reality world [116]. However, it will be necessary to realize a shift from supposedly user-centric design of technologies to actually human-centric technologies. A democratic development and spread of IoA will promote the social, economic and political inclusion of everybody (cf. SDG 10.2 [15]). IoA factories will enable people to carry out their job compatibly with the evolution and change of their cognitive and physical abilities [117], for example to cope with the extension of the working life related to ageing population in developed countries [118, 119].

Factories exploiting IoA have the potential of enhancing and better exploiting human skills (cf. SDG 4.4 [15]), thus contributing to higher satisfaction [120] and less work alienation [121]. Factories will be a qualifying learning and training environment [122] to ensure greater usability of work environments and the ability to relate industrial practices to adequate high-level skills.

Factories and hospitals (e.g. remote surgery and rehabilitation) are primary targets for IoA applications because they are characterized by highly structured and controlled environments. However, as soon as the technology is more mature, applications can be foreseen also in many other unstructured environments, such as home, entertainment, inspection and exploration.

20.2.5.3 Industrial and Technological Challenges

The development of IoA devices and systems with processors, sensors, and actuators will require the further development and integration of several enabling technologies, e.g. Augmented and Virtual Reality (AR/VR) [54, 55, 123], High Performance Computing [124], Cloud and Fog Computing [125–127], Cyber-Physical Production Systems [128], Big Data Analytics [129], ultrafast communication infrastructures and standards, artificial intelligence [130], data storage, sensors and monitoring [131], wearable devices [68], and actuator technologies.

Effective IoA systems will need to accurately reproduce sensations [132], so that proper (re)actions by humans can be generated interactively and adaptively. In particular, the development of new sensors and actuators will be fundamental to enable the sense of presence at a distance together with accurate and safe remote actions. The devices employed in IoA architectures will need to properly manage the interaction with the environment and human beings [133].

The extensive use of actuators will need new technological solutions that offer the possibility to build highly miniaturized devices, while keeping low the ratio between system mass and generated power, especially for long-term tasks. Indeed,

manufacturing and assembly limitations together with physical scaling laws hinder a further size reduction of traditional actuators (e.g. electromagnetic motors) that are able to provide significant forces and torques. Only piezoelectric motors can be scaled rather efficiently to approach the boundary of the microdomain (below 1 mm) [134]. Bioactuators represent an innovative opportunity to meet the most demanding actuator requirements. Bioactuators exploit the action of live micro-organisms, both as a source of electrical power and a means of actuation (e.g. bioactuators powered by cardiomyocytes, based on bacteria, other motile cells, explanted whole-muscle tissues, engineered skeletal muscle, or insect-derived self-contractile tissues [134]). Bioactuators can reach a volume that is orders of magnitude smaller than the smallest piezoelectric motor. Moreover, the use of living cells offers self-healing capabilities, silent operation, and use of inexpensive and eco-friendly fuel [134]. Bioactuators enable the fabrication of microscale devices and soft robotic artefacts to safely interact with humans [134].

Human Computer Interaction (HCI) technologies will help humans to deal with complex mixed-reality systems full of autonomous agents [116]. Furthermore, HCI and haptic interfaces [64] will help IoA systems to properly interpret the intentions and actions of humans.

In manufacturing applications, various devices connected with the real shop floor can provide detailed data about the status of ongoing processes. Specifically, these devices generate a large amount of intensive and heterogeneous multi-source data (*Factory Telemetry*), which have to be ingested by proper solutions (e.g. simulation tools) capable to process these data streams to extract relevant insights [135]. It will be important to investigate the potential of the new generation of storage and database systems that can also run on distributed cluster systems (e.g. NoSQL databases) [136]. In addition, the need of sharing heterogeneous data demands to develop solutions for interoperability between different systems and between systems and humans. Another important requirement for solutions supporting factory telemetry is a minimal data latency, which can be enabled by the fifth-generation (5G) mobile networks [137]. Moreover, the continuous growth of objects connected to the IoA network requires the identification of valid strategies to distribute intelligence and data among the various components of the infrastructure (sensors, actuators, microcontrollers, services and databases on cloud, etc.). To meet this need, a potential reference model can be Fog Computing that allows transferring part of the computing power and the storage space near the data sources, thus reducing their data transmission time and increasing their availability [127]. Future connected devices will be capable of sophisticated interactions thanks to flexible mechanisms of collaboration and cooperation [138]. Within the IoA network, smart objects can cooperate with humans, with other objects, and with bots (e.g. chatbots, virtual assistants, etc.) or can negotiate offered services with each other.

Workplaces of human-centred and IoA-enabled factories will need to be redesigned on the basis of specific rules of ergonomics and organized according to adaptive work rhythms to provide an environment and working conditions appropriate to the different people, regardless of their age, sex and physiological or pathological status. Indeed, the continuous increase of ageing workers (age: 55+), as well

as the need to promote the work (re)integration for impaired individuals, calls for a redesign of workplaces, even going beyond the criteria defined in international standards [139].

In a context characterized by factories where products, processes and technologies evolve through articulated dynamics, a fundamental challenge is represented by the ability to interpret complex production phenomena and identify solutions based on experience. Therefore, it is essential to invest strategically also in enabling technologies (e.g. VR/AR) to support user-centred tasks such as operator training and maintenance support by means of visual, auditory, tactile feedback and interaction, as well as appropriate semantic and ontological representations of information and knowledge to support the formalization and reuse of such experiences.

20.2.5.4 Barriers

The public opinion must be convinced of the centrality of humans in IoA for the realization of the objectives of this mission. An appropriate design of still-new technologies constitutes a fundamental aspect. Technology acceptance depends on two factors that strongly influence the users' attitude toward the employment of a new tool. Firstly, *Perceived usefulness* represents the degree to which a person believes that using a particular system would enhance his or her job performance; secondly, *Perceived ease-of-use* has been defined as "the degree to which a person believes that using a particular system would be free from effort" [140]. Visual technologies like AR/VR will play a key role to involve the population and support the users.

The close collaboration between humans and autonomous systems will pose serious problems of communication and safety. Actuators must be accurately remote controlled to interact with the environment while guaranteeing safety for humans and the environment itself. Companies will strive to exploit the opportunities offered by IoA, but an increasing number of threats could jeopardize the cyber-security of the IoA network. In particular, data confidentiality, integrity, and availability are the main features that could be compromised. For this reason, it is essential to identify new security measures that can contribute to mitigate the risks of attacks against this network, thus guaranteeing the protection of the information exchanged within the IoA network [142].

Algorithms governing IoA systems will have to understand why a user takes specific actions. Moreover, algorithms must be able to explain why specific events happen while facing decisions with life-or-death consequences (e.g. autonomous transportation systems in a factory) [116]. However, there are sectors where algorithms cannot be completely automatized because of the high risks associated with possibly wrong decisions (e.g. medical diagnosis Decision Support System (DSS), or health-related DSSs [141]).

The intensive use of technology in human-centred factories poses relevant ethical issues. Monitoring the activities of human operators and the use of personal data may be needed both for safety reasons and to implement IoA systems, but regulations will be needed to avoid misuses and protect privacy.

Europe has a long tradition in mechatronics, automation and robotics. Therefore, the development of IoA represents an opportunity to exploit a competitive advantage and be a world technology leader in this field, thus generating a relevant economic boost.

20.2.6 Factories Close to the People

20.2.6.1 Definition

Factories and civil population experienced a conflictual relationship since the beginning of the industrial revolution. Positive gains like high employment, mass production of goods, and labour rights have been coupled with industrial pollution, waste of natural resources, and work alienation. In the past, factories were built inside urban areas because of wider availability of workforce and of proximity with working place. However, especially in the case of process manufacturing, this created significant problems of severe environmental impact and disruption of the urban landscape, which is even more negative in the cities with touristic vocation and with relevant historical background, as in the case of many European cities. Therefore, the overall high cost of urban manufacturing led many industrial companies to move their production facilities outside the cities, abandoning urban plants with consequent dismantling problems that are not solved yet in many municipalities. Even if this delocalisation of production had positive impacts on urban environment, it moved environmental problems to previously uncontaminated rural or sub-urban areas. Furthermore, it was the cause of massive traffic flow of workers from cities to production locations, thus increasing the pollution generated by mobility and reducing people's quality of life due to traffic congestion and longer commuting time.

This situation generated over time a general adverse feeling against advanced and intensive manufacturing, which started to be considered as necessary for economic prosperity, but incompatible with green environment, nice landscapes and workers' quality of life. Thus, a paradigm shift is needed to re-think this relationship aiming at factories closer to the people, where closeness must be intended both as proximity and as positive relationship [143, 144]. The proposed mission is to *Design and build symbiotic and sustainable factories that are fully integrated in city districts of large European cities (population higher than one million) by 2030, minimizing their adverse effects at global and local level.*

20.2.6.2 Societal Impact

Factories are a fundamental part of the civil community and their integration in cities and local communities should be based on proper cohesion policies as well as on proper tools to manage risks and challenges, while favouring a positive economic,

societal and environmental link between urban, peri-urban and rural areas (cf. SDG 11.a [15]).

Sustainable factories integrated in urban life (i.e. *urban factories*) [143, 145] can help to increase the number of cities adopting and implementing integrated policies and plans towards an efficient use of natural resources (cf. SDG 12.2 [15]), as well as the mitigation and adaptation to climate change (cf. SDG 11.b [15]) [146].

Factories close to the civil population will need to continuously monitor the environmental effects of industrial activities that affect local context, also aiming to reduce the number of illnesses and deaths from air, water and soil pollution and contamination (cf. SDG 3.9 [15]). In 2015 the consumption of chemicals that are toxic to health reached 221 million tonnes in Europe [25]. Monitoring water pollutant in water plants should be clearly addressed both at plant level and at supply chain level (cf. SDG 6.3 [15]).

A symbiotic relationship between factories and cities can help to reduce the overall energy and resource consumption (cf. *urban mining* [147]), secure sustainable energy supply and improve access to affordable energy [145]. In addition, a more homogeneous and distributed presence of factories in the urban areas will help to better integrate production, business, and social activities, thus reducing the phenomenon of *dormitory suburbs*.

20.2.6.3 Industrial and Technological Challenges

Digital technologies for sustainability will enable factories to monitor internal key performance indicators and cooperate with the urban environment and other factories in the supply chain. Indeed, it is fundamental to measure the progress on sustainable development (cf. SDG 17.19 [15]). A close integration of information will be needed between supply chain management, rules and standards suitable for industrial sustainability, internal sensor and monitoring systems, product data management, needs and consumptions of smart cities [148].

A set of analytical methods (Life-cycle Assessment, Life-cycle Costing, Risk assessment, Social Life-cycle Assessment) can be applied by single companies to evaluate effects of industrial activities on product chain, ecosystem, and society [149–153]. Specific assessment methodologies will be needed to identify effective technologies from an environmental and social point of view.

New factory automation and management systems should natively support the participation in the energy market with reference to price and environmental targets. Such approach requires integrating the price of energy and its actual environmental impact within the multi-objective optimization strategy to be pursued. Production units could therefore collaboratively improve their operating margins and environmental benefits by reducing energy costs [154].

The use of CPS may enable a real time quantification of the impact of production activities on two parallel areas: the environmental aspects (e.g. consumption of materials, energy or items as well as solid or fluid emissions) and the related local

and global impacts (e.g. contribution to global warming, depletion of local resources and other key action areas).

Further industrial and technological challenges to be addressed include:

- Systems to monitor, manage, and treat water within factories [155, 156].
- Transparent monitoring and reduction of carbon content (e.g. CO₂ pollution) of industrial activities [157] both at plant level and at supply chain level.
- Methodologies and tools to monitor and reduce industrial noise pollution [158] of the factories in the urban tissue.
- Systems for energy management to foster efficient use of energy and to integrate information on energy quality within factories according to a multi-scale approach [159].
- Systems for monitoring and mitigating the effects of industrial activities (e.g. fine and ultrafine particle emissions [160], greenhouse gas emissions [161]) on regional and local areas to intelligently address health and climate effects by ex-ante and real-time analysis (cf. SDG 13.3 [15]).
- Energy-aware real-time control systems through the adoption and extension of predictive and model-based control techniques [162].
- Development of semantic data models for the integrated modeling of sustainability aspects at various factory levels (products, processes, resources and production systems, plant services, industrial building), both in static (e.g. configuration of plant) and dynamic (e.g. evolution of production resources in terms of status and energy consumption profile) terms [163].
- Advanced production scheduling and control to optimize energy and resource consumption profiles at system and machine level [159, 164].
- Integrated management of factory utilities (e.g. optimal real-time cogeneration) considering the thermal/electric consumption profiles of the production processes as well as sales/purchase opportunities in the market [159].

20.2.6.4 Barriers

Symbiotic and sustainable factories require a continuous impact assessment of production operations involving interdisciplinary and data-intensive processes, including data collection systems. Data management systems need to access heterogeneous data sources including sensor networks, factory information systems (e.g. Supply Chain Management tools [165] and Enterprise Resource Planning), and also remote systems (e.g. monitoring of markets for energy trade).

Digitising sustainability requires verifiable and reliable information to be reused in a modular way. Many parameters linked to sustainability are still qualitative or semi-quantitative, therefore tracking systems must be calibrated to provide reliable information. The cost of data tracking is relevant especially in case of real-time sampling systems. Industrial companies avoiding to implement expensive data tracking may benefit from a competitive advantage, therefore the publication and enforcement of regulations together with public funding and support will be fundamental to make

a profit-driven business also compatible with sustainability goals. Possible industrial delocalization to countries with less demanding regulations and less efficient production must be regulated to save employment in developed countries [166] and protect the environment in the destination country [167].

The proliferation of different sustainability standards by various public and private bodies can create double counting of specific effects and overlapping in tracking. The overlapping between protocols constitutes a serious limit for implementing accounting and optimization systems. Coordinated standardization initiatives are needed to avoid further computational barriers.

Finally, a cultural barrier should be overcome to establish the common understanding that not only manufacturing is necessary for economic reasons, but that it can successfully co-exist with urban living and can even provide social and cultural advantages to cities. To this aim, future generations should be properly educated to increase the attractiveness of manufacturing and to remove the negative bias that is the heritage of the conflictual relationship between manufacturing and civil society during the last few decades.

20.2.7 *Turning Ideas into Products*

20.2.7.1 **Definition**

Personalised production is an evolution of customization [168] that enables companies to differentiate their offer through innovative products for specific needs of a customer or a target group [169] thanks to adaptable and reconfigurable production systems [170] supported by easy-to-use product configuration systems to make processes along the supply chain efficient [171, 172]. In this scope, the proposed mission is to *turn ideas into products by transforming passive consumers into active participants in the production of their own products thanks to new technologies that can enhance and empower their capabilities*. This mission implies a paradigm shift because innovation will not originate anymore from the identification of consumer requirements; indeed, innovation and production will be taken out of the factory boundaries to allow people to be the decision makers during the design and production process in new collaborative supply chain models [173, 174].

Consumer goods (e.g. clothing, footwear, sports items, glasses) [172, 175] but also other kinds of product such as medical products (personalised orthopaedic prosthetics, dental prosthetics, etc.) or durable goods (cars, kitchens, buildings facades, etc.), and even food can be produced based on the ideas of and by customers applying an approach of self-managed personalisation. In this way, they can create products with a unique design and style, along with functional and comfort-related aspects, going beyond the conventional choice dictated by off-the-shelf products.

20.2.7.2 Societal Impact

This mission will lead to a big change for manufacturing heading towards socialization and massive involvement of consumers [176–178]. Many small and medium sized manufacturers (e.g. SMEs, fab-labs and even individuals) will participate in different market segments, while evolving into production service providers to satisfy customers' personalised requirements [28]. These entities will further aggregate into dynamic communities in a decentralized system and win bargaining power and efficiency. Moreover, new companies will basically sell ideas and their integration into new and dynamic value chains and markets (cf. SDG 9.3 [15]).

People empowerment, inclusive society and sustainability are further impacts to be considered. According to a survey by Deloitte, 36% of customers are interested in personalisation and 22% are happy to share personal data in return for a personalised customer services and products [179]. The price is not a barrier, since 20% of consumers who expressed an interest in personalised products or services are willing to pay a 20% premium price [179]. As an example, clothing (19% of customers) and furniture (18%) are two important categories where customers make personalised purchases and an increasing number of manufacturing industries and brands are adopting this paradigm nowadays.

In a broader and inclusive view, it is necessary to ensure that all customers, including people belonging to less-represented communities, are enabled to turn their ideas into design and manufacturing of their own products, according to their specific needs and wishes (cf. SDG 9.2 [15]). It is crucial to promote and increase access to new technologies and the acquisition of knowledge and skills to properly handle them. The direct involvement of consumers in the production processes will increase their awareness of the societal impact of production from economic, environmental, and political perspectives (cf. SDG 12.1 [15]).

The diffusion of technologies for *turning ideas into products* can help the development of an inclusive society (cf. SDG 10.2 [15]) thanks to potential enhancement and better exploitation of personal skills and capabilities (cf. SDG 4.4 [15]) contributing to take people away from alienating working places and facilitating the integration between leisure and work. The creation of new jobs in different sectors exploiting the creativity of people is also enabled. Moreover, consumer entrepreneurship will be promoted through novel network based financing models and means. According to that, new business models to manage such kind of scenario will have to be developed.

The implementation of the proposed mission will have an indirect impact also on sustainability since production will shift from Make-to-Stock to Customise-to-Order, thus avoiding problems related to inventories and, in particular to unsold stocks which are related to economic and environmental costs for society (cf. SDG 12.5 [15]).

20.2.7.3 Industrial and Technological Challenges

Digital technologies play an important role in this mission where the power to design and produce can be at individual or community scale. Customers will produce small and large objects thanks to easy access and integration of technologies and systems suitable for rapid change in their configuration and production. Depending on the type of product, customers may involve people or organizations with various degree of expertise that are able to conceive ideas with different levels of complexity and formalization.

Manufacturing companies need to develop new collaborative systems and easy-to-use manufacturing facilities with flexible automation [180] that are capable of producing relatively small batches of customised products at competitive costs that mimic mass production prices [181] with a human-centred design approach [182]. Not only product design, but also manufacturing operations, services, relationship between people, people and companies, society and companies will need to be changed [183].

Industrial and technological challenges are associated with different processes along the value chain including product development and capability of the customer to use advanced technologies like product configurators, advanced biometric measuring systems, and platforms for production control. Furthermore, there is a need for new flexible and agile supply chain models for decentralized production. One critical aspect is the ability to hide the complexity of technologies and organizations by means of appropriate models, digital twins, artificial intelligence, virtual and augmented reality [55], so that the consumer can concentrate on the idea to be turned into a product but at the same time receives a feedback on the implication of his requirement in terms of time, cost, viability.

New tools for the configuration and design of personalised solutions will enable people to be active (and not passive) actors in the production chain. Sensor models and tools will help to formalize their needs and expectations starting from the design of the product to the innovative services associated with its production. Design and configuration systems need to shift to the mobile economy paradigm. New digital tools will integrate consumer input in terms of requirements and specification into the product design [184]. Moreover, new methods and tools will validate the product design and transform it into manufacturing operations that are taken in consideration also for a dynamic network configuration [185].

Solutions for adaptable and reconfigurable manufacturing will be based on enabling technologies, including not only additive manufacturing [186] but also, for example, laser technologies, hybrid technologies, and other relevant innovative or traditional production technologies. Indeed, the development and production of functional components and parts of the product will be differentiated in response to the needs and demands of the consumer, thus leading to a high product variety [187]. The integration into a single machine tool of different transformation processes is

another important challenge. New technologies for innovative production processes and control [164] will allow the development of machines that will hide the complexity of the technologies and through models of the processes, digital twins and artificial intelligence will become easy-to-use for home-based designers as well as for the implementation of the customer-to-customer (C2C) paradigm where each customer can sell to other customers.

Models and tools for the creation of dynamic supply chains for personalised production are needed to implement decentralized production models where manufacturing capabilities are not necessarily concentrated in large plants but under certain conditions may be spread in several locations [188, 189]. This raises also the need to define new logistics systems where digitalization can support the tracking and provision of raw materials and components as well as supporting maintenance and usage of machines with real time remote control. New models and tools should be based on big data analytics to increase the capacity of companies to manage large quantities of data from a variety of sources (client, suppliers, machines, and social media) and support the selection and management of supply and distribution networks, based on real-time exchange of information between the involved actors [190]. Moreover, big data can be used also to activate new blockchain processes ensuring that transferred data are original and to conceive smart contracts for regulating different processes (from design, to production, to logistics).

The production and distribution chain may in certain cases be reorganized in mini-factories, i.e. decentralized and modular production facilities [191] that are managed by consumers willing to develop a new product concept or by technicians (e.g. an orthopaedic technician in a hospital lab producing body prosthesis [92]). The availability of cutting edge technologies and facilities to a wide range of consumers permits the acquisition of digital production knowledge, creativity, and collaboration. The quality and functionality level of one-of-a-kind products will have to be the same as in mass production factories.

New business models need to be developed. For instance, in certain cases the realization of innovative products could be co-financed by groups of customers through micro-sponsoring platforms and peer-to-peer platforms can be adopted for their commercialization. This will enable consumers to learn new skills and create shared job opportunities also promoting consumer entrepreneurship [192]. New business models will have to take in account all these aspects in order to exploit at best the potentialities of this approach.

20.2.7.4 Barriers

The radical innovation of personalised production through dedicated manufacturing technologies in a networked paradigm poses several barriers and critical elements to be faced, both at product and at manufacturing level.

The safe management of all personal information influencing the personalisation process, including biometric ones, is crucial. Distributed manufacturing approaches will require secure sharing of such information along the whole chain, as well as its

continuous management and update, in the case of dedicated (web-based) services accompanying the product along its lifecycle, as those intended to monitor health, activity, and performance.

Major barriers must be addressed in terms of liability since one-of-a-kind products must guarantee safety and functionality. Liability therefore will pose limitations to what can be actually decided and what has to be selected among already tested alternatives. This approach will in any case need modifications of regulations and norms, especially in potentially dangerous products as in case of novel products for healthcare. New approaches to liability should consider also the presence of non-stable production networks.

The development of new standards for sharing information on products and processes represents another crucial aspect to fully accomplish this mission.

At manufacturing level, a cultural revolution is needed for the introduction of novel personalised production. Hybrid production technologies will require major transitions both in product design (e.g. design for additive features) and in product realization, where total integration should take place at information level (therefore affecting data formats and interoperability), at technological level (implying the partial disclosure of company mutual technical capabilities) and at organizational level (to become active actors in networked value chain paradigms).

Finally, new regulations for intellectual property rights will be needed to fully take advantage of innovation and knowledge sharing that empowers consumers thanks to the diffusion of ideas and their transformation into products.

20.3 Conclusions

After highlighting the potential of mission-oriented policies to boost research and innovation, this chapter presented seven missions focused on manufacturing industry but with larger societal impact. Some of the enabling technologies needed to accomplish the missions are related to the results of the research projects funded by the Italian Flagship Project *Factories of the Future* [5], as shown in Table 20.1. Further relevant missions can be identified and other specific goals can be associated with the proposed missions.

The accomplishment of a mission for research and innovation requires the clear demonstration of how specific innovation goals have been reached, while supporting the wide uptake of innovation to generate industrial and societal impact. Therefore, effective research infrastructures are needed to improve the exploitation of promising scientific and industrial results. In particular, the following chapter of this book [11] analyses how pilot plants can help to overcome the so-called *Valley of Death*, i.e. the phase between Technology Readiness Level 6–7 and 9. Industrial research and pilot plants can be sustainable only if integrated (public-private) funding mechanisms and innovation partnerships are implemented.

Table 20.1 Mapping of the *Missions* versus *Factories of the Future* research projects

Mission	Related research projects	Topics
Circular Economy (Sect. 20.2.1)	Zero Waste PCBs [33]	Recovery of residual value from post-use products
	WEEE Reflex [36]	Automated technologies for circular factories
Rapid and Sustainable Industrialisation (Sect. 20.2.2)	Pro2Evo [53]	Formalization and sharing of production knowledge using ontologies
	MaCISte [58]	Renewable energy
Robotic Assistant (Sect. 20.2.3)	Xdrone [64]	Multi-sensor, multi-modal map building
	FACTOTHUMS [68]	Safety in human/robot cooperation, wearable devices
Factories for Personalised Medicine (Sect. 20.2.4)	Fab@Hospital [92]	Personalised medicine and business models
	SILK.IT [93]	Biomaterial for LoCs
	PLUS [109]	Fabrication technologies for LoCs
Internet of Actions (Sect. 20.2.5)	Xdrone [64]	Haptic interfaces
	FACTOTHUMS [68]	Wearable devices
Factories close to the People (Sect. 20.2.6)	PROBIOPOL [156]	Waste water treatment
	MECAGEOPOLY [161]	Energy and emission efficient industrial processes
	IMET2AL [162]	Predictive and model-based control techniques
	GECKO [164]	Advanced production scheduling and control
Turning Ideas into Products (Sect. 20.2.7)	Fab@Hospital [92]	Personalised products and mini-factories in hospital labs
	GECKO [164]	Advanced production control
	Made4Foot [189]	Supply chain configuration

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