ManuFUTURE

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SRIA 2030

STRATEGIC RESEARCH AND INNOVATION AGENDA

Report from Manu*FUTURE* High-Level Group, December 2019

FOR A COMPETITIVE, SUSTAINABLE AND RESILIENT EUROPEAN MANUFACTURING

Manu*FUTURE*

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Table of contents

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AM – Additive Manufacturing European Platform
AET – Agriculture Engineering and Technologies
Joining – Joining Sub-platform
ET – European Tooling Platform
4ZDM – Zero Defect Manufacturing
Manu*FUTURE* National and Regional Technology Platforms Network

Other ETPs and organizations:

ARTEMIS - Embedded Intelligent Systems European Industry Association
ConXEPT – Consumer Goods Cross ETP
ECTP – European Construction, built environment and energy efficient building Technology Platform
EMIRI – Energy Materials Industrial Research Initiative
EuMaT – European Platform for Advanced Engineering Materials and Technologies
EWF – European Welding Federation
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0.

Introduction

Ø. Introduction

Manufacturing **is the backbone of the European economy,** with some 2.1 million manufacturing companies in 2014 employing near 30 million people and generating EUR 1 710 billion of value added. The **European Union is the world's biggest exporter of manufactured goods, and is a global market leader for high-quality products.** Manufactured goods, with a trade surplus of EUR 153 billion in the first semester of 2016, greatly contributes to the overall positive trade balance of the European Union. Machinery, transport equipment and chemicals are responsible for the highest share in European exports[1].

Manufacturing is a complex ecosystem including small and larger companies, creating a strong capacity to deliver high added-value solutions through constant innovation and, hence, **creating jobs and sustainable growth.** Manufacturing enables many high added-value services (for example, product design, software development, logistics and other support services) justifying the creation of up to two indirect jobs for each direct job in manufacturing.

Currently, society is undergoing a **major paradigm shift,** as important as the social transformation in the first industrial revolution. This shift is a global phenomenon, affecting the ways we live, work and behave. It is driven by an unprecedented increase in the development speed of science and technology, a fast diffusion of knowledge, new consumer preferences and global competition.

To **secure high added-value jobs and ensure regional development and wealth creation, Europe needs to sustain and reinforce its position in manufacturing, to promote an inclusive economic growth.**

In this context, in which competition is becoming stronger and going up the value chain, and consumers are becoming more demanding, **Europe will have to address new opportunities and increase its investment in research and innovation towards manufacturing, in order to ensure competitiveness and long-term success.**

[1] Manu*FUTURE* Vison 2030: Competitive, Sustainable and Resilient European Manufacturing, Report from the Manu*FUTURE* High-Level Group, December 2018, ISBN 978-989-95853-7-9.

The **Manu*FUTURE* Vision for 2030** is presented in the document "Manu*FUTURE* VISION 2030: Competitive, Sustainable and Resilient European Manufacturing".

This document details the Strategic Research and Innovation Agenda proposed by the Manu*FUTURE* European Technology Platform. Chapter 1 presents a summary of the Manu*FUTURE* Vision and Strategy for 2030, while Chapter 2 describes the Manufacturing Research and Innovation Ecosystem and its unique characteristics. Subsection 2.3 presents an **integrated strategy for linking basic science to applied research in Manufacturing,** cutting across the different stages of research and development, i.e., from basic science, fundamental and applied research to market uptake, including education and training, entrepreneurship, and innovation infrastructures that are necessary to address the dimension and complexity of research challenges in Manufacturing. This approach is presented in detail in Annex 1.

Chapter 3 describes the most relevant Science and Technology Challenges, namely: Adding value in the system of manufacturing, Horizontal and vertical integration, The Road to Circular Economy and Decentralised Technical Intelligence.

Chapter 4 describes the Research and Innovation Priority Domains, which is the first Building Block proposed by Manu*FUTURE* to reach its Vision in 2030. Ten Research and Innovation Priority Domains for successful European Manufacturing are presented: Manufacturing technology and industrial equipment; Digital Transformation; Robotics and flexible automation; Nanotechnologies and materials; Biological transformation; Customer-driven manufacturing; Human-centred manufacturing; Agile manufacturing systems design and management; Circular economy; and New business models and logistics networks.

Chapters 5 and 6 present the other Building Blocks for successful manufacturing, namely: Innovation and Entrepreneurship and Education and Training. Chapter 7 identifies relevant cooperation with other Initiatives.

1.

Manu*FUTURE* VISION, strategy and building blocks for 2030

1. Manu*FUTURE* VISION, Strategy and Building Blocks for 2030

Manu*FUTURE* envisions that while global competition is becoming increasingly challenging, Europe will reinforce its position because of its **technical and technological leadership and capacity to handle complexity.** Europe will **specialise in the engineering of complex and highly interconnected value creation processes and systems.** Its experience, creativity,unique tradition and identity will support the consolidation of the European manufacturing.

In 2030, the European manufacturing industry will be delivering **solutions of excellence,** ensuring individual user satisfaction (including customised products and services), high quality and environmental and social sustainability, fostering an i**nclusive economic growth.**

Europe will be the **leader in manufacturing engineering for highly personalised and complex products and services** in a broad range of sectors, including aeronautics, automotive, production equipment, renewable energies, space, and defence.

Europe will be at the forefront of **resource efficiency and circular economy** implementation, which will contribute to its competitiveness at a global level and support its environmental sustainability. Manufacturing systems in Europe will be flexible and resilient, with optimal balance and integration between humans and machines. The European workforce will develop new skills in order to be prepared to address these challenges.

Europe will be the leading "solution provider" in **production technology, digitalisation, resource efficiency and circular economy implementation,** which can only be achieved through the continuous development and exploitation of new technologies. Research and innovation will promote industrial digital transformation, thus enhancing the competitive strengths of European companies, products, productions systems and services.

Starting with a strong scientific and technical leadership, the Manu*FUTURE* Vision evolved over time. Moving from being purely focused on ensuring competitiveness in its early days, to the inclusion of sustainability requirements, the 2030's Vision now also addresses the need for a resilient and adaptive manufacturing ecosystem able to cope with increasing levels of sophistication and environmental and social requirements.

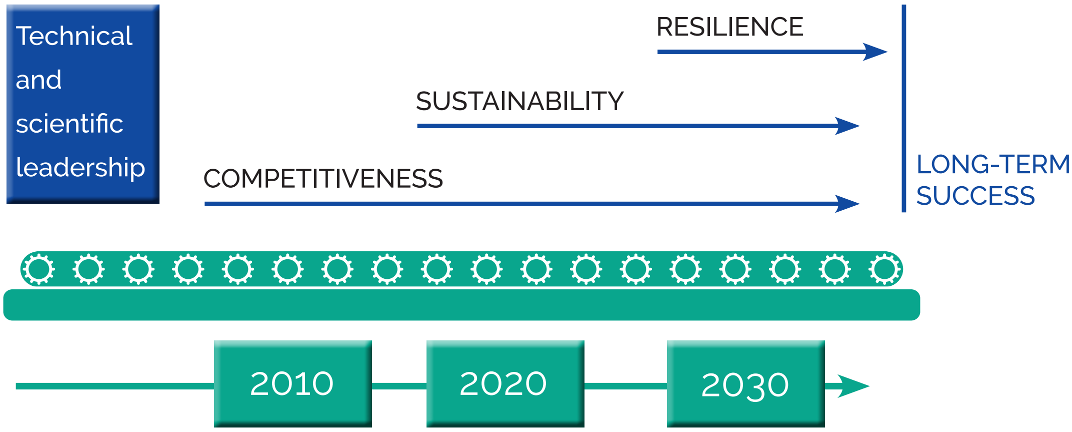


Figure 1 – High-level vision for European Manufacturing 2030

In order to achieve its goals, the Manu*FUTURE* 2030 Vision defines three building blocks: **science and technology, innovation and entrepreneurship, education and training.** Chapters 5, 6 and 7 detail these building blocks.

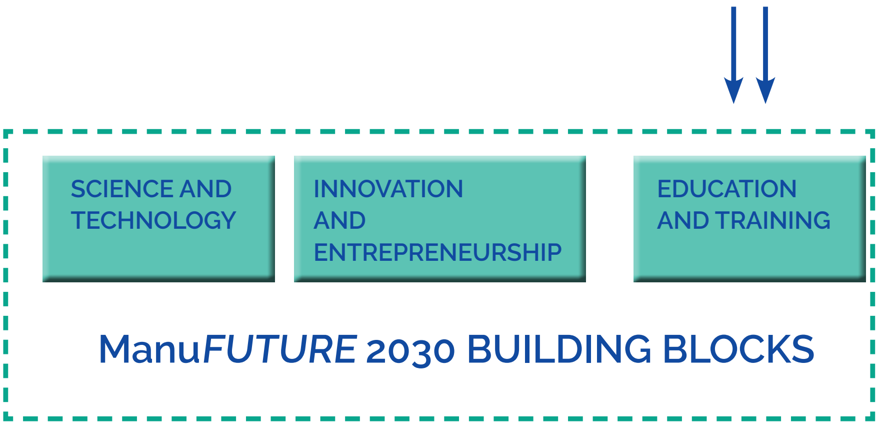


Figure 2 – ManuFUTURE 2030 Building Blocks

The detailed **Manu*FUTURE* Vision and Strategy for 2030** is presented in the document "Manu*FUTURE* VISION 2030: Competitive, Sustainable and Resilient European Manufacturing".

2.

The Manufacturing Research and Innovation Ecosystem

2. THE MANUFACTURING RESEARCH AND INNOVATION ECOSYSTEM

2.1 Leadership in key enabling production technologies and processes

One of Europe's main strengths is its excellence in manufacturing processes, systems, industrial machinery and the related domain knowledge. Only by building upon these strengths, the progress in digital manufacturing can be valorised and the industrial leadership be ensured. Not only for global competitiveness, but also for addressing global challenges, Europe must ensure the availability of future building blocks of advanced manufacturing, for instance, in areas such as photonic production technologies, additive manufacturing functional integration, nano & micro manufacturing or joining and assembling.

The instrument of choice for the implementation is pre-competitive (TRL 3-6) collaborative research between European partners, thus creating the European added value, particulary when technological risks are high, but the risk to distort competition is low. Complementary, a close link to basic science is needed in order to identify and develop promising elements for future manufacturing, earlier than competitors.

2.2 Leadership in the manufacturing innovation ecosystem

A highly competitive and resilient European manufacturing system will be based on a comprehensive Manufacturing Research and Innovation Ecosystem that overcomes the fragmentation of the past. In 2030, joint efforts and strategically aligned investment decisions of all the innovation actors from different sectors across multiple governance levels will be achieved:

- multi-actor: stakeholders from public authorities, civil society and financial institutions to industry, universities and research organisations;
- multi-sector: various industry sectors and political "sectors" along the knowledge triangle "education – research – innovation" (e.g., synchronising education, research, industry and regional policy), with a strong interaction between those providing and using advanced manufacturing technology;
- multi-level: interlinked European, national and regional programmes and initiatives.

As a result, in 2030, Europe will have a worldwide leading innovation ecosystem that acknowledges the broader socio-ecological environment as an important driver for manufacturing innovation and in which the impact and strategic importance of manufacturing is measured in terms of value added and jobs, both direct and indirect.

Europe will introduce new products and technology into the market faster than any other region at a global level, reinforcing its added value and market share.

2.3 Linking basic science and applied research in Manufacturing

The history of science evolved step by step from the antique holistic philosophy and nature observation into many specialised disciplines (in-depth experts and expertise). All of these disciplines evolve curiosity-driven further in depth and periodically split up into more sub-disciplines. Expertise has become so detailed, that a horizontal communication between the disciplines in science is hardly possible. More technical disciplines pick up knowledge and concepts from basic science and leverage on them to solve practical problems or improve technologies. Until today this is almost exclusively a pull-process from the practical application side.

Relevant innovations impacting our lives and society stemmed from research and innovation schemes mixing together basic science and applied research, e.g., through large collaborative endeavours towards an ambitious objective (A.1.1) or around the emerging of a technology (A.1.2). In these cases, shortcutting the traditional research and innovation processes entailed a faster innovation cycle.

The dimension and complexity of research challenges in Manufacturing calls for the collaborative endeavour of excellent researchers from different disciplines, cutting across the different stages of research and development, i.e., from basic science to applied research until market uptake, including education and training, entrepreneurship, requiring relevant research and innovation infrastructures.

Today, innovative collaborative research concepts and solutions could be pursued for a better coordination across disciplines and supporting the implementation of specific actions to promote and facilitate the bidirectional circulation of knowledge and people between the different stages of the innovation cycle:

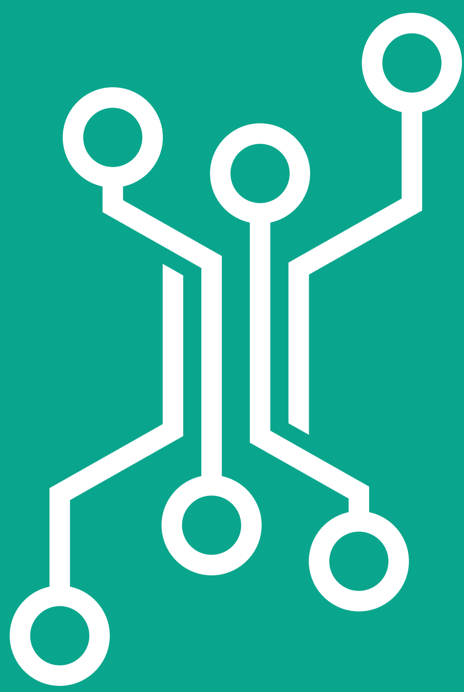
1. Objective-driven research: basic science at the interface between different disciplines joins applied research to propose new solutions and new devices.
2. Technology-driven research: new enabling technologies start to grow exponentially and attract basic science, applied research, capital, applications.
3. Upstream-swimming research: applied research identifies the knowledge bottlenecks that hinder for future developments and joins efforts with basic science to address these problematic areas

These schemes require the involvement of different scientific communities supporting the definition of relevant research objectives, technologies as well as research and technology gaps.

A more detailed insight into these challenges and some practical examples highlighting the constraints affecting the linking between basic science and applied research in Manufacturing are reported in **Appendix A.**

3.

Science and Technology Challenges



3. SCIENCE AND TECHNOLOGY CHALLENGES

3.1 Adding value in the manufacturing system

MANUFACTURING IN THE 21ST CENTURY IS A COMPLEX AND HIGHLY DYNAMIC SOCIOECONOMIC SYSTEM THAT BEGINS WITH THE DESIGN AND CREATION OF PRODUCTS AND ENDS WITH THE RECYCLING OF USED RESOURCES (FIGURE 3).

The first objective of the manufacturing system is to manufacture and to deliver products that meet or exceed the users expectations (B2U = business to user, the personalisation aspect both in B2B and B2C). A second and less trivial objective is to create added value and benefits for social and public communities over the entire life cycle of products. If this second objective is not achieved, the system cannot be sustainable. The system is highly dynamic due to the permanently changing boundary factors ("drivers"), such as market and customer requirements, economic, financial, political and governmental conditions, technical innovations and technical trends.

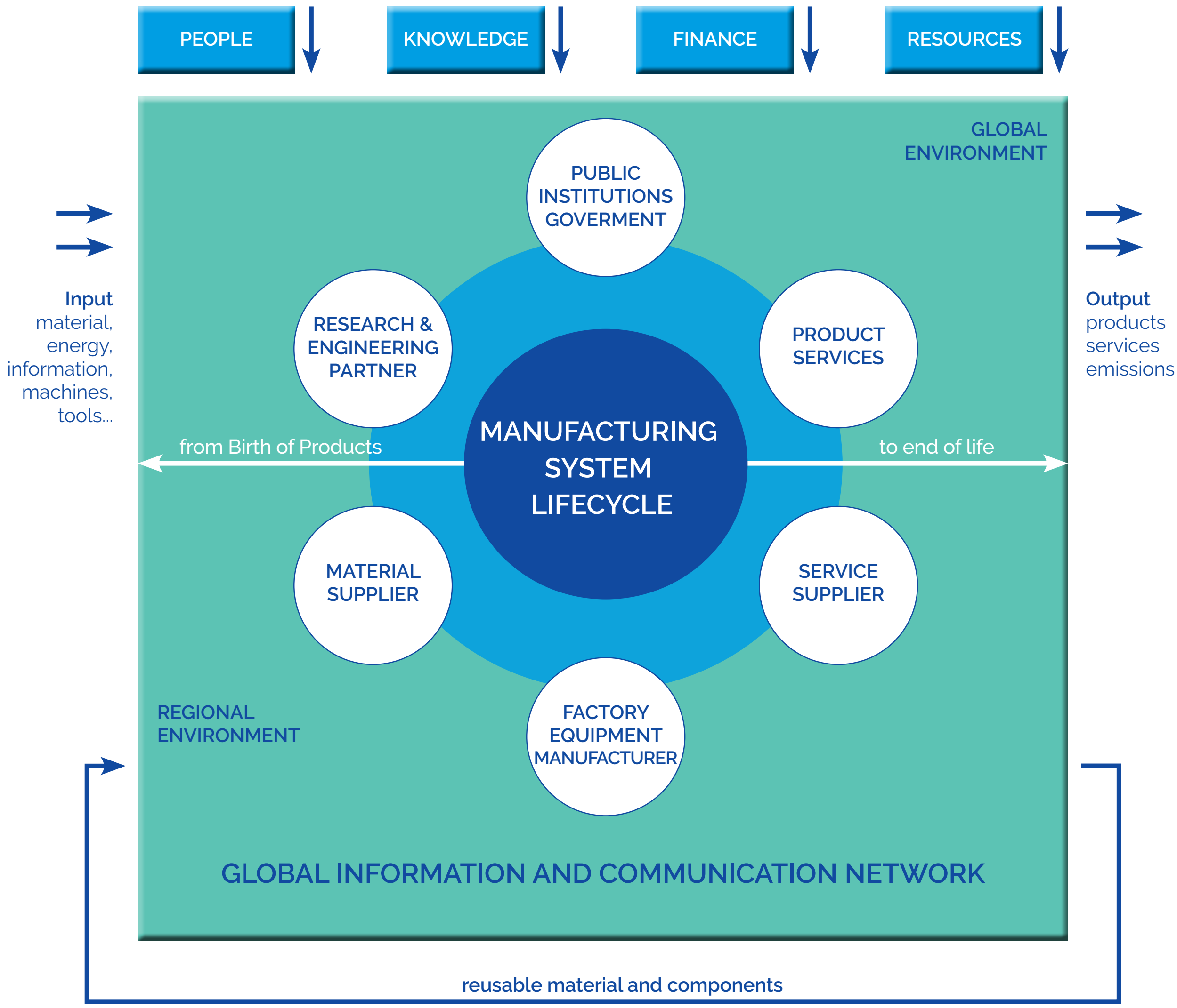


Figure 3 – The Manufacturing System (Source: Westkämper, Loffler)

The European Manufacturing System is influenced by fluctuating driving factors and global competition. The dynamic system can only survive through higher effectiveness and efficiency in its main industrial sectors, and considering complex interconnections with global supply chains and networks for energy, material, information and communication, and, more generically, in socioeconomic systems.

In the past century, manufacturing was focused on the physical elements for making products via effective usage of resources. **Now, this view has to be transformed into manufacturing as a system, strongly supported by digital technologies, aiming at increasing productivity levels in an orchestrated value network to achieve a leading position in the global competition:**

- Provision of relevant information in the early phases of the system design by predicting the developments of markets and technologies and by integrating users and customers;
- Development departments and R&D partnerships transformed into complex and open innovation ecosystems;
- Stable value chains evolve into complex and flexible value networks with intensive information sharing;
- Life cycle orientation from design to end-of-life (remanufacturing or recycling) for each physical product;
- Lifecycle data management, associated to each manufacturing phase from the system design to manufacturing, usage, maintenance, reconfiguration, re-use and recycling;
- Products connected to the Internet of Things, sharing information with other products and systems, including the original manufacturer, wherever they are used;
- Integration of public and private organisations, which are related to any processes in manufacturing.

This view also takes into account the already ongoing changes in the cost structure of manufacturing, from direct work to indirect operations, knowledge and technology ecosystems and the connectivity between manufacturer and customer/user in the complete life cycle of products. It includes the protection of workers in the factory and of the product's user (safety, privacy, and preventing abuse). It reaches out via service operations to support customers/users wherever they are located, reflecting on the responsibility of manufacturers for best usability and reliability, and recycling after the use phase. Industry 4.0 solutions and (sub-) system standards offer new fields for adding value.

3.2 Horizontal and vertical integration

The new Manufacturing system's view is multilevel, from technical processes on the factory floor to networking and business operations in the upper level (Figure 4). Micro and macro levels are connected in real time by internal and external ICT networks. It is now possible to implement manufacturing control and management as an integrated multilevel architecture from physical to system level and enable technical intelligence for fast reaction and (self-)optimisation.

The increasing integration of organisations within the ecosystem of the manufacturing value networks reflect on the fact that they are increasingly becoming cooperation partners, influencing the overhead and indirect costs and offer strategic competences for the development of manufacturing.

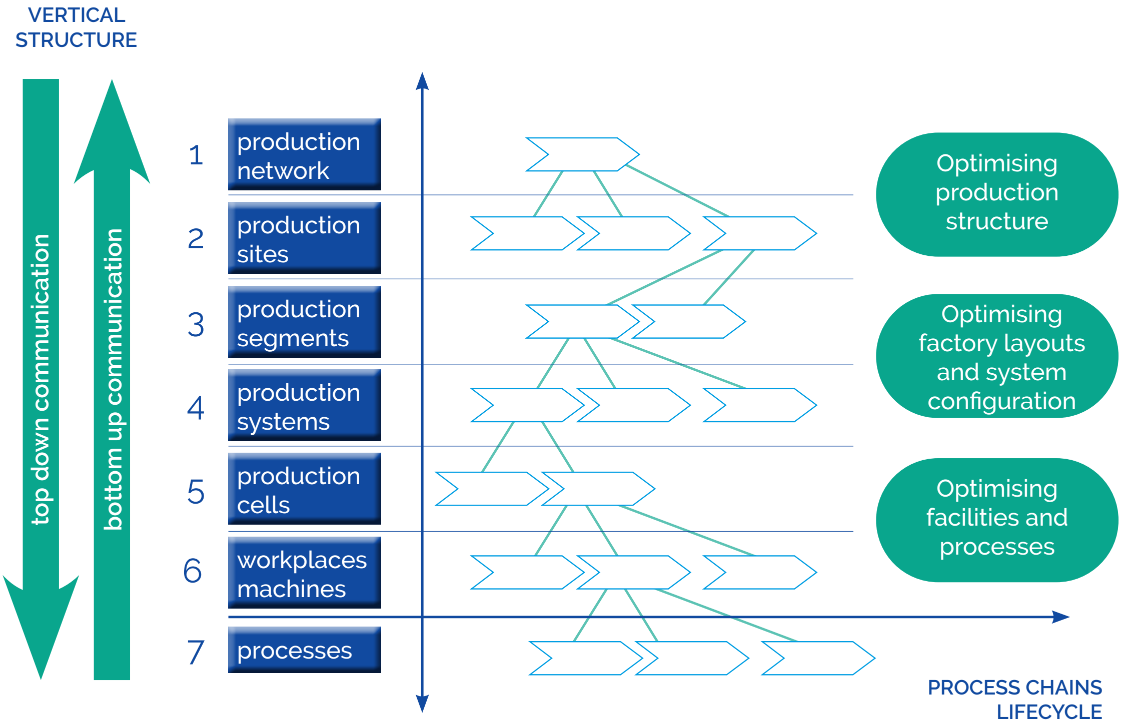


Figure 4 – Levels of a Manufacturing System (Source: Westkämper)

The efficiency of the new enlarged manufacturing system depends on the efficiency of each process as well as on the **synergy** between the cooperating partners. Transparency, trust, seamless interfaces, real-time operations are possible due to the high-performance and high-reliability communication networks. International standards and European public regulations are required for reliable, real-time, cost-efficient and trustworthy manufacturing systems.

Industry 4.0 predicts a digital transformation of Manufacturing and influences all operations at all levels. There is the technical trend to implement **technical intelligence in the networks at all levels,** which offers the potential for new business models and reduced consumption of energy and materials.

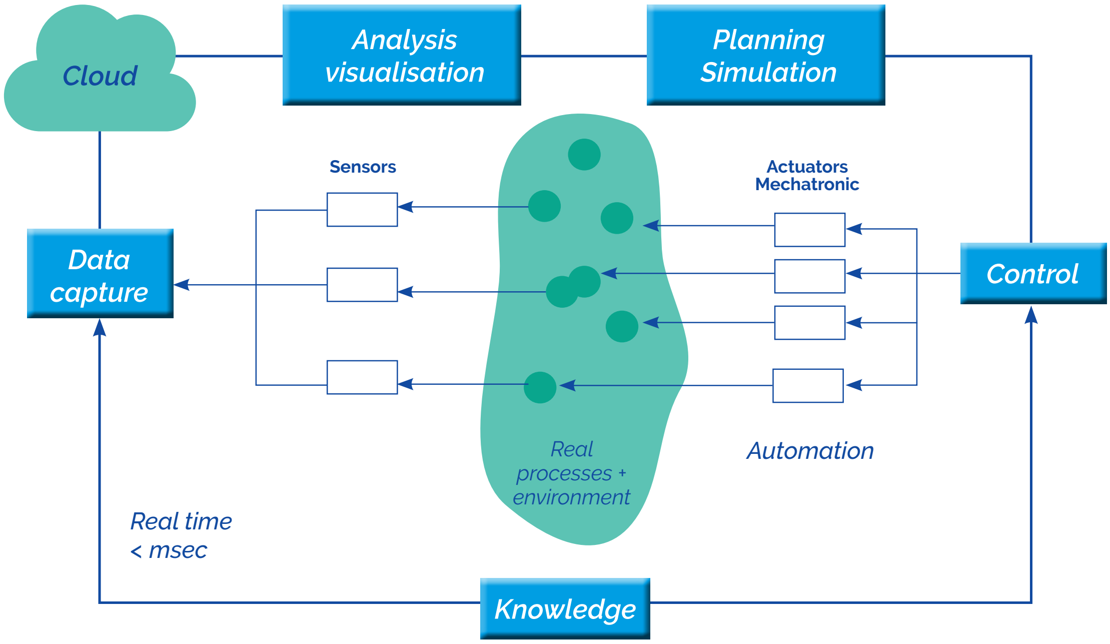


Figure 5 – Cyber Physical system - Industry 4.0: single-sign on, look + feel, everywhere, anytime (Source: Westkämper, Loffler)

Manufacturing systems of the future are characterised by multi-sensor networks for supervising processes and environment and for collecting data (Figure 5). Increasingly sensitive and cost-efficient sensor technologies help to measure various parameters that influence the process, including in situ measurements for process monitoring. This monitoring allows to manage processes in real time and to discover critical conditions or defects in order to pre-empt quality decline or shutdowns. Sensor networks collect data that can be stored and processed close to the processes (edge computing) or uploaded to a private or public cloud network. Data is available at anytime and everywhere in the holistic manufacturing system and can be analysed with artificial intelligence, improving the high-level systemic and the detailed process knowledge, predicting future events and adaptively controlling processes in real time. This allows preventing defects, operating in capable parameter ranges, the diagnosis of machines and systems and enables new human-machine interfaces.

3.3 The Road to Circular Economy

As it can easily be seen in Figure 3 manufacturing systems are the driving factors for circular economy and therefore have a specific responsibility for their execution. Circular Economy requires an even more enhanced level of integration along the life cycle and value chain across sectors and system boundaries.

For instance, recycling companies at the very end of the product life cycle need much more detailed information about the design and life cycle data of products compared to current practices in order to close the loop in a much more efficient and effective way. On the other hand, the requirements and possibilities of recycling and remanufacturing need to be known by the product designers and the manufacturing system designers. Moreover, at the very beginning of the life cycle, the outstanding challenge for material suppliers (steel and other metals, plastics, among others) is the transition of becoming carbon neutral so as to mitigate climate change.

Another relevant current obstacle is the definition of key performance indicators (KPIs) across all involved levels along the product life cycle. New approaches and methodologies are needed to assess impacts and master complexity across the different system boundaries and communities. Figure 6 shows the main levels of production and consumption, socioeconomic, including regulation and the ecological and natural environment we all are embedded in.

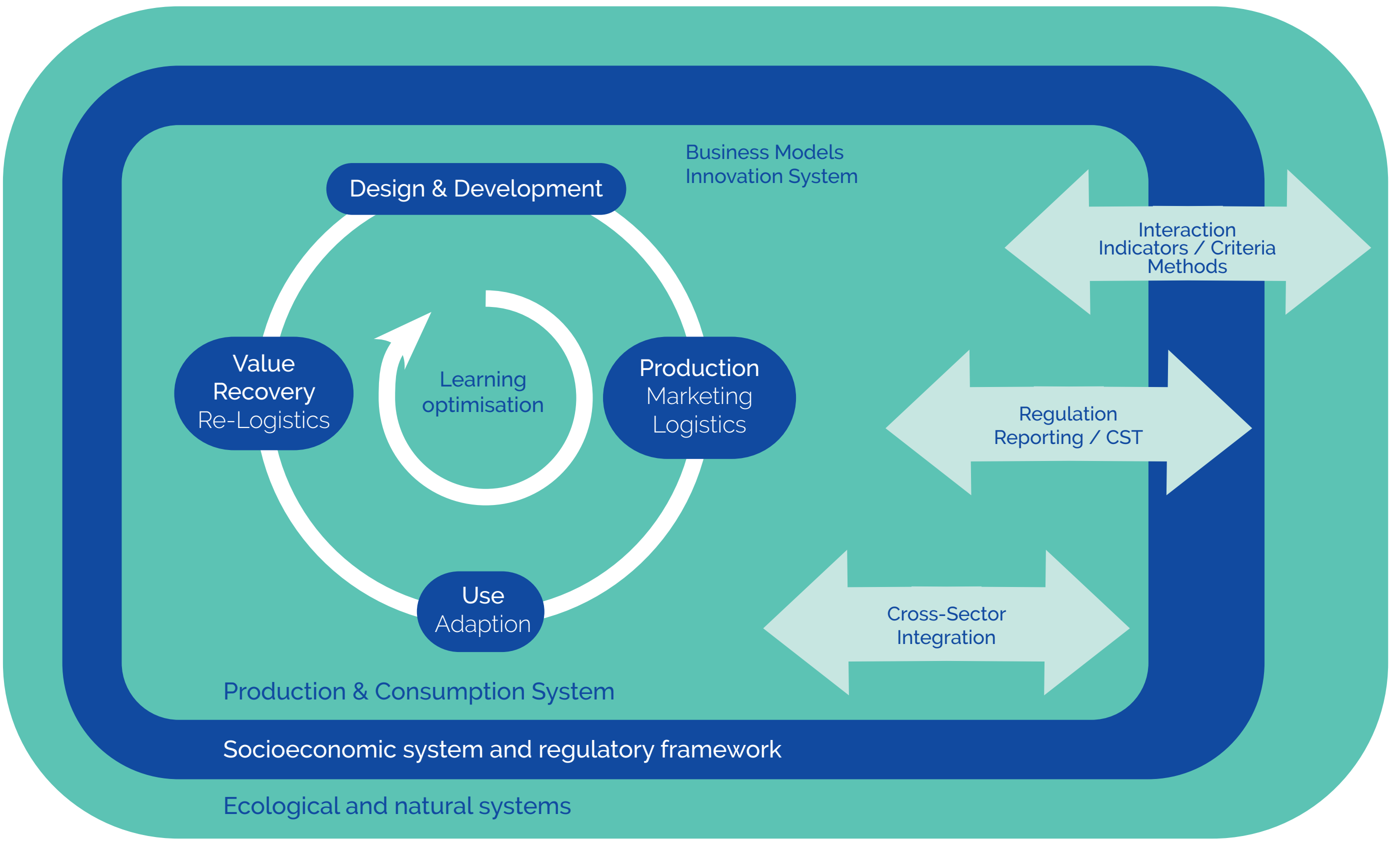


Figure 6 – Levels to be integrated for an effective circular economy (Source: VDMA)

Closing the (data) loop, even in very preliminary stages, and defining jointly accepted key indicators will enable learning and optimisation processes to simultaneously evolve and improve at all levels.

3.4 Decentralised Technical Intelligence

"Decentralised, autonomous systems with embedded intelligence acquire a far greater significance in the digital ecosystems of industrial value creation (B2B) than in the B2C sector." (2030 Vision for Industry 4.0, German Platform Industrie 4.0). The implementation of technical intelligence is amongst the most important areas for increasing productivity and efficiency in future manufacturing. Research programmes should boost the competences in manufacturing organisations to achieve solutions for processes, technical components and technical systems in all sectors of manufacturing industries (Figure 7 gives an overview).

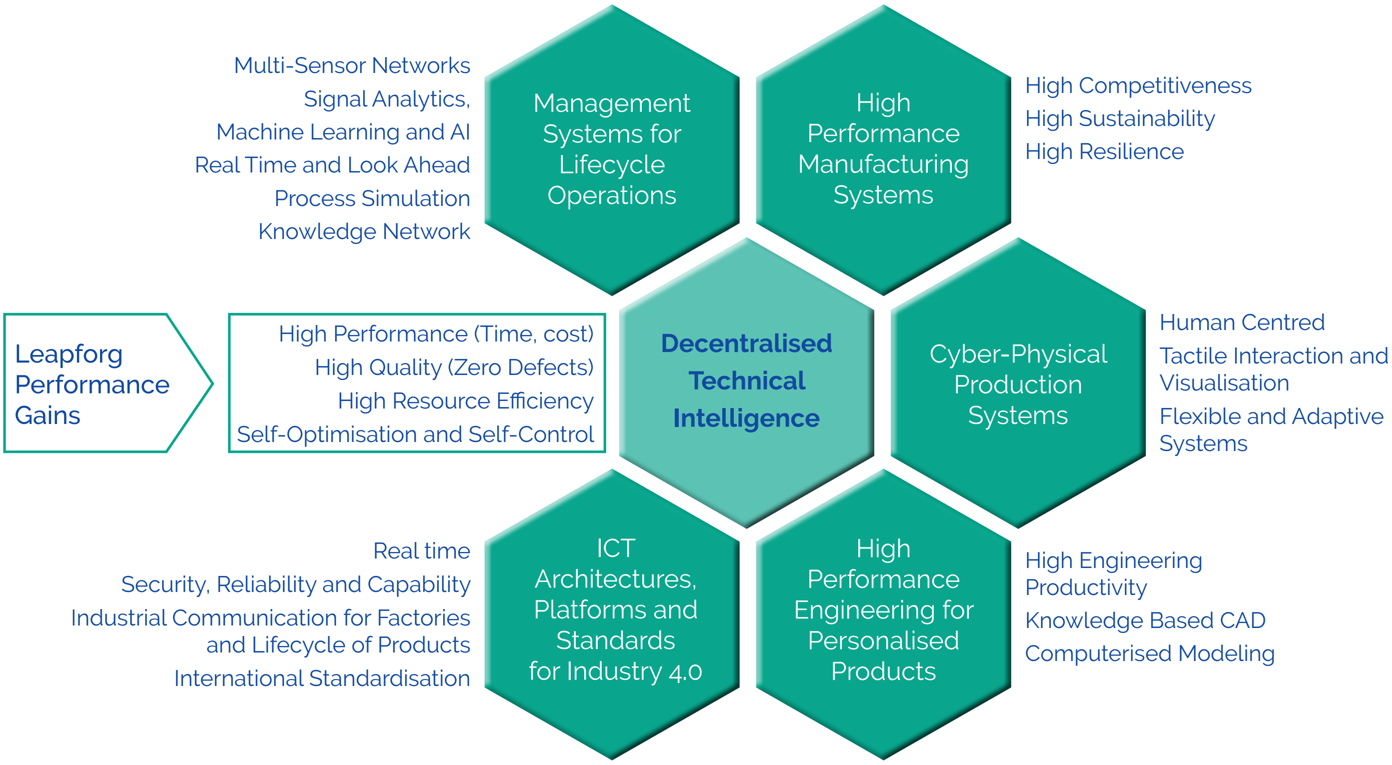


Figure 7 –The visionary manufacturing system for adding value over the life cycle with decentralised technical intelligence (based on System Technologies Industrial Reference Architecture for Factories - IREFA)

ICT Architectures, Platforms and Standards for Industry 4.0

Industry 4.0 requires many technical solutions for real-time supervision, monitoring and control of manufacturing processes in the life cycle of products and in the manufacturing environment. Digital sensors based on scientific measurement technologies for pre-, inline- and post-process are used to manage processes with high performance and accuracy. The development of innovative multisensory digital solutions (sensor fusion) is required to connect, control and optimise manufacturing operations.
There is a big market for soft tools for the modelling and simulation of physical processes with strong relation to fundamental research and mathematical tools.

Key sectors: plant engineering, process industries, machine tools, energy and power systems, sectorial machinery (wood working, packaging, agricultural machinery, construction equipment).

High Performance Engineering for Personalised Products

The costs of engineering depend on the complexity and efficiency of the engineering and design departments - measurable in productivity/hour in industry. All influencing factors like innovation speed, reliability, grade of customisation and diversity are increasing so that the human productivity in engineering becomes the critical success factor of companies. Customised solutions have a chance to fulfil the quality requirements of the markets. The focus of the projects in this field is the development of knowledge-based engineering tools, which allow effective cooperation and implementation of scientific-based methodologies in the set of tools for engineers. Europe must lead the field of system engineering and implementation of intelligent solutions in the work places of engineers and designers.

Key sectors: automation, industrial software, robotics, textile/leather machinery

Cyber-Physical production systems

Cyber-physical production systems are highly integrated flexible manufacturing systems connected through real-time management and control systems exploiting a digital twin/shadow. The digital model of the system is the result of the digital engineering and planning processes and the online updating of the elements of the system and the system environment. It is expected that the system configuration can be adapted by means of Artificial Intelligence in relation to the demand of manufacturing load and decisions to optimise. A factory becomes a complex, lifelong and highly integrated system, which operates in the "room of parameters" for best performance and zero defects. Priorities in this area are reconfigurability, remote operations and optimisation by Artificial Intelligence.

The components' industry (e.g., pumps, drives, actors, control units, gripper, effectors etc.) is the backbone of manufacturing industries with highly specialised companies. Technical solutions are characterised by mechatronics with embedded sensors and actuators. There is a trend to miniaturise the components, to reduce weight and material consumption and to integrate more and more functionalities with software. Research priorities are the modularisation and integration of software functionality to support customisation of final products and create possibilities for intelligent diagnostics to monitor in usage phases. Connectivity with high performance wireless communication systems (e.g., 5G) is essential in the near future in order to connect and integrate a physical entity with its entity in the 'cyber' space.

Key sectors: electrical automation, robotics, assembly, machine vision, productronics, surface technologies, micro-nano manufacturing, electronics, photonics, waste management & recycling, building automation, food production, agriculture technologies, drives, pumps, fluid technologies, energy and power systems

High Performance Manufacturing Systems

According to Figure 1, manufacturing systems have to be highly competitive and to become increasingly sustainable and resilient. To achieve these objectives, zero-defect manufacturing has to be targeted, autonomisation and (self-)adaptivity, supported by decentralised intelligence, play a crucial role. Anyeffects on the environment have to be monitored and taken into account by the management systems for smart manufacturing.

Key sectors: systems engineering, lifecycle engineering, manufacturing management, ultraefficient manufacturing technologies

Management Systems for Lifecycle Operations

Learning manufacturing systems are based on a system architecture with an ICT backbone for the product lifecycle, which allows collecting experiences and historic data (quality, productivity, utilisation, behaviour etc.), to look ahead and learn in a virtual environment (learning from the future) and to support users with knowledge and best practice. Learning factories implement artificial intelligence (AI) in their ICT systems with process oriented edge or cloud computing technologies, sensor networks and learning simulation connected in realtime with shop floor machines and robots. Learning elements can also be implemented in tools for planning and management, including in the supply chains and service operations.

Project priorities are the implementation of AI in all computerised operation in manufacturing.

Key sectors: software & automation, machine vision, robotics, assembly

3.5 Proposed Research and Innovation Priority Domains

The priorities presented in section 3.4 are essential crosscutting and enabling competences and promise substantial leverage effects and impact with a **view to mastering societal challenges and advancing industrial excellence and competitiveness.** They are needed in a broad range of sectors. In particular, however, the relevance and potential impact are evident with regard to the key sectors in manufacturing such as manufacturing equipment and engineering. Bringing these priorities together in a framework for science and technology allows us to define a **matrix for research and innovation priority domains** as shown in figure 8 with orientation to decentralised technical intelligence in manufacturing systems. These research and innovation priority domains are detailed in chapter 4.

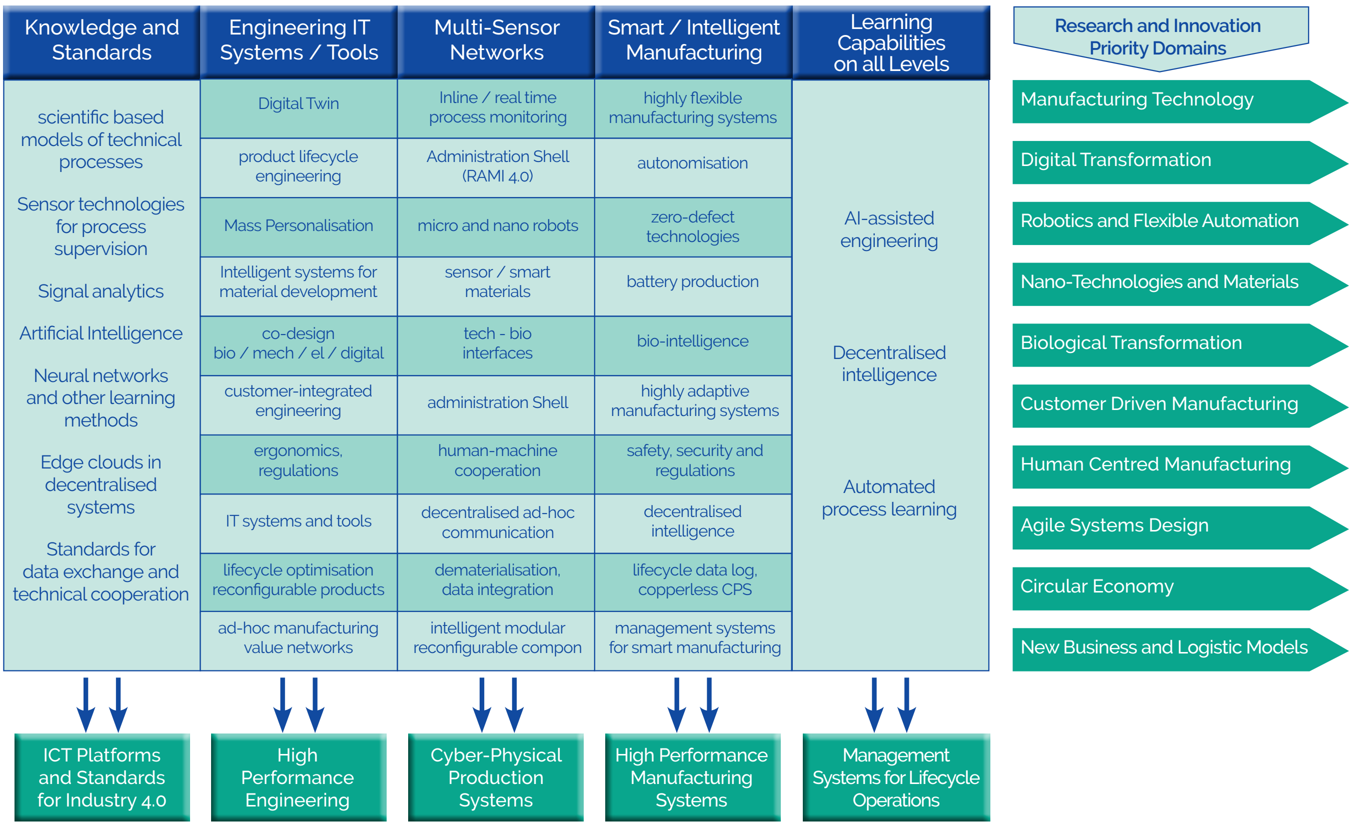
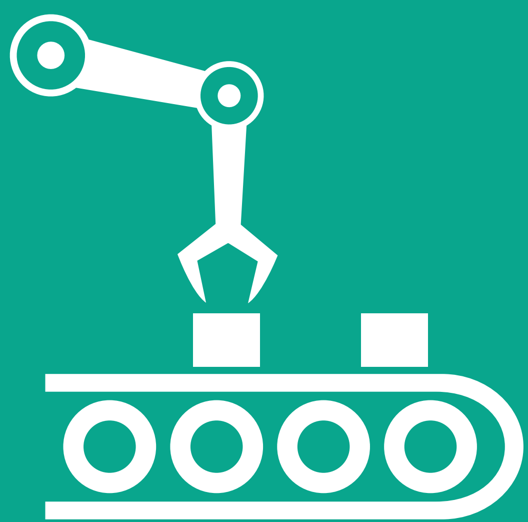


Figure 8 – Road towards technical intelligence

4.

Research and Innovation Priority Domains



4. RESEARCH AND INNOVATION PRIORITY DOMAINS

The Manu*FUTURE* Vision 2030 proposes Science and Technology as the first building block for a successful manufacturing in Europe. The competitiveness of companies and the sustainability of societies are strongly related to the continuous success in investments in research, development and innovation (R&D&I).

As presented in the Vision document, in the current competitive environment, Europe will only be able to keep and further improve its position in manufacturing and to secure the current level of employment if it is able to ensure a technological leadership at a global level. To overcome the identified challenges and to take advantage of foreseen opportunities, Europe must invest more in fundamental research, applied research, also involving social sciences and humanities.

The next sections describe 10 research and innovation domains towards 2030 and the respective main research priorities identified.

For each priority domain the types of research activities that are proposed: (F) Fundamental Research, (A) Applied Research and Technological Development or (P) Pilot implementation and Demonstration. For the achievement of the Manu*FUTURE* Vision and the innovations described, the focus will be mainly on collaborative applied research, pilot implementation and demonstration. Some priorities are identified as suitable for fundamental research, meaning that it was considered that new fundamental knowledge would be relevant for the development of the topic and the goal is to motivate new research work at this level.

Proposed Research and Innovation Priority Domains	
Enabling technologies and approaches	Manufacturing strategies
1. Manufacturing technology and processes	6. Customer driven manufacturing
2. Digital transformation	7. Human centred manufacturing
3. Robotics and flexible automation	8. Agile manufacturing systems design and management
4. Nano-technology and new materials	9. Circular economy, resource and energy efficiency
5. Biological transformation of products, processes and value creation	10. New business models and logistics networks

Figure 9 – Research and Innovation Priority Domains proposed by the ManuFUTURE Vision 2030 and SRIA.

4.1 Manufacturing technology and industrial equipment

In the verge of the **fourth industrial revolution**, the investment in the *development and implementation of digital technologies* needs to be coupled with a strong *European leadership in* ***manufacturing processes*** *and* ***related industrial equipment.*** Promoting the integration of *digitalisation and manufacturing technologies will valorise the great European heritage and will reinforce the European position in both domains.*

Thanks to its excellent manufacturing and engineering know-how, Europe is still the leader in the engineering of highly effective and complex life-cycle oriented products, processes and value creation (eco) systems. Novel concepts and technologies will reinforce the European capability to design, manufacture and provide the world's more advanced ***production equipment and manufacturing systems,*** which will be capable to efficiently manufacture high-quality products, complying with the *Circular Economy* requirements at a competitive cost.

Future manufacturing will move to new paradigms:

- ***Nature Inspired Manufacturing that*** *will lead to more sustainable design and manufacturing ecosystems, from the organisational to the technology, by combining different "actors and activities" with efficient processes to recycle and reuse materials.*
- ***Bionic Manufacturing, which,*** through technology, will enhance and augment relevant human capabilities. It is the winning combination for highly automated and robotised processes and is capable to provide flexibility and adaptability to new customer requirements.
- ***Fully circular digital and physical threads,*** that will implement a use-centric set of relations aiming at providing the required specific product and service, while optimising the usage of resources, including materials and energy (also in transports), creating a balanced and sustainable ecosystem.

Linear production is under the process of being intelligently re-re-organised towards more circular production consumption recycling systems. Circular economy aims at fulfilling the values of prosperity and wellbeing of populations and the conservation of resources and the environment, while reinforcing European competitiveness. To this end, new technologies and methods are needed to materialise the life cycle represented in the picture below.

Manufacturing equipment in circular economy

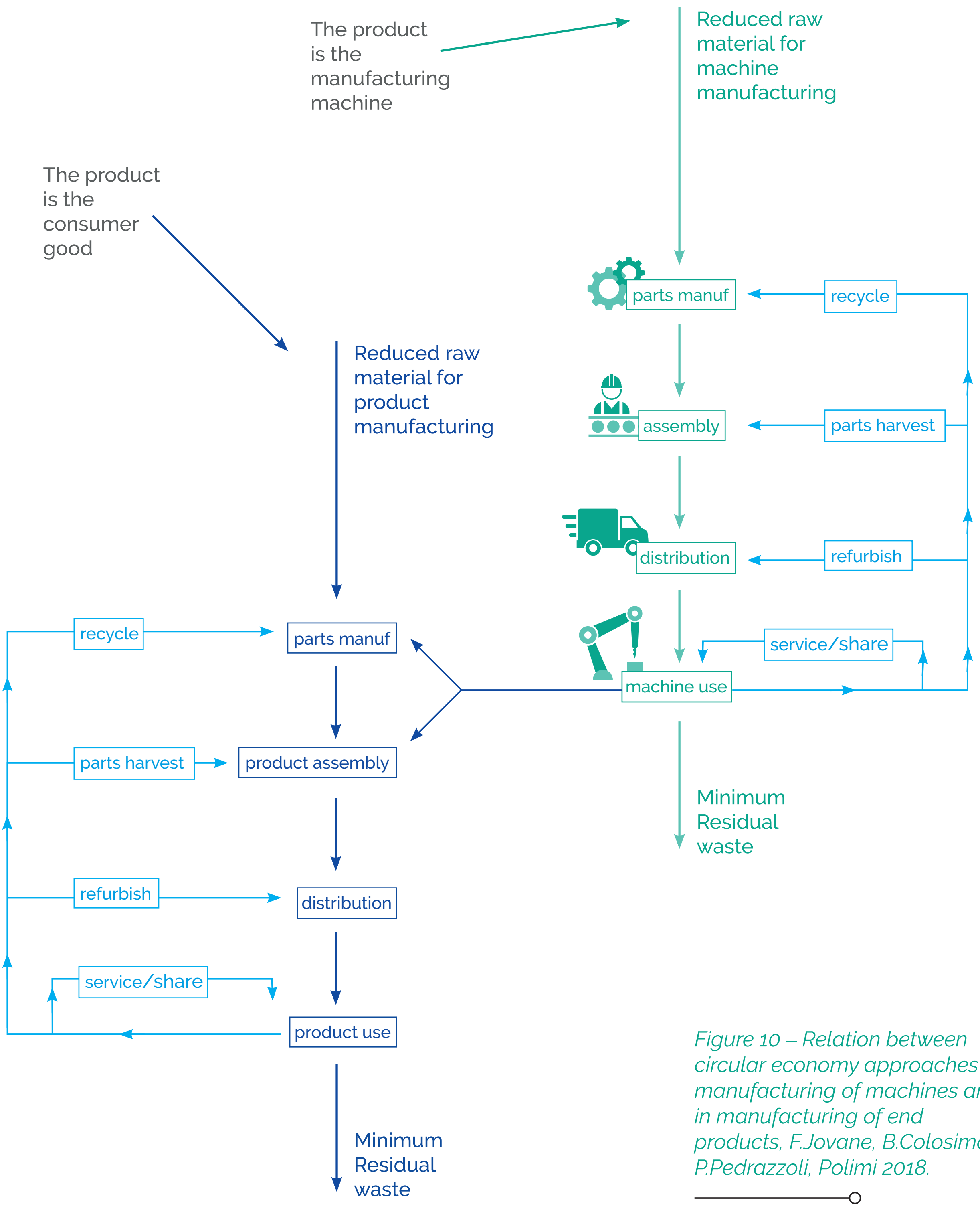


Figure 10 – Relation between circular economy approaches in manufacturing of machines and in manufacturing of end products, F.Jovane, B.Colosimo, P.Pedrazzoli, Polimi 2018.

Europe will become a leader in **recycling and circular economy** processes and technologies, which will become competitive and a significant market opportunity. ***De-manufacturing*** facilities will handle a high variety of products in different life cycle stages. ***Remanufacturing*** plants will be the main driver towards the increase of reuse, repair and remanufacturing of products, providing machinery and systems, technologies and know-how to manage these phases. For high value and high-complexity products re-manufacturing and de-manufacturing activities will rather be integrated with manufacturing plants. A key challenge for the successful exploitation of new technologies relies on the identification of the right applications and markets and the development of sustainable business models.

Future manufacturing technologies should be 1) accessible (knowledge and money) to a large extent and easily pluggable into existing systems, 2) digitalised and I4.0 enabled, 3) capable of making the previous settings obsolete and underperforming.

Research must address core needs (improving technology operational effectiveness, efficiency and productivity), advanced needs (improving value chain operations, enhancing customer engagement/co-design) and transformational needs (creating new, innovative processes for entirely new markets and customers, managing and using data from all stakeholders to drive production, make informed business decisions and create new business models). The systems of tomorrow will be based on the interaction of many different special disciplines like engineering sciences, computer science, sociology, work and economics as well as business administration. Many aspects have to be considered and coordinated for the development of such systems, such as the producibility, the user friendliness, the networking opportunities, the safety and the sustainability.

Research and Innovation priority domains in 'Processes and Technologies'

ADVANCEMENT IN ADDITIVE MANUFACTURING (AM) (A/P)

The continued industrialisation of additive manufacturing technologies will create evolving needs for technological development, addressing topics such as raw materials standardisation, work piece dimensions, materials and alloys (e.g., aluminium, titanium, copper), working atmospheres, better surface properties, surface integrity and functional testing methodologies, health and safety regulations.

The development of new applications will create the need for significant advancement in materials, typically feedstock materials, coupled with an increase in build rate, which will possibly enhance the competitiveness of AM (also for the manufacturing of larger structures with unique features) and enlarge the potential filed of application. Additionally, additive manufacturing needs further developments for process stability, monitoring and control, for the development of competitive and reliable production equipment. Indeed, a key step for the industrial application of AM, in particular for highly demanding applications, is to develop technologies for quality management (all over the product life-cycle), including, but not limited to, process stability and process control.

Finally, in order to promote the establishment of an ecosystem, throughout the full value chain, for industrial application of AM technology, it is necessary to ensure the continued development of standards for AM.

ADDED-VALUE ADDITIVE MANUFACTURING FOR LARGE STRUCTURAL COMPONENTS (F/A/P

New pathways must be developed for AM of structural/functional parts to find its way as an enabler of faster product-to-market approaches. This means creating innovative and unconventional techniques for higher process productivity and lower costs, from the product design office to the factory floor. Focus shall be in: 1) overcoming current metal AM drawbacks, by limiting its application to the production of small parts, and improving its competitiveness as a direct manufacturing technology for medium and large dimension parts, and 2) leveraging the potential of composites AM in order to enable the manipulation of fibre alignments to unparalleled levels. The development of both metal AM and composites AM systems shall include: i) design for AM (DfAM) knowledge, tools, rules, processes, and methodologies, and ii) sensor technology, control methodologies and coupled technology-microstructural physics-based models (relation between microstructure aspects and distortions and warpage, fatigue properties and reduced surface roughness) for product topological and topographical optimisation and process simulation.

COMPETITIVE COMPOSITES PROCESSING (A)

Cross-fertilisation platforms among different composite manufacturing technologies, as well as fibres, matrices, modified and hybridised materials shall be developed, fostering their faster adoption and strengthening their role in the supply chain, thus enhancing the overall competitiveness of composite-based processes and products. Increasingly automated processes should be enabled, integrating smart materials, intelligent moulds and process components with sensing and actuation capabilities, as well as robotised material handling and lay-up systems, capable of providing enhanced process and monitoring capabilities, such as heating and temperature management, resin recognition, curing stage, pressure monitoring and defect detection. These shall enable the data collection required for dynamically data-driven end-to-end engineering platforms, integrating simulation-based process design, cognitive automation and zero-defect approaches, oriented to the manufacturing of small to large composite parts and its assembly in complex structures.

The sustainable use of materials needs to anticipate the end of life impacts ahead, including impact on ecosystems, recycling opportunities, among others, and reject non compliant solutions.

HIGH PRODUCTION RATE OF COMPOSITE STRUCTURES (P)

Composite structures mainly aim for low weight, heavy duty/fatigue, wear and corrosion resistance. The challenge is to achieve economically viable high rates serial manufacturing, while maintaining the primary goals. The need to develop new energy efficient processes for serial production of composite materials is a research and technological development that needs to be addressed.

SURFACE ENGINEERING (A)

A combination of texturising and surface coatings has the potential to deliver surfaces with several functionalities and features such as hydrophobic, antimicrobial, self-cleaning, durability, noise reduction, friction and aesthetic.

The full potential of texturising and surface technologies (e.g., sol-gel, physical vapour deposition) is yet to be discovered and includes design, surface modification technologies, scale up and process control, and the characterisation and properties of the final system or component, including quality control and non-destructive examination.

MINIATURISATION AND FUNCTIONAL INTEGRATION (A)

Making components smaller and smaller by integrating more functions in surfaces and in concentrated spaces is a cross-cutting enabler for a broad spectrum of applications – ranging from sensors, micromechanical systems, microfluidics, low-energy components, smart surfaces to bio-hybrid components. Products can become smaller, lighter, more robust and more energy efficient. This not only requires new and improved micro and nano-manufacturing processes, which are precise, repeatable, fast and easy to be scaled up, but also integration of physical processes with digital technologies.

HYBRID PROCESSES (A/P)

Nowadays, a multitude of conventional and non-conventional manufacturing processes is available, each with its own specific characteristics. Combination and integration of different processes will pave the way for flexible and efficient manufacturing systems. Therefore, approaches, software tools and hardware modules need to be developed towards the selection and combination of different processes in order to create a flexible, reconfigurable system, capable of responding to rapid changes in customer needs. Manufacturing processes are always in evolution: new materials, manufacturing technologies, sensors, the application of digital technologies, innovative process assistance elements (e.g., ultrasonic, cryogenic, etc.), thus opening up unexplored possibilities for hybrid processes.

Technologies range from AM-based processes to joining, cold-work, heat treatments, among others, to be combined and integrated in Hybrid systems capable of connecting flexibility with efficiency and cost reduction.

EFFECTIVE PROCESSING OF HYBRID MATERIALS (A/P)

New manufacturing concepts to be explored for the flexible and dynamic production of hybrid and/or functionalised structures shall be developed. It shall integrate manufacturing processes, capable of generating tailored features and geometries but above all the functionalities, often combining materials of mismatching character and local treatments. Current manufacturing solutions are still strongly material, process and/or technology-specific and, even if their combination is technological feasible, the related high costs and overall inefficiency preclude any type of hybridisation from high volume fabrication. Advances in KETs can be integrated in established machinery concepts, providing wider processing ranges to enhance material's applicability, and ultimately compatibility and coprocessing. This includes: i) forming joining hybridisation as well as the dissimilar functionalisation of the individual constituent materials; ii) new hybrid machinery concepts integrating appropriate technologies for flexible, extended or combined materials' processing; iii) new experimental configurations and procedures appropriate for in-line materials /part characterisation considering their specificities regarding non-conventional composition, structure, geometry and/or dimension, as well as off-line testing under loading conditions (static / dynamic, environmental) representative of the new process technologies and expected multi-functionality.

OPTIMISED JOINING FOR NEW MATERIALS, STRUCTURES AND MANUFACTURING PROCESSES (A)T

Traditional joining technologies for new materials have limitations since they are normally "a one case solution", meaning that the technology can only be applied for each multi-material combination or each new material. Such an issue has limited the use of multi-materials and new materials in industry due to the cost involved in adaptation and integration of these technologies in the manufacturing chain. Dissimilar material joining, including joining of composites, multi-phase and coated materials reflect the continuous advancement of the use of multi-material across all sectors: this creates engineering challenges on how to join these materials like metals, ceramics, fabrics, composites, multiphase, coated and polymers. These joints need to operate at versatile environments, to be easy to access and repair and to have a low environmental footprint (either in the materials used for the preparation of the joint or during their life). It is also required that the processes used to join these multi-materials can be easily integrated into the manufacturing chain.

ACTIVE, SMART AND INTELLIGENT PACKAGING (A/P)

Packaging systems used for foods, pharmaceuticals, and several other product types have the potential to extend shelf life, to display information on quality and to improve safety. Intelligent and smart packaging involve the ability to sense and measure the attributes of the product having active functions beyond the passive containment and protection of the product. This information can trigger active functions, thus making the package an active IOT device in the product/factory life cycle.

RESILIENT PROCESSES (A/P)

Manufacturing processes have been constantly evolving and improving in terms of accuracy, reliability and robustness. However, the majority of manufacturing industries rely on establishing appropriate process parameters through extensive experimentation and trial-and-error, using specific, usually strictly controlled materials. When any of these need to be changed, manufacturing systems are slow to respond, thus reducing flexibility.

Therefore, there is a need for new methods and tools, enabling self-learning and self-adaptive manufacturing processes, driven by simulation/digital twins as well as historical data, adapting the process to variable feedstock quality, reducing or even eliminating setup/changeover time and defective parts.

ZERO-DEFECT STRATEGIES FOR SMALL-BATCH MANUFACTURING (F/A)

New methods and tools to increase the potential of zero-defect strategies for the manufacturing of small-batches in a multi-stage manufacturing need to be developed. Strategies for the application of self-adaptive solutions, such as Machine Learning and Artificial Intelligence, are needed in order to hinder the propagation of errors. New methods and tools for profile monitoring of functional data and geometrical product features are needed to minimise the defect of the chain and to facilitate the implementation of zero-defect manufacturing (ZDM) strategies. The results of this research are relevant and applicable in many industrial sectors and companies, namely those dealing with smallbatch manufacturing. Additionally, dynamic machine control systems together with geometric feature monitoring can prompt the adaptation of process plans based on the degradation state of the shopfloorresources.

SYSTEMIC BIO-INSPIRED MANUFACTURING PLATFORMS (F/A/P)

Truly systemic manufacturing platforms shall be enabled by developing novel bio-inspired manufacturing concepts, which shall leverage the current implementation of advanced cyber-physical systems (integrating hybrid twins, cognitive automation, Artificial Intelligence, among other state-ofthe-art techniques) to unprecedented resilient production environments, introducing a new manufacturing paradigm. The hypothesis is that, by mimicking self-sustainable living processes with corresponding functionalities, such platforms would simultaneously present optimum operational performance and extreme autonomy to react/adapt to any change in the production conditions. Such a step change in the design of manufacturing systems and processes requires however intricate interdisciplinarity between a series of research fields from areas as distinct as Biology/Life sciences and Engineering, to develop efficient and added-value biomimetic manufacturing solutions, also pushing for new approaches/models in the different KETs and engineering processes.

Legend: F – Fundamental Research, A – Applied Research and Technological Development, P – Pilot implementation and Demonstration.

4.2 Digital Transformation

Digital transition affects manufacturing industry at all levels, from future markets and business models to machines and workers at the shop floor. Despite changes in purpose and tools, the digitalisation of manufacturing systems and networks (by means of cyber-physical production systems) capable of empowering continuous digital-real synchronisation and digital continuity[2], , will change the manufacturing paradigms. Digitalisation provides the means to address challenges such as mass customisation, lot size one production, re- and de-manufacturing and zero-defect manufacturing and enables continuous improvement in flexibility, productivity, accuracy, security and sustainability.

A key element of digitalisation scenarios is the capability to handle and exploit the variable forms and unprecedented amounts of data produced by e.g. manufacturing lines, supply networks, products, customers, users and markets. Artificial Intelligence (AI) will enable the knowledge extraction from big data generated and captured at all levels from consumer behaviour, product use, manufacturing, global supply networks and products end-of-life. AI will support all human's activity in manufacturing with a special emphasis on analysis and decision-making (thanks to advanced forecasting and simulation technologies, cloud and edge computing, big data analytics and learning systems). The next generation of communication technologies further accelerates the digital transformation allowing fast and reliable data transfer on the factory floor and in the supply networks. In addition, AI and enhanced connectivity solutions support the servitisation of manufacturing industries as data from customers and users can be efficiently analysed so as to develop new and better product service systems.

Just as the complexity of cyber-physical production networks (and the associated big data flows) opens up new possibilities for smart manufacturing, it also gives rise to new risks. While horizontal integration and data sharing across the value chain from product design to service and end of life are urgently needed, data security and confidentiality has to be guaranteed. This calls for next generation of digital platforms for manufacturing that enable not only data fusion from different sources and tools to analyse and process data, but also the means to protect and control. Sensitive information may also be accessed without permission. As malware attacks increase in volume and complexity, there is a clear need for cybersecure solutions that take into account the complex manufacturing environment with a variety of machines from different providers using different protocols.

[2] Digital continuity is the ability to maintain the digital information available all along the factory and manufacturing network life cycle.

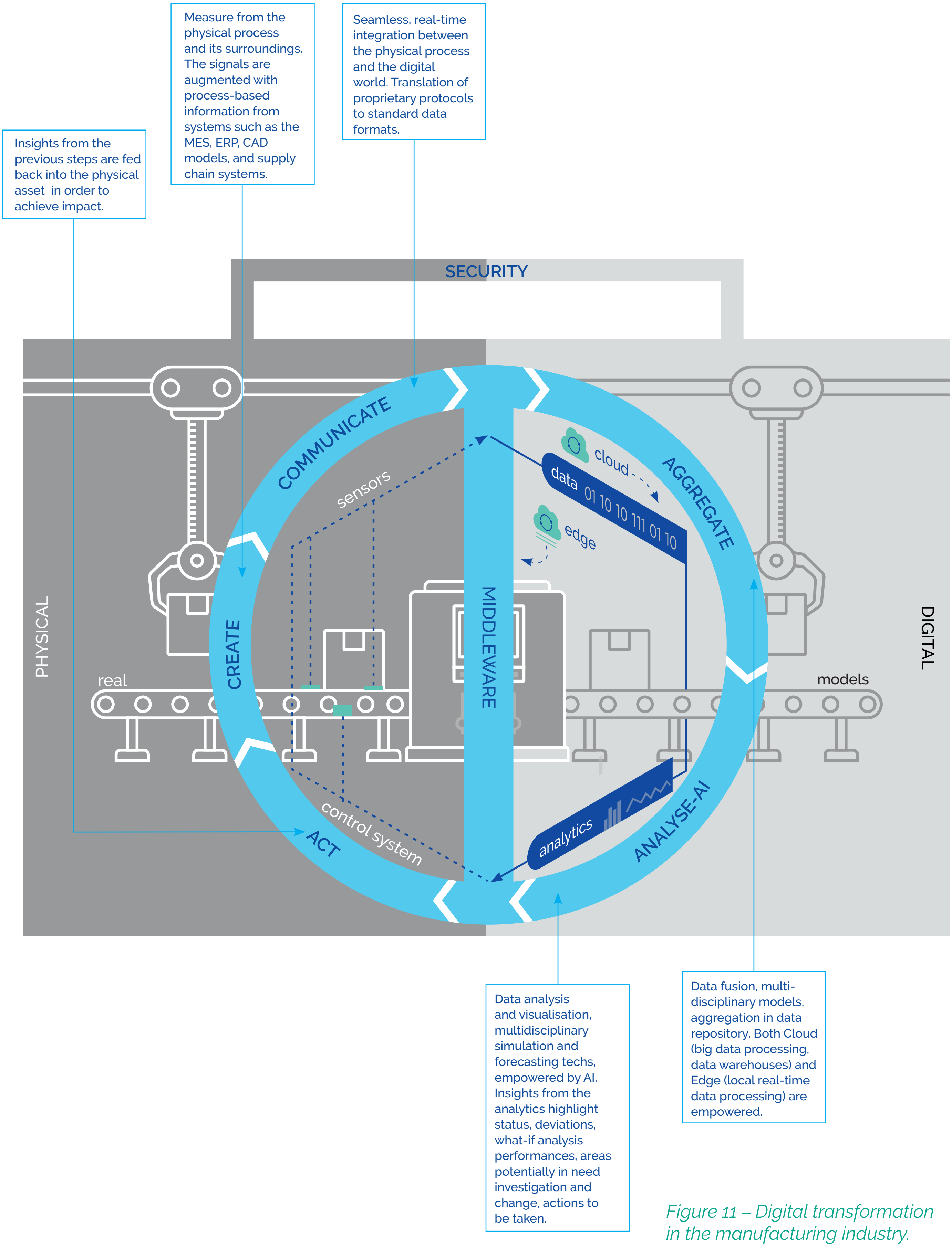


Figure 11 – Digital transformation in the manufacturing industry. (Source: adapted from Deloitte University Press).

Research and innovation priority domains for the digital transformation:

QUALITY in production systems

CLOUD-BASED AND EDGE-BASED CYBER-PHYSICAL SYSTEMS FOR EFFICIENT IN-LINE ROOT-CAUSE ANALYSIS IN THE MANUFACTURING OF COMPLEX HIGH ADDED-VALUE PRODUCTS (A)

Learning and diagnostic methods for the efficient identification and assessment of non-conformance root-causes in complex products (multi-material, 3D-printed, highly customised product, …) will leverage the huge amount of data generated by cyber physical production systems (CPPS), both at cloud (data at rest) and edge levels (data in motion), towards efficient zero-defect manufacturing. The research will need to address and demonstrate integrated intelligent platforms, exploiting machine learning, Artificial Intelligence and real-time feedback and control, leading to novel data-driven insights, and enabling data sharing between different stakeholders. The key objective is also to reduce the delay in feeding back of quality information to design and engineering, when compared to the existing solutions, and to minimise costs.

Blockchain / Distributed Ledger solutions have the potential to support a new form of the decentralised data collection and sharing with a consensus of replicated and synchronised data, geographically spread across multiple stakeholders.

MACHINE / DEEP LEARNING FOR AUTONOMOUS QUALITY IN THE SMART FACTORY (F)

Machine / Deep learning has become one of the primary drivers and approaches within AI in industry. However, remains a complex field that needs a scientific consolidation, actual implementation and validation. In factory environments, there is still the need to assess if Deep Learning or other Machine Learning techniques (including Ensemble learning) will enable the creation of models, which can support quality-related tasks, such as anomaly detection, fault detection and classification, product quality control, virtual sensors deployment, and machine behaviour forecast.

SMART SENSORS SYSTEMS FOR IMPROVING QUALITY AND USE OF RESOURCES (A)

Smart sensors based on vision systems, laser scanners, X-ray, among, offer the possibility to deliver an enhanced digital image of the actual product, to identify defects and to monitor compliance (e.g. relevant for automation in the food processing sector). "Marrying" the signals with simulation models and linking different data sources (through AI-based approaches) will offer a digital representation of product and processes reliable and constantly updated. Smart sensors coupled metrology systems for intelligent inline measurement can also be enablers for Product/Process Manufacturing Fingerprinting.

Research and innovation priority domains for the digital transformation:

DYNAMIC and FLEXIBILE production systems

DIGITAL AND SMART MANUFACTURING PLATFORMS FOR MASS CUSTOMISED PRODUCTS (P)T

Digitalisation enables the manufacture of customised and smart products (with embedded software, sensors, connectivity and AI). However, manufacturing systems for these kind of products (i.e. systems comprising 3D printers, robots, electronics, powering and connectivity) are often operating in isolation and (in most cases) are not connected over digital platforms. Pilot platforms could demonstrate the successful implementation (and promotion) of the integration of digitalisation and manufacturing technologies.

DIGITAL PROCESS PIPELINES (A)

When designing a new product, companies are often unaware of the challenges related to the actual manufacturing process, and, more brodly, to the whole lifec ycle of the product. Typically, the feedback from production or customers results in revising certain aspects of the design after a relatively long period of time. Seamless data exchange and processing are required in order to facilitate connection between design, manufacturing and recycling phases, thus increasing the knowledge content and its exploitation.

NEW DESIGN AND ENGINEERING TOOLS AND DEVELOPMENT METHODS (A/P)

In order to increase productivity and address sustainability, European companies will have to excel even more in problem-solving capacities and in the supply of innovative reliable solutions. Operational excellence in production is increasingly coupled with the excellence in the orchestration of innovation in a multi-stakeholder, interdisciplinary environment. Therefore, there is a strong need to enhance the engineering and design capabilities and efficiency of European innovators – engineers, designers, material scientist, entrepreneurs (also promoting on-demand engineering and knowledge sharing services). This will not only increase competitiveness, but it will also contribute for reducing the skills and knowledge gap and easing the shortage of engineers and data scientists. This should happen through a multidisciplinary approach, shaping the next generation of knowledge-based engineering, and system engineering tools, improving the understanding of system behaviour, modelling and simulation, delivering and integrating easy-to-use solutions and more efficient testing and validation methods, also taking into account automated, creative design systems (e.g., generative design technology to quickly produce high-performance design alternatives). Advances and increased capabilities in this area are also a precondition for enhanced customer-involvement in the development and design of personalised solutions.

CYBER PHYSICAL SYSTEMS OF SYSTEMS FOR DYNAMIC PRODUCTION AND LOGISTICS (A)

New Artificial Intelligence methods, architectures and tools are needed to enable cyber physical systems to promptly adapt process plans, parameters and production based both on the needs of the value chain and on the detected quality of the parts under processing. The objective is to dynamically adapt to the market needs while, at the same time, minimising the propagation of defects during the production processes. As data needs to be shared at a production-network level, security and privacy play a relevant role and must be addressed. It is also expected the integration of manufacturing data into business decision, through advanced prescriptive analytics, to make a parametric analysis of business KPIs and estimate error/risk or predictions of this KPIs. New methods and approaches for selfoptimisation of manufacturing networks also include the extraction of knowledge from the historical process data (big data sets consisting of process parameters and outputs/responses) and development of process model (process digital twin) using AI techniques.

INTEGRATING NEUROCOGNITIVE PROCESSES WITH AI IN FACTORIES AND VALUE NETWORKS (F/A)

Innovative companies are witnessing the beginning of a massive shift towards neurocognitive manufacturing, which studies and combines humans' cognitive capabilities with the sensing capabilities of machines, computational models, intelligent assets and Artificial Intelligence. These systems will be able to largely collect, transfer and analyse various forms of data, processes, and workflows within the manufacturing to make smart decisions in real-time, optimising the operations and enhancing the workforce. Additionally, existing manufacturing management systems that are mainly driven by human action, like TPM or FMECA, need data processing analytics to address new data-human interaction challenges, such as weak feedback loops and lack of sharing and detection of good and bad practices.

However, the use of AI in real processes will have to meet the highest standards concerning safety, reliability, quality and precision. Furthermore, AI in industry requires the capability to work with rather small data sets, which needs to be integrated using context knowledge and transfer learning. Research for AI in industry must be geared towards concrete applications in business and industry, based on context-dependent acquisition, selection and assurance of data quality and secure connectivity. These questions must be addressed in a cross-border, multi-disciplinary and application-oriented research areas.

DIGITAL TOOLS IN MANUFACTURING (A)

Virtualisation of local and distributed production systems and development of decision support systems, based on simulation models and optimisation tools adherent to reality and constantly synchronised, for the design and operation of production systems are of cornerstone importance. This includes the development and implementation of methodologies and tools both edge-based and cloudbased. Simulation, optimisation and forecasting, must be oriented towards the design and operation phases of flexible and high-performance production systems. The outcomes of those tools, empowered by interoperability through Asset Administration Shells, can positively affect the manufacturing processes also by the technology development of augmented and virtual reality at the shop floor. The creation of a hybrid manufacturing simulation models (e.g., model of a machine, cell, line, site), containing analytical and data-based models, will allow for tools oriented towards different scenarios to include maintenance and production optimisation based on hierarchies of mixed data and analytic models at different levels.

KNOWLEDGE AND DATA FUSION FOR MANUFACTURING (A)

Current plants can generate a significant amount of data streams. Big data refer to multiple streams of complex high-resolution, high-speed data (signals from different sensors, images, video in the visible and infrared ranges). All this information is often stored but not properly managed. Novel approaches to combine different levels of information coming from experts, measurement, digital-twins/simulations; big data streams inline and in-site should be developed. These novel approaches should not just provide a sequential use of these different sources of information but define novel approaches to fuse, combine and calibrate all the information to better drive the manufacturing processes and systems towards enhanced flexibility and responsiveness. Additionally, transparency is needed to get meaningful insights from data in a production system: shop floors can be considered as extremely complex systems where small variations or disturbances can create a huge effect. Superb decision-making support, increased awareness, efficient use of resources, prompt reaction to unpredicted events and reduced defect rates should be the final targets.

Research and innovation priority domains for the digital transformation:

DIGITAL-REAL CONVERGENCE in production systems end ecosystem

DIGITAL TWIN OF FLEXIBLE MANUFACTURING PROCESSES (A)

Understanding and modelling the manufacturing processes is crucial in order to further enhance the productivity of each single process steps as well as the whole process chains. In order to fully exploit the potentials of such understanding, sophisticated models of existing processes (ranging from flexible materials behaviour and proprieties, to complex processes such as additive manufacturing or EDM) need to be combined with data from product design, process planning and actual field data. Methods for a better understanding of product manufacturing, structure, and performance, will lead to digital twins that better mimic and simulate complex processes. Consequently, future Digital twins could be the "single source of truth" at any moment in time, and the reliable foundation on which control and management systems make operational and tactical decisions (also thanks to trustworthy short-term predictions about the performance of the system).

Complex Digital twins bring together and synchronise data from different sources (also from unstructured sources where data can be gathered, for example, from artificial vision) and require many experts to collaborate, designing new reference models and consolidating them, to make possible complex combination of data and derive meaningful conclusions. Every resource in a flexible automation production framework, is accompanied by its digital twin, that 'owns' and manages the ownership of the resource, becoming the single access point to the resource (thus making the digital twin to be online, embedded, highly available, upgradable while remaining operational). Digital platforms that will combine and compare data from different sites is a necessity for effective decision-making.

MULTI-LEVEL SIMULATION SYSTEMS (A)

Modelling and simulation tools are key in optimising manufacturing processes. However, such tools and approaches are often tailored to a specific process and scale, and have limited connection and interaction with other tools. In order to simulate a complete system though, process/machine models at various levels are required, from micro to macroscopic (multiscale and multiphysics). Models need to form building blocks of a larger "simulation system", feeding input from one to the other in a closed loop iterative manner, allowing a complete simulation of a production system. Additionally, modelling and simulation tools meant to support new production processes and systems are needed, beginning from the specification of requirements. There is also a need for modelling and characterisation of advanced materials and their manufacturing technology, in particular for (multifunctional & structural) materials and (nano)surfaces.

AUGMENTED END-TO-END VIRTUAL MANUFACTURING SYSTEMS (A)

After several key steps have been achieved in the development of advanced Virtual Prototyping and Virtual Manufacturing solutions, a complete and mature end-to-end virtual manufacturing system – based on deep linkage between 3D models simulations, 0D/1D system modelling and real-time process control and optimisation bridging design and production – is still missing in the industrial manufacturing sector. Now, also introducing Artificial Intelligence, further advances are needed for gathering dynamic data-driven multi-field modelling and simulation of manufacturing processes, multiscale and multi-variate modelling of operational performance of highly demanding and complex structures (for virtual testing of products, tools and machines), efficient design optimisation techniques, data knowledge/extraction at a simulation level, interlinked with novel control systems, advanced sensors and non-destructive testing/inspection (NDT/NDI) systems with cognitive capabilities capable of reacting to unpredictable situations, to plan their further actions, and to learn and gain experience from previous manufacturing processes, i.e. to autonomously increase the system operation range.

DIGITAL SERVITISATION (A)

Building successful business innovations based on data and services call for a visionary approach to future markets. This requires manufacturing companies to combine deep domain expertise with a thorough understanding of related digital technologies and value for customers. Increased availability of data coming from the product usage phase allows targeting individual customers' needs, by providing personalised services and by expanding their range in both B2B and B2C markets. This requires innovations at both technological level and business model level. On the one hand, research is needed to integrate data sources in smart products, to manage secure data flows of sensible data and to extract from them the relevant business features thanks to AI (thus creating advanced digital images of product/processes). On the other hand, new business models capable of capitalising such innovation are essential for making them stick in the digitally driven markets of tomorrow.

DIGITAL MARKETPLACE FOR EXCHANGE OF QUALIFIED RESOURCES IN DYNAMIC VALUE NETWORKS (A/P)

Digitalisation of assets and resources is the main driver that disrupts the traditional static supply chain to dynamic value networks that are arranged on demand to couple the needs of buyers with the providers of manufacturing capacity. In the last years, the manufacturing domain has witnessed a global challenge for selection of the dominant production services marketplace. If Europe is to succeed in this race, it needs to exploit its own platform-enabled responsible marketplace that makes the manufacturing capacity available, as well as other virtual and physical assets, closer to the production demand in order to achieve their smart matching, even in non-obvious situations, by leveraging on machine learning techniques. Actual exploitation of existing marketplace and digitalisation of assets and resources are the main driver of this paradigm shift, which disrupts the traditional static supply chain model and establishes dynamic value networks that are arranged on demand to couple the needs of buyers with the availability of sellers of manufacturing capacity. The possibility to include blockchain technology as a mean to provide smart contracts, to enable identification of assets and to support traceability of exchanges and intellectual contributions (for instance in idea-generation processes) occurring along value creation shall be considered to increase the value for the customer.

NEXT GENERATION INDUSTRIAL DATA MANAGEMENT (A/P)

The digital transformation of industrial/manufacturing companies will create data in quantity and quality never seen before, fostering an enormous potential for their businesses. These companies are now becoming conscious of this reality but lack skills and resources to deploy a continuous strategic process of data management and governance. Nevertheless, only a very small percentage of industrial data is currently used in a way that makes sense or adds value. Several approaches to assess maturity and define digital transformation roadmaps are today proposed both in research and practice, yet none of them addresses explicitly and in detail the data strategy and governance required to explore the full potential of this movement. There is a need to develop a systematic approach to support industrial/manufacturing companies to deploy a strategic data management process, especially in this context. An effective and strategic data management process will provide companies with data awareness and data maturity, enabling an effective data-driven approach to their decision-making.

CYBERSECURITY AND CONNECTIVITY (P/A)

It is clear that connecting the internet to the shop floor has the potential of bringing substantial advantages. The question is how to tackle the cybersecurity and connectivity issues in a heterogeneous real life environment without blocking the production or cause dangerous situations. New methods, architectures and algorithms need to be developed considering the unique requirements of the Internet of Things adopted in manufacturing. Scattered approaches need to be unified and standardised in order to accelerate their implementation in the industrial environment. Providing solutions to reliable, fast and secure connectivity, enabling decentralised and remote control, are of top priority. Research in this field will affect all the manufacturing areas where IoT is implemented and secure data exchange and/or remote access is required. Additionally, real-life production systems are a mix of new and older equipment and technologies, often bought from different technology providers, dealing with different communication protocols. It is clear that bringing the internet to the shop floor has the potential of bringing substantial advantages. Then the question of how to tackle the security issue in such a heterogeneous real-life environment without blocking the production arises.

THE INTERNET OF WEARABLE THINGS IN MANUFACTURING (P)

Never before has computing been small enough to be worn on the body, leading to the creation of unobtrusive technologies that are revolutionising manufacturing (e.g., voice based hands-free devices, capability extenders, etc.). Wearable technologies boost the convergence between the physical and digital world and enable more seamless workflows, meaning greater productivity. This new paradigm is empowered by advancements in microelectronics, ICT, big data and cloud computing, supporting employees to be more productive, easily report mechanical problems, service disruptions and other potential issues at the shop floor level, and, simultaneously, enriching the digital representation of factories with worker-related data. Research is needed to consider human factors and social aspects related to factory work when new technologies are introduced to enhance work productivity.

Legend: F – Fundamental Research, A – Applied Research and Technological Development, P – Pilot implementation and Demonstration.

4.3. Robotics and flexible automation

Robotics

Robotics is coming of age, not only in manufacturing but also and increasingly in other domains of industrial and human activity, such as agriculture, food and service sector, medicine and health care, gaming and recreation. Remaining key research issues are finding ways for robots to cooperate safely and smoothly with humans. This has repercussions on how the robots are built in order to ensure physical safety of humans, and on how humans are interacting and cooperating with the robots. This requires soft robots and task-based programming in a natural way. Controlling **multi-robot systems,** such as groups of drones or automatic guided vehicles (AGVs), require innovative control strategies, eventually biologically inspired. The use of robots in industrial as well as non-industrial areas, like in medical and service applications, requires the development of new components, such as sensors and actuators, often miniaturised. The invasion of robots and other high-tech automated (manufacturing) equipment in industry and in the every-day life of people requires an increasing 'intelligence' **(autonomy, learning capability)** of these artefacts and ways of **natural communication with humans** (learning by demonstration, gesture input, etc.), as in collaborative robots (cobots) and autonomous vehicles, to increase their autonomy and to simplify the human/robot communication. Finally, an innovative use of **the mechatronic design methodology** is needed to enhance the reconfigurability (by modularity), flexibility, precision, (variable) stiffness, size (e.g. by miniaturisation), performance, mechanical and control interfaces, and to augment the human physical and cognitive capabilities (exoskeletons, assistive devices such as the 'iron nurse'). Robot manipulation skills have to improve dramatically, as illustrated by the **Moravec's Paradox:** 'what is easy for humans is difficult for robots and vice versa'. This requires innovative developments in all robot components: grippers, control algorithms, sensors, configurations.

Flexible automation

Flexible automation, encompassing robotics, aims at **enhancing the efficiency, autonomy, autonomicity (homeostasis), flexibility, scalability, resilience and robustness** of manufacturing systems. The role of humans in future flexibly automated systems will remain essential. **Distributed manufacturing execution system architectures** have to be developed to harmoniously integrate humans into the overall manufacturing system. **Reference architectures,** structure-oriented rather than function-oriented, enabling all the above mentioned properties, are needed. **Real-time digital twins,** as single sources of truth, must equip the underlying manufacturing system with (short-term) predictive power.

Help from cognitive sciences is necessary to describe the digital twins of the human components in the manufacturing system. **Multi-agent distributed control algorithms,** taking into account the tasks related and environmental constraints, and eventually biologically inspired should be developed in order to provide robustness and scalability to the system. The developed reference architectures and manufacturing execution systems should be generic, so as to be applicable in different areas, industrial manufacturing, as well as related production areas, such as agriculture, food industry, health care, construction and home.

The knowledge base of cognitive sciences will increasingly need to be considered with the i**ncreasing interaction of humans with robots** and flexible manufacturing systems, in manufacturing, agriculture, food, medicine and health care. Context-based **human behaviour prediction** in (multi-)human-(multi-)robot cooperation is one example. **Trust** in and **socially accepted behaviour** of humans or in organisations has to be modelled in the reference architectures and control systems of robots and flexible automation systems. **Cybersecurity** measures, eventually based on **block chain technology,** have to ascertain full safety at all levels of the value chain. The use and control of companion robots will benefit from input by the **cognitive sciences.**

Progress in the so-called **Artificial Narrow Intelligence (ANI)**[3] will be needed and used as a tool to advance the projects on robotics and flexible automation. Of particular interest will be advances in **model-based control, artificial neural networks, big data analytics, deep learning, machine learning** (e.g., reinforcement learning), to make artificial intelligence more predictable and eventually certifiable. These topics are not included as separate topics in the list of research themes, but are implicitly incorporated in the listed topics as necessary or useful tools.

[3] ANI is used to distinguish from General Intelligence, which includes subjects as consciousness, embodiment, situated cognition, social intelligence, which are still poorly understood characteristics of human intelligence are just starting to be captured by AI.

Research and Innovation priority domains in Robotics

TASK-BASED PROGRAMMING OF ROBOTS (F/A/P)

If robots are to become more flexibly applicable for manipulation tasks, new software templates need to be developed for robots to learn, by demonstration, how to execute complex manipulation skills. These skills must be easily reconfigurable and quickly switchable within a family of similar tasks. The robot should guarantee the safety of the human operators it is interacting with, thereby taking into account events happening in its environment. This requires a wealth of actors and sensors to make the robot 'soft' and aware of its environment.

Full autonomy of the robot is still utopic. The human must supervise the robot's actions, intervene and correct when necessary. Therefore, the human is not eliminated but relieved from repetitive or heavy work. He may eventually supervise several robots.

The application of this methodology in several application domains (car assembly, electronics assembly, warehousing, equipment manufacturing) requires investing in formalising the domainspecific knowledge such that the software templates already contain the domain knowledge. This way, the task demonstration by the operator can be limited to the variability in time and space in which the templates are to be used; the intention of the templates must be pre-programmed.

INTRINSICALLY SAFE ROBOTS (A)

Robots that are to work in the vicinity of humans have to behave safely and dependably. This means that collisions must be avoided by suitable spatial proximity sensors. If collisions occur they must be physically harmless, which requires the robot arm to be covered with a soft skin, which at the same time acts as a distributed touch sensor, just like in the human skin. The joints should be soft as well, thus exhibiting a low mechanical impedance. All these sensor inputs should be incorporated into the control software for the robot to generate safe trajectories. Aspects of cognitive and perceived safety are equally important to consider. Systems can be perfectly safe, if the user does not trust them, there is a problem (cf. airplanes).

MOBILE MANIPULATORS FOR LOGISTICS (A, P)

Mobile manipulators are a promising technology for factory environments designed for the human use, due to the combination of mobility and dexterity. New high speed and high precision localisation and navigation control algorithms will allow mobile robots to replace traditional conveyors, with clear advantages in terms of layout flexibility. The current use of mobile robots as rolling conveyors is limited to the current precision of the localisation systems and, therefore, operations made on these rolling conveyors can only be executed by human operators. The use of industrial robots, or other automation equipment on parts transported by rolling conveyors, require a new generation of control algorithms to enhance the overall precision of the rolling conveyors. Light, but strong, safe and energy-efficient robots, eventually with innovative configurations, are needed to be mounted on mobile platforms. The present generation of cobots lacks these features.

MULTI-ROBOT SYSTEMS - ROBOT SWARMS (A/P)

Fleets (swarms) of robots will increasingly become operational. Examples of this are fleets of intelligent AGVs in warehouses, swarms of drones for package delivery or reconnaissance missions, fleets of intelligent wheelchairs in retirement homes or hospitals, robot submarines for underwater repair, exploration and ocean floor exploitation.

Distributed algorithms are to be developed to coordinate the behaviour of the swarm. The behaviour of swarms of social insects is a logical source of inspiration for controlling robot swarms in manufacturing or other settings. Suchlike algorithms allow for easy scalability, reconfigurability and lead to resilient/robust systems.

There is a need for centralised/decentralised control, enabling the fleet to work under task and environmental constraints, exhibiting multi-agent learning and self-repair surfaces by 'graceful control of degradation'.

FLYING, FLOATING OR DIVING ROBOTS FOR MANUFACTURING (A/P)

Drones are recent additions to the robotics world. They have distinct advantages over the classical configurations: they can move over large distances without requiring complex ground infrastructure, such as rails or a flat floor and they do not occupy permanent floor space. These features make them interesting for a variety of manufacturing-related tasks, such as logistic tasks (transportation and manipulating of goods over short or long distances). Assembly tasks with drones are imaginable and potentially interesting because an assembly system with drones occupies very little floor space. Building assembly drones requires considerable research to guarantee high positioning accuracy needed to assemble parts with low tolerances. This requires the development of novel sensor systems working accurately over large spaces and position control algorithms.

The technologies developed for drones can be extended to include manufacturing-related activities on or under water, such as repair of drilling rigs, erection of offshore wind turbines.

ROBOT MACHINE TOOL (A/P)

The use of robots as machine tools has been a dream for a long time. They are already in use for operations in which there is no contact between the robot end effector and the environment, such as for 3D printing, and where high positioning accuracy suffices. Using a robot as a machine tool, where cutting forces occur between the tool held by the robot and the work piece, requires robots with high stiffness. The passive mechanical structure of the robot cannot guarantee the high stiffness of a machine tool. Active stiffness control through the robot drive motors is required, and more importantly, direct endpoint position measurement is indispensable. High challenges lie ahead to achieve this. Besides the material removal processes, typical other manufacturing processes that can use robots as machine tools are: surface finishing processes using compliant tooling (e.g., abrasive belt grinding) or other end-of-arm tooling as potential, considering accurate material removal models, deburring of castings; 3D-printing, laser cutting, laser melting deposition, etc.

SHARED AUTONOMY IN MANUFACTURING – COBOTS- COOPERATIVE MANIPULATION (F/A/P)

Cooperation between human and robot requires the sharing of the autonomy between both actors. This can be physically, for example, when the human takes the robot by the hand to guide it to a certain position to correct the pre-programmed end position. This can also be by the control computer correcting a wrong trajectory executed by the human operator. Applications where shared control can be useful are cobots, free ranging AGVs, (haptic) joystick controlled wheelchairs and other assistive devices. Software development is needed to merge the autonomy of the interacting actors (intention estimation, trajectory generation).

ROBOT SKILL ACQUISITION (F/A/ P)

Making robots more autonomous requires a training phase during which the skill has to be transferred from the human operator to the robot. This requires a data capture during the human execution phase and the subsequent translation of this data set into a robot program that allows the acquired skill to be executed by the robot. Taking a spray painting robot by the hand and manually execute the painting job and subsequently play back the captured robot coordinate data stream is a straightforward case. Acquiring a robot casting deburring skill is a much more complicated task as it requires considerable research effort, involving AI techniques such as neural networks, Kalman filtering, etc., to transform the mechanical impedance (forces, positions) of the human arm into the impedance of the robot holding the deburring tool.

AUGMENTING THE HUMAN (A/P)

Robots can augment the human capabilities in different ways: by increasing the load carrying capabilities of humans (power multipliers, iron nurses', exoskeletons, assistive devices (rehabilitation robots), by reducing the cognitive load (wearables) and by simplifying and enhancing the communication with robots (cobots, assistive devices).

Extensive research and development is needed in many aspects: hardware, software, shared autonomy in order to obtain usable products that can benefit humankind.

HANDLING SOFT AND LIMP MATERIALS (A/P)

Handling soft and limp materials is relatively easy for humans but is a real challenge for robots. These handling tasks occur frequently in manufacturing industries (e.g., furniture, clothing, shoe industries), as well as in non-manufacturing areas, such as agriculture (fruit harvesting), health care (handling bedridden patients, making up beds, rehabilitation), etc. Many pending problems in robotics (suitable sensors, grippers, smart intuitive programming and machine design) need a solution to achieve progress in this important but difficult area.

ROBOTS IN CONSTRUCTION (A/P)

The inroads of robots and other flexible automation into the manufacture of homes, building and other civil engineering structures has remained limited so far. Automating building construction is closely related to the developments in modular building technology. Building cranes have to be turned into large robots by introducing more accurate positioning through sway compensation control schemes and shared autonomy algorithms. 3D printing of complete building is on its way but needs developments in the hardware, in the deposited materials and in the automatic deposition software. Autonomous road and railroad construction also offers high automation potential.

Research and innovation priority domains in flexible automation:

REFERENCE ARCHITECTURES FOR FLEXIBLE MANUFACTURING SYSTEMS (F/A)

New reference architectures are required to combine the advantages of hierarchically structured (predictable) performance with those of hierarchical systems (flexibility, robustness). Holonic or multiagent manufacturing system architectures have shown much potential. They are based on a structurally, rather than functionally-oriented reference architecture of the system and on a strict separation of concerns. Such architectures make the system easily scalable, extendable, and robust against disturbances. A real-time digital twin, emulating the system and its dynamics, as single source of truth at any time allows short-term predictions of the system behaviour.

More research is needed to adapt the reference architectures to more application domains. The interaction with existing planning systems is to be further explored. In multi-plant configurations and when subcontractors and Original Equipment Manufacturer (OEM) companies are involved, trust considerations (in humans and infrastructure) can be incorporated to make resource allocation more reliable. Another open issue is how to incorporate planners or schedulers, which provide valuable information in a hierarchical setting when they are available, into the more heterarchically-oriented holonic execution system to give expert advice.

The reference architecture allows to smoothly incorporate the human as a system resource. The description of the human holon in the digital twin of the system will require the help of sociologists and psychologists. The availability of a reference architecture along the lines explained here solves in a generic way a vast set of problems associated with flexible automation in different disciplines different from or adjacent to manufacturing. Examples of this are logistics, inland navigation transport, health care, open air engineering, railway operations, smart grids, e-health, smart homes, etc.

AUTONOMIC ROBOTS AND FLEXIBLE MANUFACTURING SYSTEMS (A)

Autonomic systems are different from autonomous systems. An autonomous system can stand on its own and tackle unexpected events independently during the execution of a task.

An autonomic system is a system that keeps itself in optimal condition, regardless of the task it has to execute. When something wrong happens it degrades gracefully. Very much like a human who keeps his/her body temperature constant and keeps breathing

unconsciously. In medical terms it is called 'homeostasis'.
A robot or a manufacturing system has to keep running as well as possible under all circumstances. When one degree of freedom fails, it still can execute a reduced set of motions. A machine tool that overheats or works at high ambient temperatures can still produce parts at a reduced accuracy. An autonomic machine keeps its accuracy intact under temperature disturbances.

Suitable sensors should be developed or selected and software should be developed to compute the remaining capabilities of the system based on the sensor readings.

Condition monitoring and prognostics is a field in full expansion. There is a need for the development of suitable sensors for a range of variables to be measured. Big data analytics should extract relevant features out of the captured data clouds. Storage of the huge amounts of raw data increasingly poses serious problems. Not the data itself is important but rather the extracted useful information. Artificial neural networks may help for data reduction. Learning algorithms can make the system smarter by learning from past experiences.

TRUST, SOCIALLY ACCEPTED BEHAVIOUR AND CYBER SECURITY ISSUES IN FLEXIBLE AUTOMATION – BLOCK CHAIN TECHNOLOGY (A)

The increasing involvement of humans in flexible automation systems, particularly in multi-plant manufacturing systems make it necessary to include trust considerations into the manufacturing execution systems and in the digital twins that emulate these systems. The flexible manufacturing execution systems must be laid out in such a way that their 'decisions' remain socially acceptable.

Similarly, cybersecurity has to be ascertained, particularly in multi-plant manufacturing systems and in the virtual companies emerging in the increasingly global economy. In this respect, the advent of blockchain technology should be carefully scrutinised as an eventual candidate to guarantee absolute cybersecurity of the data used in the manufacturing execution systems.

RECONFIGURABLE MANUFACTURING SYSTEMS (A)

Flexibility of the manufacturing system can also reside in the system hardware by reconfiguring the system components. It is however much more difficult to realise than with software reconfigurability. **Modularity** is the key issue here. Research is needed to define the modules and most importantly their mechanical and control interfaces to allow easy reconfigurability. The importance of this issue is becoming higher by the recent emergence and success of the hybrid-manufacturing concept by which several manufacturing processes are combined into the one machine.

Besides the hardware and control components, other modules that should be considered to be integrated are product visualisation modules and inspection systems. This is particularly important when a real-time digital twin is to be the 'single source of truth at any instant of time.

Legend: F – Fundamental Research, A – Applied Research and Technological Development, P – Pilot implementation and Demonstration.

4.4 Nano-technologies and materials

In order to support EU manufacturing growth and competitiveness in the international arena, research and technological development on **New Materials and Nanotechnology,** will address societal and industrial needs and will need to be at the top of the EU agenda. In order to provide radically new solutions in terms of the material itself, Nanotechnology plays an essential role, as it allows to design and develop new materials with extraordinary new properties and functionalities for a wide range of applications, which cannot be achieved otherwise. In this context, the economic impact of Nanotechnology is expected to grow significantly in areas such as energy, automotive, aeronautics, space, defence, construction and other major industrial sectors. Additionally, and more specifically, in the context of EU Manufacturing, the development of nanotechnologies and materials will also drive the need for new manufacturing processes aimed at delivering or integrating them, as well as the need of improving existing production equipment, etc.

Nanotechnology will further improve and revolutionise the more traditional and commodity products, such as paper, by taking them to a superior level (e.g. new properties) and/or by reducing their production costs. In this sense, major technological breakthroughs, thanks to Nanotechnology, have already happened and more are expected to occur in the near future. For example, nanomaterials, such as nanocellulose, may lead to the substitution of transparent plastic films (used in packaging) for more environmentally friendly materials.

Also, a new class of materials is foreseen, that is, low-carbon or carbon-neutral. In this case, the final properties of the manufactured material could be the same, however, the manufacturing process would need to change.

It must also be noted that Nanotechnology has an impact throughout the entire industrial manufacturing value chain from the nanomaterials production (e.g. graphene and carbon nanotubes, nanoparticles, nanocellulose and other nanofibers, etc.) all the way to the production of nano-enabled materials (e.g. polymers, ceramics, metals, composites, coatings, etc.) and the derived consumer products creation (e.g. lighter-weight vehicle parts, thermal dissipation composites for aerospace applications, high-performance and self-healing concrete, corrosion and wear-resistant coatings, thermal insulation materials, air-purification photocatalytic products for buildings, novel electrodes and batteries, etc.). Obviously, prior to the manufacturing of a new nano-enabled product, it is important to use the safe-by-design approach and to take into account the potential environmental, health and safety (EHS) impact of any given nanomaterial. One of the barriers for deployment of nanomaterials is to scale up their production process and incorporation in bulk and surfaces. The automation of the process, minimising the personnel interaction with nanomaterials, is an important issue.

One major trend, identified in the Manu*FUTURE* Strategy for 2030, is the **Resource Efficiency and Circular Economy.** In recent years, Consumers and Society are increasingly demanding more sustainable products, as it is becoming clear to everyone that the planet has finite resources. One of the key aspects to provide new sustainable products, and to optimise our use of these limited resources, lies in Advanced Materials and Nanotechnology, which will play a key role regarding the physical properties of all sustainable European products and components, as well as in the processes needed to manufacture, re-manufacture and recycle them. In the future, all nano-enabled materials and derived products will need to be designed to be more durable, environmentally-friendly and easier to recycle, apart from possessing all the other functional (or multi-functional) properties required to meet our ambitious societal challenges. This will require large-scale nanomaterial production processes to be more cost-effective and robust, while maintaining high quality standards and low environmental impact. In this scenario, green processes (e.g. hydrothermal) will play a key role.

Developing complex new products - or second-generation commodity products - based on new sustainable materials and Nanotechnology will lead to new high value-added businesses boosting the EU economy and will also improve the competitiveness of our current EU manufacturing industry. It is also expected that the sustainability itself will be an important source of differentiation and competitiveness for our manufacturing industry in the global market.

It is envisaged that material encoding could also become a major trend. For this, fundamental research will need to be carried out aiming at embedding data or information within the material (perhaps at the nanoscale) without the need to integrate complex electronics, which would hinder recyclability. Another need for these intelligent materials could be in the detection of counterfeit products. This is especially interesting in relation to the use of block-chain enabled keys that will allow trusted authentication as well as increasing consumer safety.

Another trend is that dense metals are increasingly being replaced by lighter metals or by polymer composites. However, each one individually does not meet all requirements for mechanical, electrical and thermal abilities and may need to develop the right surface treatment; moreover, providing multi-functional products, expected by these markets at the right cost, is boosting the need for further integration of functional elements (materials, electronic components) in the structure and, at the same time, setting up new processes to reduce cycle times and produce net-shape parts. Nanotechnology, combined with other Key Enabling Technologies (KETs) such as Advanced Materials and Advanced Manufacturing, can lead to lighter and multifunctional structures and therefore answer to major European Missions.

Durability of materials and prediction of their lifetime will have an important influence to reduce maintenance cost and minimise the use of raw materials. The use of secondary raw materials will be a challenge as it might need some upgrade in terms of performance and durability. Components should then be designed so as to assure durability, reuse and energy efficiency. Tribology is a great tool to achieve this goal.

Finally, there is great potential for business in the EU around recycling or de-manufacturing plants. However, these will probably only be economically viable if the materials and derived products are designed to be recyclable or de-manufacturable from the beginning. Current materials are usually designed solely from the regulatory, performance and cost point of view. Unless there are regulations in place regarding the need for considering issues such as recyclability and circular economy, there will not be enough pressure to move this forward at a commercial level.

Research and Innovation priority domains in Nano-technologies and materials

MULTI-FUNCTIONAL MULTI-MATERIAL SYSTEMS (F/A)

New design and processing approaches guided by Artificial Intelligence and other computational methodologies to ensure the competent deployment of functionalised multi-material components, by considering the overall efficiency (technical, environmental, economic) of each integrated material component, including its disassembly and individual recovery and re-use, in the sense of Circular Economy. This shall be supported by the co-development of innovative high fidelity computational multi-scale material modelling and simulation techniques, materials design optimisation methods, for example., machine-learning and generic algorithms, and advanced experimental characterisation test setups. The use of multifunctional materials should be promoted as enablers for such systems as well as the design for hierarchical systems and locally functionalised and/or reinforced materials, as a means to achieve highly optimised nano-enabled systems.

NANOMATERIALS FOR ADVANCED AND HIGH-PERFORMANCE COMPOSITE MATERIALS (A/P)

New nanomaterials are required to provide new functionalities to conventionally used polymer, metal and ceramic-based composite materials, and to improve their suitability for conventional manufacturing processes (minimising the effort in terms of process adaptations and potential negative effects in other performance properties). In addition, such nanomaterials must be industrially available in large amounts and at affordable prices to ensure European non-dependence on nanotechnologies for composite materials. The nanomaterial production processes must be robust, cost effective, easily scalable and with low environmental impact; and the use of raw materials (either natural or recycled) widely available in Europe is also imperative. Development of tailor-made nanomaterials, oriented for enhanced compatibility in targeted materials and applications should also be an important focus. Tailoring includes their availability in physical formats that will ease their introduction into the final applications (e.g. in the form of masterbatch, fibres, 3D structures, films, coatings). Support of introduction of such nanomaterials into semi-products is something that also should be targeted from research to industrial scale.

NOVEL RAW-MATERIALS AVAILABILITY FOR COMPOSITE MATERIALS (A/P)

Further gains in composite materials and related structures are highly dependent on the availability of raw materials that are used for their manufacturing. A wide range of performance properties and processing characteristics would be possible through the use of different polymer matrices, fibres, and additives, including nanomaterials. In addition, these raw materials also need to be provided in suitable formats, such as pre-impregnated materials, reinforcement fabrics, commingled yarns, liquid resins, polymer films, or masterbatches, to make possible their use for composite materials manufacturing. This includes combinations of new polymer/fibres combination in prepreg materials, hybrid fibres systems and the introduction of new and improved polymer (thermosets and thermoplastics) and fibre-based materials. Such developments are critical building blocks for future multifunctional and high performance lightweight composite materials.

SMART, HYBRID AND MULTIPLE MATERIALS (A/P)

Design, modelling and manufacturing processes of multi-metallic, plastic-metal or composite-metal components and high-performance materials. Structures and components with integrated functions and tailored material properties and location-specific properties. Enhanced, faster joining capability with a range of materials.

LIGHTWEIGHT STRUCTURES BASED ON ADVANCED AND MULTIFUNCTIONAL MATERIALS (P)

Development of nano-enabled multifunctional lightweight structures (composites as polymer-matrix and metal composites, aerogels, coatings, surfaces, adhesives and/or any other polymeric materials) through the industrial production of nanoscale structures in unprocessed form, intermediate products with nanoscale features and nano-enabled products to foster innovation in key industrial sectors and support the development and market uptake of KETs.

SMART MATERIALS AND FUNCTIONAL PRINTING (F/A/P)

Design, modelling and manufacturing processes integrating smartness to parts. Structures and components with integrated functions (functional printing) and selective deposition or texturing. Another specific technical-related issue that needs to be addressed is the development of connectors (flexible, robust, etc.) that are also needed. In addition, other general issues must also be addressed, such as recyclability, repairability and standarisation.

In terms of the materials: The development of novel materials for fully printed devices (e.g. for sensing or electronic functionalities) are needed, together with the optimisation of conventional processes for those materials. The challenge of printing directly on a 3-dimensional part and on any substrate (e.g. composite, metal, or other plastics) beyond what is currently possible (i.e. PET, PC, PMMA or PU in plastics, glass and some ceramics). A wider range of technologies and innovations is needed to achieve the objective.

ADDITIVE MANUFACTURING WITH NANOPARTICLES (A/P)

Design and fabrication of components/tools through the use of nano-reinforced alloys, concrete or polymers, especially designed and prepared as feedstock material to improve the part properties (mechanical strength, toughness, hardness, or wear resistance, etc.). Thermal conductivity of plastics and composites has been seen as a disadvantage in the replacement of traditional metals in some applications. Nanomaterials can be enablers of this property in plastics and composites. They also open the possibility to tailor the thermal conductivity value, thermal management and pathways. Focusing on this property is important for future smart materials based on the combination of nanomaterials with plastics and composites.

NANOFABRICATION TECHNIQUES TO CONTROL SURFACE PROPERTIES (F/A/P)

Nanofabrication can be used to nanopattern different substrates to implement functionalities on the surface of injected/thermoformed parts or others. Based on the control of the surface roughness, several functionalities related to surface energies (icephobicity, anti-fog, etc..) or to light interaction (anti-reflecting, structural colours, etc..) can be tuned; these and other functionalities (e.g. aesthetics-related) should be exploited for new product development using texturing at different scales (femto, pico, nano, micro texturing and other nanofabrication techniques).

NEW NON-NOBLE-METAL BASED CATALYSTS (A/P)

A high number of industrial processes are based on reactions, such as hydrogenations, hydrogenolysis and oxidations, based on highly expensive and scarce supported noble metal catalysts. In addition to this, many energy conversion and storage technologies (such as fuel cells, rechargeable metal-air batteries, unitised regenerative cells, and water electrolysers) use electrocatalysts based on noble metals (e.g., Pt, Ru, Ir). To head towards sustainability, catalysts based on cheap and abundant nonnoble metals able to provide the same or similar performance are needed.

MATERIALS DESIGN AND PRODUCTION FOR FUNCTIONALITY, DURABILITY AND ENERGY EFFICIENCY DURING USE BUT CONSIDERING THE REUSE AND RECYCLING PHASE (A)

Prediction of the lifetime, modelling and scale up of the production of new materials and nanomaterials, considering composition, microstructure, production process and finishing, functionality and performance during use in order to increase lifetime. It is really important to assess both durability and energy efficiency during the use. For that, tribology is an important tool for reproducing, in a laboratory, the working conditions of the application to address in the design phase of the component, the right material that might reduce the energy consumption and to increase its lifecycle. These materials should be integrated in products (whenever possible) allowing traceability in order to facilitate or simplify recycling or reuse.

In addition, the design and manufacture of engineered components depend to a large extent on the availability of materials property and processing data qualified for use in the industry sector involved. However, material specifications from suppliers often provide for a range in compositions, microstructures and as-supplied properties, which means that designs then allow for the poorest performance in the range. This has led to over-designed products with excessively conservative allowances for known component failure modes. There is a need to tighten up materials data management, and the models used for its interpretation, so that better engineered and cost-effective products can be delivered without leading to unacceptable risks of failure in service and product insurance implications. An efficient methodology for addressing these issues is the production of open access material databases so that all in the value chain are fully aware of the data, and that newly derived data is provided at the highest quality.

MATERIALS, COATINGS AND FLUIDS RESISTANT TO HIGH TEMPERATURE MANUFACTURING SYSTEMS (P)

Manufacturing systems (e.g., high-pressure injection moulds, hot stamping) have a limited lifetime due to the hard working conditions. New materials and surface treatments have to be developed to resist higher temperature, oxidation and thus increasing the durability and reducing manufacturing cost (OPEX) in industry. Modelling and characterisation techniques need to be combined in order to reduce the experimental work, reproducing the critical failure mechanism at the laboratory to implement in the industry.

NEW MATERIALS FOR JOINING (A)

Joining of speciality materials with enhanced properties; Low electrical resistivity and low thermal conductivity joints; High performance Joining of non-metallics; Micro and Nano Joining. Joining dissimilar materials is challenging especially when trying to minimise the use of adhesives to facilitate recycling. Galvanic coupling of dissimilar materials and corrosion resistance of joint and welding is an important issue that are still seriously limiting the system lifecycle.

NANOCELLULOSE-BASED FUNCTIONAL MATERIALS AND PRODUCTS FOR MULTI-SECTORIAL APPLICATIONS (A/P)

Research and development is required on the scale-up of production of functionalised cellulose nanofibers and nanocrystals, which are natural nanomaterials that can be easily obtained from renewable resources (e.g., trees, annual plants, paper, cardboar, etc). At the same time as addressing the pilot-scale manufacturing of the functionalised nanomaterial itself, the potential of these bio-based and biodegradable nanomaterials must also be demonstrated by developing novel nanocellulose-based functional materials and products, with wide-ranging applications, including food packaging, environmental remediation filters and sponges, thermal insulation materials or materials for skin treatments to name a few. It is foreseen that the superior properties of these bio-based materials will displace in many applications existing materials, which are currently widely used despite their negative environmental impact and inferior properties.

ADVANCED LARGE-SCALE MULTI-FUNCTIONAL COATINGS FOR STEEL AND OTHER METALLIC SUBSTRATES (A)

Research on the design, formulation and application of novel large-scale multi-functional coatings that enhance the durability of steel and other metallic material-based products is urgently required, particularly for those products that are large and exposed to extreme environmental conditions. Unless these coatings are proven for products with large dimensions, the targeted applications, i.e. offshore, will not be impacted. This research will also address the need for multi-functional coatings in a variety of different industrial sectors. For this, an evaluation of the different technologies available (including Thermal Spray, Sol-Gel, Electrodeposition, Advanced paint systems, PVD, CVD, ALD, etc.) should be performed initially depending on the end user requirements and on the different properties or functions that are sought in each case. The main aim of this project will be to identify the best solution to the problem of corrosion-resistant coatings for steel, which can be used in extreme conditions such as in off-shore applications, with dramatically improved lifetimes with respect to current products and eventually offering added functionalities on request (e.g., self-cleaning, anti-icing, anti-fouling, etc.). The new coatings and production processes shall be environmentally friendly, not hazardous and safe in the workplace and shall eventually replace toxic and hazardous substances currently in use.

Additionally, they should work in combination with monitoring systems that provide, in time, online information about the material and component degradations due to corrosion, bio-fouling, fatigue, icing and erosion.

INDUSTRIAL MANUFACTURING OF ADVANCED MATERIALS (P)

The introduction of new nano-enabled advanced materials in industrial production lines is needed to secure their wider market uptake. In many established sectors, the introduction of new materials and innovation has to deal with a huge factor scale that is often difficult to overcome. As an example, the urgent technical needs related to metal forming (metalworking processes) for materials like new superalloys, Metal Matrix composites, light alloys and nanocomposites and in particular the manufacturing of semi-finished products (bars, tubes, wires, plates, etc) lack the availability of midscale plants. This gives no possibility for SMEs to access production facilities that are able to provide this kind of processes at the scale needed for small series production, thus blocking the introduction of these advanced materials into advanced products.

Legend: F – Fundamental Research, A – Applied Research and Technological Development, P – Pilot implementation and Demonstration.

4.5 Biological transformation

Biointelligence - the future of sustainable value creation systems

A more efficient use of natural resources is a main task for our modern society, whose fulfilment would both relieve our ecosystem and counteract societal challenges such as emerging resource conflicts. In order to keep our wealth and well-being, new forms of value creation are needed. These will arise with the biological transformation of value creation[4].

For the process of biological transformation, three stages of development can be distinguished, which finally lead to an absolute fusion of the technosphere with the biosphere. First of all, a bionic-inspired approach allows, in the stage of **inspiration,** to transfer evolutionary biological phenomena into value-added systems. In a further stage, the knowledge of biology in the form of an actual **integration** of biological systems contributes to the improvement of value-added processes. The comprehensive **interaction** between technical, informational and biological systems has, as a third stage, the disruptive potential to fundamentally restructure existing production technologies and structures, and transfer them to a so-called bio-intelligent value-added system. Biointelligence is the convergence of the digital transformation with the biological transformation.

[4]As a recent reference, 114 highly ranked experts were interviewed, workshops with more than 200 participants were conducted and a comprehensive picture of the strengths, weaknesses, opportunities and risks of Germany was drawn and set into international comparison, in the scope of the German BMBF funded research study BIOTRAIN. Additionally, more than 250 technology examples were collected and rated according to their potential in biological transformation. More than 200 research studies and over 150 design topics were finally determined, and are expected to revolutionise the industrial value creation.

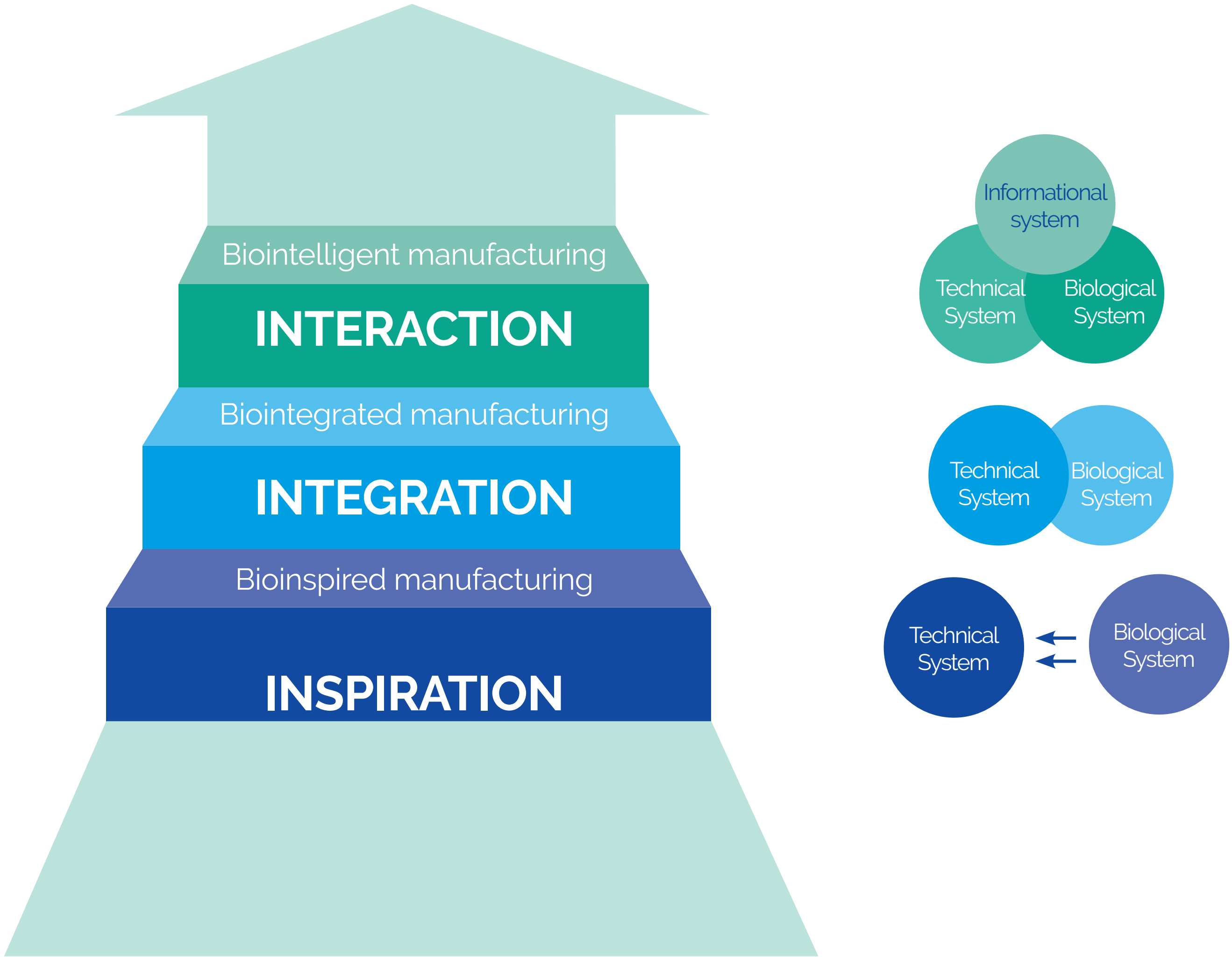


Figure 12 – Biointelligence - the future of sustainable value creation systems.

How is this new kind of bio-intelligent value creation realised?

The basic disciplines biotechnology, engineering and information technology provide the necessary tools for this process. Methods of adaptive data processing (self-learning algorithms) are just as important as additive manufacturing or biotechnological production processes. Their combination and intelligent networking, including biological components and principles for their optimisation, are the key to a bio-intelligent economy that enables prosperity and healthy and sustainable (qualitative rather than quantitative) growth.

How far ahead is the biological transformation?

The foundations of the biological transformation are already laid. Bionic principles are studied and utilised since decades. The digitalisation of the industry gives way to distributed, parallel computing and artificial intelligence. The first elements of biointegrated manufacturing are realised and tested both in research labs and in start-up companies, like sensors with living neuron cells.

How does the world change through biological transformation?

The pipeline economy and the principle of linear supply chains are being transformed into decentralised platform economies with intelligently controlled value-added cycles. Bio-intelligent value-adding cells, which no longer remain exclusively as delimited entities (factories, buildings), are able to autonomously adapt their architecture to the optimal solution of a production order and to organise themselves as regional socio-technical cells. These cells have all the necessary information to exchange resources and to use them intelligently, to adapt themselves to environmental conditions and spontaneously and autonomously network and communicate with each other.

The type of consumption and the materials used will change fundamentally. Decentralised, highly flexible and adaptive "Smart Biomanufacturing Devices" (SBMD) are revolutionising the majority of consumer products. These production units are coupled with self-learning algorithms to process regionally available, inhomogeneous bio-based materials (e.g. bioreactors, biorefineries) or to process directly according to the principle of additive manufacturing. Household and agricultural waste, highly efficient urban gardening plants, horizontal gardens or microalgae reactors on building facades, as well as obsolete, disused products serve as sources of raw materials and energy. Industrial companies provide SBMD technologies and local manufacturing hubs for more complex products, and develop digital blueprints for the products in close and direct exchanges with consumers.

New manufacturing technologies, production processes and manufacturing systems engineering will reinforce the European capability to design, manufacture and provide the best production equipment and systems on a global level. More specific fields of engineering such as product design engineering, mechanical engineering, mechatronics, and electrical and electronic engineering will also contribute to better European products and factories, as well as to better services provided by European manufacturing industries.

Research and Innovation priority domains for the biological transformation

BIO-INSPIRED STRUCTURES, MECHANISMS AND PRINCIPLES OF THE BIO-INTELLIGENT MANUFACTURING SYSTEMS (F/A)

Decentralised, autonomous cell-based, highly networked manufacturing systems and value networks will be highly adaptable and resilient. They have a high potential for self-optimisation, high efficiency and transparency.

BIOSENSORS (F/A)

Biosensors are composed of a biological sensing element (enzyme, antibody, DNA, receptor or complete cell) in direct contact with a physical sensor (transducer). Few examples exist, like a highly sensitive "electronic nose" for gas sensing. A systematic evaluation will reveal many more application areas and bio-sensing principles, to be demonstrated in application-specific implementations.

BIOACTUATORS (F)

Nowadays, research is exploiting many physical and material effects to realise smart actuators. However, all of them are still far from the efficiency and energy density of physiological and biological actuators. One of the consequences can be to use artificially grown biological actuators in a life sustaining microenvironment. Further optimisation may allow to reduce the biostructures and along with it the life-sustaining system to the necessary minimum.

ADDITIVE MANUFACTURING OF BIO-INTELLIGENT MATERIALS (A)

3D printing of bio-active materials and even biological cells have been demonstrated in basic research. The development towards highly reliable and efficient additive manufacturing will also reveal further application scenarios and printing materials.

ENZYMATIC PROCESSES (F/A)
Enzymatic processes are currently used in cleaning and in food manufacturing, as bioleaching is also used in the extraction of metals from their ores using living organisms. In the future, the extraction of raw materials from waste will be much more important and enzymatic processes promise efficient solutions. Further developments may lead to other material transformations, even very localised and/or as manufacturing processes, e.g., in microelectronics, micro-systems and polymer electronics.
MICRO-BIOREACTORS (F)
Material transformation, as it is widely used today in large bioreactors, could be developed to be used in smaller and even micro-bioreactors as manufacturing processes for local generation and dissolution of materials. Stimulated photoemission and photoswitching of the genome, as it is used today in biological research, could be used to monitor and control the processes.
SMART BIO-MANUFACTURING DEVICES (F)
The results of the research topics mentioned above, combined with synthetic biology, bioelectrochemistry, and artificial intelligence could allow the development of self-optimising biomanufacturing devices for local manufacturing of consumer goods.
BIOCOATING AND BIOINOCULANTS (F,A)
Exploit the potential of different biotech-based solutions to offer protection of products across different sectorial activities, such as protection from microbial degradation and/or affording them with antimicrobial properties
BIOPACKAGING (F/A)
Exploit the potential of different bio-based solutions for packaging applications, including the use of new biomaterials, technologies for bioencapsulation, among others, which could offer suitable and sustainable approaches for manufacturing processes.
ECOLOGY-BASED MANUFACTURING (F)
Re-thinking manufacturing units based on nature based principles of ecology that could offer integrated and sustainable perspectives to industries.

BIOREFINERIES (F/A)
Integrated solutions of biorefineries for sectorial clusters to extend the use and applications of products and co-products across the value chains and to produce new materials and products.

Legend: F – Fundamental Research, A – Applied Research and Technological Development, P – Pilot implementation and Demonstration.

4.6 Customer-driven manufacturing

The capability to address the requirements and needs of each individual customer will be a key differentiation and competitive factor. Mass customisation (i.e. the manufacturing of customised items with productivities typical of mass production) is becoming inevitable for many consumer goods, especially for personal items (e.g., biomedical implants, dental sector, clothing and shoes). Today, the rapid increase of industrial internet is creating the conditions for a **propagation of a completely customer-driven manufacturing, throughout the whole process chain:** from the customer to the retailer or to the OEM company, then upstream to the first and second tiers, etc. Customers will be able to configure, personalise or customise the products they need, increasing their role in product conception and design, thanks to **open** collaborative **platforms,** e-marketplaces and social media frameworks. Novel user-friendly solutions for **digital configuration/product design,** virtual modelling and design of functionalised products (e.g., topologically optimised) will be available. New **smart design solutions** will have to be developed together with novel approaches to co-design and generative designs. Many digital design functions will have to be directly connected to the customers' choices.

SMART DESIGN	• Digital twins • Smart design x • Functionalized product
CUSTOMISED PROCESS	• Additive manufacturing • Rapid tooling • Costomized resources management
DATA-AUGUMENTED CUSTOMIZATION	• Diffused sensing • In-situ in-line data feedback • Digitally connected machines

Figure 13 – Customer-driven manufacturing - concept and main research priorities.

The customers' input provided by end users and by smart products (IoT) during their life will propagate the process chain requiring a profound transformation of manufacturing processes and systems and will enable extensive data analysis along the value chain. To this aim, a clear link to logistics and supply chain management should be established, in order to directly include customers or their individual demands as requirements to the manufacturing processes, which will become more versatile and resilient, while maintaining or even increasing their current levels of productivity. Processes allowing complexity freedom (as **additive manufacturing**) will have an ever-increasing centrality in the industrial process chain. Many current manufacturing processes will have to evolve and be developed in order to be able to realise customised products at reduced costs. Other traditional processes, which are inherently rigid because they require preparative time-consuming manufacturing of expensive equipment, will have to find new developments towards **mass customisation** via rapid tooling options and will have to increase their robustness. Respective new processes must be developed.

Diffused sensing, continuous monitoring and digital manufacturing can pave the way to a novel generation of customised manufacturing, where the "personal" state of each resource (tool copy, machine, material batch) can be traced in-line to decide appropriate actions for efficient and resilient manufacturing. Small batches, one-of-a-kind/personalised production will further need novel solutions for transfer learning and **in-situ process qualification,** especially in highly regulated sectors (e.g., biomedical implants, aerospace), where the real obstacle to personalisation is represented by the rigid qualification standards.

Research and Innovation priority domains in Customer-driven manufacturing:

SMART DESIGN

GENERATIVE DESIGN FOR PERSONALISED PRODUCTION (A/P)

An important asset to bring mass customisation and personalised manufacturing closer to sustainable production paradigms is the development of **design platforms.** These tools should be targeted to properly collect and address customers' requirements towards optimised conception and design of individual and specific products. To this aim, new smart CAD/CAM solutions have to be developed to provide the ground for implementation of computational and generative design within the boundary conditions set by the technology. **Co-design** activities, where industry experts can have the opportunity to involve customers as contributors in the creation of products, should be further developed. Novel design solutions should provide more satisfied customers, increase the product quality (embedding biometric and personal data) and establish a better product-consumer relation due to the interactive process. This latter aspect can result in **customer interaction** in stores, centres/corners for personalised manufacturing, bringing new game-changing services, which include final users in the product conception and design.

FACTORIES OF THE FUTURE MANUFACTURING THE PRODUCTS OF THE FUTURE: COLLABORATIVE PLATFORMS FOR VALUE CREATION (A/P)

More products that incorporate digital technologies are becoming more than a bundle of functionalities. The products of the future will become platforms for value creation for both the customer and the product provider. **Co-operation between man and machine** needs to be considered based on artificial intelligence and data driven approaches. More agile offerings centred on customers' needs and preferences are expected from this research priority line. New technologies that enable to capture **customer opinion and feedback throughout the product's life cycle** are important. Research on this field will affect the value-adding proposition of current and new solutions while providing the customers with more complete and fulfilling results.

SOCIAL MEDIA IN MANUFACTURING (A)

New models and approaches considering customer involvement through **social networks** need to be considered. Extracting social media data and integrating them in manufacturing is important, providing data throughout the product's lifecycle. Product platforms that connect social media data with production and supply chain control need to be explored. Research in this field will affect product design, production and supply control and is expected to affect customer's involvement in manufacturing.

DESIGN FOR ADDITIVE MANUFACTURING (A)

Design for Additive Manufacturing means taking into account the advantages and restrictions of different AM processes during the design phase of a product. There is a great need for development, and perhaps even more for the spread of knowledge on design for AM. New methodologies are needed for design of parts and design an entire product family instead of a single product for production by AM, or the production of an AM enabled process chain.

Research and Innovation priority domains in Customer-driven manufacturing:

CUSTOMISED PROCESSES

PERSONALISED MANUFACTURING (F/A/P)

Thanks to the Industry 4.0 paradigm shift (distributed sensing and big-data data gathering), customisation can finally move from the product to the **process stage.** Personalised manufacturing means being able to handle each resource (tool copy, material flow, rough part and machine) considering its specific history and current state. Due to increasingly cost-effective sensing, novel digital models should be designed and developed to follow each **resource consumption trajectory** in order to guide specific actions (process parameters, substitution and maintenance policies) and promptly react to unpredicted events.

NOVEL SOLUTIONS FOR EFFICIENT MASS CUSTOMISATION VIA AM (F/A)

Additive Manufacturing is in principle able to achieve "complexity for free", thus paving the way to a new generation of personalised production (biomedical, dental, aerospace sectors). However, many gaps need to be filled to let AM act as an efficient and viable solution for mass customisation: the excessive cost of design, when it is attributed to one single copy of the product; finishing of complex surfaces or elimination/reduction of supports; excessive time to produce a defect free product. This action focuses on the research needed to achieve efficient mass-customisation via AM.

MASS PERSONALISATION (A/P)

Adaptive production models and the development of technologies to implement mass personalisation need to be accelerated. New ways (including new business models) to exploit modern networks to capture the customer requirements and include them in a product design need to be examined and combined with global manufacturing networks.

This field is interconnected with all the levels of manufacturing and, thus any, research connected to it.

MASS CUSTOMISATION OF COMPOSITE STRUCTURES (A/F)

The great challenge is to provide appropriate procedures, design solutions and manufacturing processes to achieve mass customisation of composites. Composite structures mainly aim to low weight, heavy duty low fatigue, and resistant to wear and corrosion. The challenge is to achieve manufacturing with high output rates together with competitive costs. The need to develop new composite materials and energy efficient processes is a research and technology goal to be addressed.

NEW RAPID TOOLING TECHNOLOGIES (A)

Conventional forming and machining processes need to quickly adapt to the frequent design changes required by the customers. Conventional manufacturing processes for metal or ceramic tools are too expensive to meet the ever-increasing requirements of short product lifecycles and mass customisation. New tooling design concepts, new materials, surface treatments and new manufacturing processes, which need to be rapid, cost efficient and robust, must be developed.

Research and Innovation priority domains in Customer-driven manufacturing:

DATA-AUGUMENTED CUSTOMISATION

PROCESS QUALIFICATION VIA I4.0 FOR MASS CUSTOMISATION (F/A)

New technologies as AM allow in principle mass customisation, given their specific capability of producing complex shapes without the need of expensive tools and moulds. Unfortunately, a strong barrier to mass customisation in highly regulated sectors (aerospace, biomedical implants) is represented by process and product qualification standards, which tend to freeze the process conditions and limit the number of product variants.

Thanks to the impressive amounts of sensing and in-line data availability, novel approaches to **digital qualification** should be based on process signature rather than on product testing. This paradigm shift in qualification will have a significant impact on highly regulated sectors such as aerospace and biomedical, in which the product personalisation is particularly interesting for the development of new businesses.

TRANSFER LEARNING AND SCALING-UP FOR ZERO-DEFECT CUSTOMISATION (F/A)

When small lot or one-of-a-kind/personalised production is considered, an important barrier consists in time and resources wasted in the trial-and-error experimental campaign that has to be carried out to realise defect free products. Transfer learning should be aimed at defining approaches and tools to "translate" the knowledge and the experience acquired on a given machine, material and product geometry to other machines, materials and product geometries. Similarly, novel solutions for scaling-up results obtained at the laboratory level should be developed in order to reduce industrialisation time. Information provided by IoT quality feedbacks from similar products/machines/laboratories should be used if possible as a reference.

ZERO-DEFECT IN PERSONALISED PRODUCTION (F)

New methods and tools for monitoring and controlling quality in one-of-a-kind or small lots scenarios need to be developed. In fact, typical approaches for quality monitoring, control and optimisation assume large-scale production. New solutions and approaches for zero-defect manufacturing of personalised products have to be developed.

I4.0 FOR CUSTOMISED MANUFACTURING SYSTEMS (A/P)

Self-adjusting plug and produce devices that are able to ensure rapid response to high-frequency customer changes are becoming a fundamental pillar in the new manufacturing paradigm. Real time planning and control of reconfigured manufacturing systems is a barrier that needs to be overcome to allow fully resource utilization, rapid customer response and high efficiency. New digital models, algorithms, and self-adaptive, autonomous and perfectly coupled technologies must be developed to enable customer driven-manufacturing in modern factories.

Legend: F – Fundamental Research, A – Applied Research and Technological Development, P – Pilot implementation and Demonstration.

4.7. Human-centred manufacturing

Human beings in manufacturing will play a primary role. While replacing humans in repetitive, hard and dangerous tasks, new manufacturing technologies will empower humans in terms of creativity and decision power in key areas. Technology will support human activity and augment its capabilities to higher levels of effectiveness and added value. New interfaces between humans and machines and between machines will enable new advances in human-machines interaction and cooperation.

The research related to this theme will address four main areas:

1. **Understand** how the human workers behave and reason in a manufacturing environment in which they have to relate with intelligent production technologies, analyse and structure their knowledge to share, exploit and preserve it.
2. **Protect** the workers in manufacturing in order to increase their safety and the compliance of the working environment in terms of well-being and quality of working-life requirements, as well as with respect to the introduction of new technologies in the working environment.
3. **Support** the workers in manufacturing who take care of variable individual skills, in particular of young and aging workers, also considering the psychophysical and the socio-relational aspects enable them to perceive and act in complex socio-technological environments.
4. **Empower** human workers in terms of skills, flexibility and adaptability, leveraging on their skills and expertise through continuous learning and the support of intelligent technologies.

Factories will be designed to provide an appealing and challenging environment for humans, attracting the best professionals and talents into European manufacturing.

Research and Innovation priority domains in Human-Centred Manufacturing:

UNDERSTAND

ADVANCED BEHAVIOURAL AND COGNITIVE MODELS FOR HUMANS IN MANUFACTURING (F/A)

This research will address the development, validation and testing of new advanced models for the humans in the manufacturing environment. These models will address two main directions: the first one is the modelling of the human workers' behaviour aimed at analysing and understanding the actions they are executing in order to predict and prevent risks. The second one is related to the modelling of cognitive processes in the decision making and learning. Adaptations in the organisation of work enable technological innovations to be successfully implemented and to reach "full potential"[5]. Approaches and methodologies coming from different disciplines have to be taken into consideration, i.e., human science, artificial intelligence, psychology, etc.

BEHAVIOURAL AND COGNITIVE HUMAN-MACHINE SYSTEMS (A/P)

This research will address the development of neurocognitive approaches for manufacturing modelling, developing and testing human-machine interaction paradigm fusing human and artificial sensing and operating capabilities. This research will take advantage of cognitive science, interaction models and technologies, mathematical models, computational models, artificial intelligence, sensors and actuators. These systems will be able to largely collect and analyse various forms of data, processes, workflows within the manufacturing to make real-time smart decisions in collaboration with the humans, allowing a smooth and safe human-machine interaction.

[5] Context: it is known from a.o. Erasmus Innovation and Concurrentie monitor that the success of technology is affected for >70% by adaptations of the work organisation.

ANALYTICS FOR DATA-HUMAN INTERACTION (A/P)

Data processing analytics for new data-human interaction challenges of existing manufacturing management systems that are mainly driven by human interaction like Total Preventive Maintenance (TPM) or Failure mode, effects and criticality analysis (FMECA). It is expected that analytics will enhance such systems, avoid weak feedback loops and evolve to RT update including the sharing and detection of good and bad practices.

SKILLS AND KNOW-HOW MANAGEMENT (F/A/P)

Manufacturing skills and know-how is tightly linked to the role of the human workers and the preservation and continuous improvement of them is constantly at risk, both when looking at the present market demand and also in the future. It is required not only to requalify the current generation of workers (but at the same time preserving their know-how in existing manufacturing processes) but also to develop systemic mechanisms to boost the attractiveness of the youngest generation and make them ready to act in manufacturing environments. Acceptance and adoption of new technologies by workers in terms of new skills/capabilities, attitudes, implications for cooperation in (work)teams and adaptive performance.

NEW LEGAL FRAMEWORKS FOR HUMAN WORKERS

The use of advanced technologies (e.g., sensors, cameras, digital assistants, etc.) is creating new challenges for jurisprudence and its practical application. From a legal perspective, new types of contracts, the sharing of data, errors in collaborative production process, new work environments, new skills and roles for the workers, a value of the work provided by humans that is more difficult to recognise and assess, all these play a key role in the definition of the legal framework for workers in Europe.

KNOWLEDGE MANAGEMENT AND SHARING (F/A/P)

The sharing and codifying of knowledge in factories requires the development of models that represent knowledge and the capability to make them available and usable. This is relevant for aspects linked to the knowledge of the production or design process among the various employees working in different corporate functions. In order to exploit fully the non-structured knowledge within factories, it is necessary to develop multidisciplinary research that has references in the ICT, machine learning and in the interaction design sectors, in which various skills in the area – such as psychology and engineering – must converge in models supporting knowledge management.

Research and Innovation priority domains in Human-Centred Manufacturing:

PROTECT

NEW MATERIALS AND NEW TECHNOLOGIES FOR SAFETY IN THE WORKPLACE (F/A)

New materials and new technologies for safety in the workplace based on interaction between the operator and the working environment, in where he is called to operate, can be developed to improve the quality of work and to ease its conditions. Moreover, this priority requires the study and development of new materials, with high mechanical and thermal energy absorption, products (sensors, work clothes) and tools for safety in the workplace.

BIOSENSORS AND MATERIAL FOR HUMANS IN MANUFACTURING (F/A)

Biosensors for health monitoring and early disease detection. Sensorised smart, aesthetic and comfortable materials and surfaces are needed to protect physically and cognitively human workers from demanding complex manufacturing environments.

WORKPLACE DESIGN FOR HEALTH AND SAFETY (F/A/P)

The design of workplaces embedding new interaction technologies, advanced machinery and digital tools entails the need of assessing health and safety aspects beyond the current practice, regulations and standards. In the case of the complex technologies and human-machine systems risk factors that are difficult to discover, have to be evaluated, both during the design of the equipment and in an operational context.

DESIGN OF NEW EQUIPMENT, INTERFACES, PERSONAL PROTECTION DEVICES (F/A/P)

New equipment, interfaces and devices such as smart devices, virtual, mixed or augmented reality, or intelligent assistants requires new methodologies to assess their safety with respect to different classes of workers. This will require fundamental concepts of ergonomics relating to the human-machine interaction to be updated with respects to new equipment to be used. This will require design concepts that are centred on human beings, assessment analyses for different classes of products and workers, as well as specific standard and regulations.

Research and Innovation priority domains in Human-Centred Manufacturing:

SUPPORT

TRAINING ENVIRONMENTS (F,A)

Existing learning environments do not fit the needs of future manufacturing work places. The workers on the shop floor need to be trained with contextualised learning technologies (e.g., augmented and virtual reality). Specific information on problem solving and modelling of the industrial context need to be combined in order to strengthen the ICT knowledge of the workers. These new technologies will support the implementation of a smart learning environment that enables future workers in smart decision-making and smart production processes.

Education and training anticipates and meets the skill requirements of advanced manufacturers, while remaining broadly consistent with long-term projections of labour demand.

ACTION-BASED LEARNING FOR HIGH ADDED-VALUE MANUFACTURING SKILLS (A/P)

Application of the concept of teaching factories for the development of associated training and skills in added-value manufacturing, thus providing employees with cross-disciplinary skills, preparing them to integrate new technologies and giving them the ability to combine knowledge. The aim is to design and plan "hands-on" trainings, in which employees can directly experiment the technologies, in order to ensure an immediate return and applicability in their factories.

HUMAN-CENTRIC DATA AND INFORMATION MODELS AND TOOLS (A)

Current shop floor information management models and tools are based on principles of decades ago and are not adequate to the demands of complex socio-technological environments. Information technology evolution has made possible to develop and use hybrid digital informational content combining multimedia content with augmented reality and 3D modelling and visualisation. Immersive environments can also be explored to provide human worker a more efficient interaction with data and information in the shop floor. Moreover, these new approaches are the basis for effective knowledge management, training and learning.

Research and Innovation priority domains in Human-Centred Manufacturing:

EMPOWER

AUGMENTED HUMANS - UNOBTRUSIVE ASSISTING TECHNOLOGIES FOR WORKPLACE SUPPORT (F/A)

Even though today's smart assistive technological devices are still clumsy and heavy, in the next years, development in soft advanced materials, artificial intelligence, and mechatronics will lead to the creation of natural-to-use and smart skin-tight suits. Such lightweight and flexible devices will enable people with specific impairments to perform tasks they could not accomplish before, by providing outrageous feats of strength (heavy lifting, mobility support) and capabilities to physically interact with the manufacturing surroundings in a shared workspace.

INTUITIVE DIGITAL TOOLS FOR EMPOWERED OPERATORS (A)

This research aims to develop new intuitive digital interfaces that assist operators in different types of manufacturing operations. The tools should significantly facilitate the achievement of quality performance targets and the normal execution of the tasks. Wearable and multimode interaction technologies will boost the convergence between the physical and digital world and enable more seamless workflow, translating into a greater productivity. The results of this research priority are relevant and applicable in many industrial sectors and companies.

NEW PERFORMANCE MANAGEMENT SYSTEMS FOR HUMAN-CENTRED MANUFACTURING ORGANISATION (A)

Decisions on the division of work between human, workers and production technologies have been based so far on productivity/economic criteria. We need to develop performance models that enable a new paradigm in manufacturing, in which the performance measurement is aligned with the complexity of the world. Performance measurement should be multicriteria, including criteria in social, environmental and economic sustainability. In particular, more comprehensive human and social performance criteria should be developed to be weighted with economic criteria. These new performance management systems will be the cornerstone to (re)design factories and manufacturing networks.

HUMAN-MACHINE PROCESS AND SYSTEM DESIGN (A/P)
The increasing degree of interaction between workers and automatic machine requires new methodologies supporting the design of production systems as well as the flexible assignment of tasks. Even if the functions of humans and machines will remain separated, assignment decisions are requested to be flexible and dynamic grounding on the skills of the worker, the characteristics of the products, for example, personalisation, the specific status of the system or the worker (overloading, end of a shift, etc.).
HUMAN-CENTRIC WORK ORGANISATION AND PLANNING (A/P)
Advanced methodologies and tools for flexible and reconfigured work organisation considering the status of the resources and the processes, ergonomic aspects and associated risks, age-appropriate assignments, qualifications and skills of the workers as well as their training, in a way that is integrated with the overall plant organisation and planning.

Legend: F – Fundamental Research, A – Applied Research and Technological Development, P – Pilot implementation and Demonstration.

4.8. Agile manufacturing systems design and management

In the search for differentiation and competitive advantage, manufacturing companies evolved in order to be able to reduce time to market and to better address the needs and preferences of each customer. New strategies, methodologies and tools to design and manage the manufacturing systems of the future will enable unprecedented levels of agility, modularity, flexibility and resilience. These will have to consider the capabilities of new digital and process technologies and enable the implementation of new business models and manufacturing strategies.

Reducing production series and response times requires agile production systems, including: very efficient supply chains, machines, plans and factories easy to reconfigure and multiskilled workers.

At the machine level, robots and additive manufacturing machines represent the perfect model of machines for agile paradigm: high flexibility to produce (or move) any component, regardless its shape, and also easy to reconfigure. Development of these technologies will go hand in hand with agile manufacturing implementation.

The agile manufacturing requires knowledge-driven factories, in which supply chain needs large amounts of data to be efficient, quick reconfiguration of a machine or a plan also needs a lot of data and the management of competences as multiskilled workers also need knowledge management plans and tools.

The complete organisation and roles in the factory had to be switched with knowledge and data used at the bottom of the hierarchy. Knowledge and skills go down in the hierarchy with production data. Social sciences will have to help how to fill the gap in this new knowledge hierarchy amplified by the generation gap with digital natives in figuring. Most of these new functions will be done by new software tools. New digital assets will be mandatory for machines reconfiguration, but also for production optimisation (including maintenance, energy saving, employees competences). At a factory level or at a production line level, new organisational structures appear to share production resources between different enterprises.

Agile production in SMEs pose specific challenges as they need light and efficient tools designed and adapted for their small size and available resources. These tools will have to integrate the technical, organisational and human aspects, thus enabling the appropriation by the operators.

Research and Innovation priority domains in 'Agile manufacturing systems design and management'

GLOBAL MANUFACTURING NETWORKS AND DYNAMIC SUPPLIER NETWORK CONFIGURATION AND MANAGEMENT (A)

Considering globalisation, complexity of supplier networks today and their variability, establishment of supplier networks configuration and management through the adoption of information technologies and enabling network-wide connectivity for coordinating complex interdependencies is required. To exchange data with common tools is mandatory at a worldwide level. Research on this field will be highly usable in integrating new technologies in existing Configuration and Management network systems, including the management of supply chains under uncertainty.

DECISION MAKING TOOLS FOR FLEXIBLE ASSEMBLY LINES RECONFIGURATION (A/P)

New methods to control autonomous production units enabling the reconfiguration of the shop floor for smaller series. Should enable the introduction of flexible production resources such as autonomous mobile manipulators, capable of repositioning themselves on the line and allow the exchange of both parts and grippers between robots. New decision-making methods should support the generation of safe and efficient reconfiguration plans.

ADAPTIVE AND AUTONOMOUS PRODUCTION CONTROL (A)

With more production data available, adaptive control is the next step. New approaches in production monitoring interfaces, including human-in-the-loop, are important so that operators may contribute. Data-driven algorithms that enable autonomous control will improve decision support. In-process sensors for machine diagnostics support decision making both in quality control, availability and in maintenance planning. Unified real-time platforms that will gather data from different sources need to be developed. Research in this field will affect both production sites and networks.

MANUFACTURING SYSTEMS COGNITIVE DIGITAL TWINS (A)

New approaches connecting production system-related data to digital twin systems able to support decision-making are required. There is a need to develop platforms that will combine and compare data from different sites for effective decision-making. Algorithms that will be able to make complex data combinations and that will derive meaningful conclusions are a main challenge.

The result of this research will improve the utilization of resources at a production level, and will need a high level of digital continuity.

NOVEL CONTROL AND SENSES BASED AUTONOMOUS ROBOTIC SYSTEMS (A/P)

Sensor-based reconfiguration of flexible robotic cells integrating multiple sensors such as vision, tactile, RFID, presence sensors are needed to adjust the operation to part types and dimensional variations and to assume complete autonomous robotic systems. Machine learning, dynamic modelling, identification and analysis of robotic systems will be used to simulate their individual components and to predict their kinematic and dynamic behaviour under variable operating conditions. Hybridisation of basic components contributes to guarantee the safe and smooth cooperation with operators and a regulatory and normative development.

INDUSTRIAL ROBOTICS AND DEXTEROUS MANIPULATION TECHNOLOGIES (A/P)
Cooperating robots, investigating approaches to control autonomous and mobile robotic production units can change tasks and position in the shop floor to enable random production flow. Dual arm robotics mimicking the human motion during production. Dexterous and innovative handling and processing devices.
HYBRID PRODUCTION SYSTEMS (A/P)
Wearable or smart devices to augment operators' abilities in cooperation with robot systems, enabling the future manufacturing agile organisation. Augmented reality applications for human operators superimposing information while enhancing the operator safety and acceptance. The ability to interact and to collaborate with human operators will be critical for production flexibility while maintaining cost effectiveness.
ARTIFICIAL INTELLIGENCE (AI) ENABLED ROBOTIC SYSTEMS FOR MANUFACTURING (A/P)
Autonomous manufacturing systems enabled by the incorporation of AI methods for decision-making at the planning and execution stage. Robotic systems will achieve local autonomy, relying on data from their sensors and also from the Industrial Internet. They will also contribute to a collective perception, sharing these data with all other production resources.
LEARNING PROCESSING MACHINES FOR VARIABLE RAW MATERIALS (A)
Learning processing machines should enable smart adjustment to differences in dimension, variety, location on multiproduct processing lines (different types of raw materials), recording and saving the former optimal adjustments, analysis of Big data to optimise adjustments.
TRACEABILITY AND CONNECTIVITY TO HARMONISE INTEGRATED SUPPLY CHAINS (A/P)
On-time delivery and optimisation of raw material delivery, with processing capacities, traceability optimised inventory level route management systems, to harmonise the whole processing lines (efficiency and quality), monitoring the compliance with the requirements throughout the whole supply chain. Analysis of data for the identification of weak points, quality hazard levels and related alarm signals.

QUALITY PLANNING METHODS TO ANTICIPATE THE DETECTION OF NON-CONFORMANCE QUALITY DURING SYSTEM DESIGN (A)

New quality planning methods that anticipate quality issues during the system design stage, by capturing the effect of inter-stage correlations, of fixturing and of non-ideal part variations. The objective is to significantly reduce the likelihood of defects and to minimise costs.

The results of this research are relevant and applicable in many industrial sectors and companies.

DYNAMIC CONTROL OF PRODUCTION QUALITY TARGETS (A)

New methods and tools for dynamic control of production quality target performance during the system lifecycle. The objective is to minimise ramp-up times among system reconfigurations. The results of this research are relevant and applicable in many industrial sectors and companies.

ARTIFICIAL INTELLIGENCE AT THE SHOP FLOOR (A)

Introduction of the equipment and production lines that integrate the self-monitoring, selfassessment, self-learning and self-adjusting concepts with artificial intelligence technologies for production systems at the shop floor level.

IMPLEMENTATION OF ADDITIVE AS PART OF A HYBRID PROCESS (F/A/P)

Optimisation of intelligent process chains requires an increased degree of integration of the different processes in the production chain. The requirements for such an optimised integrated process chain depend on the requirements of the specific applications of the products. Integrated hybrid manufacturing solutions can include:

- Combination of several operations in one single machine,
- Development of a standardised generic interface between different machines/ production units
- Versatile configuration to form an integrated hybrid-manufacturing cell or hybrid manufacturing process chain.

In order to achieve a machine neutral generic solution with high degree of flexibility, a wide involvement of different stakeholders throughout research and industry is needed.

Legend: F – Fundamental Research, A – Applied Research and Technological Development, P – Pilot implementation and Demonstration.

4.9. Circular economy

Circular economy is a paradigm aimed at considering all the actors contributing to the manufacturing chain as inhabitants of a common ecosystem. A major consequence of this metaphor is the need to consider a global picture of the manufacturing ecosystem addressing both specific components and the whole system.

In this scheme, a primary aspect is the role of **materials and energy** and the impact on the environment coming from their consumption. The use of renewable resources should be addressed and, at the same time, energy **recovery** and material **recycling and reuse** have to become essential factors. The research in this area has to address solutions to minimise the costs and environmental impact of manufacturing, namely by reducing the consumption of water, energy and raw materials and shifting to renewable raw materials (e.g., recycled, bio-based, etc.).

Circular flows of the products also need to be considered during their use phase, including repairing and reusing, in which the interactions with users and retailers increasingly shifting their share in the ownership of products and act as service providers by pursuing pay-per use business schemes. These circular product flows have to be accompanied by circular data flows along the whole lifecycle, as described in 3.3.

In this perspective, several manufacturing-related functions such as **maintenance and refurbishing,** assume an important role. Moreover, circular economy is also applied to components instead of being used in whole products, pursuing their reuse in new products and/or new functionalities. The shift towards a circular economy requires the design of longer lifespan products that are easier to repair and **maintain, upgrade and refurbish, with new and enlarged customer services.**

Finally, in a technological perspective, research efforts will need to focus on **processes, technologies, skills and facilities devoted to maintain, repair, upgrade, remanufacture and/or recycle products and their components**, being another major future challenge for Europe's manufacturing. Remanufacturing facilities will operate together within closed-loop supply chains to manage the whole lifecycle of products. New solutions for optimal energy efficiency, recovery, harvesting and storage are needed to enable Europe leadership in resource efficiency and sustainability.

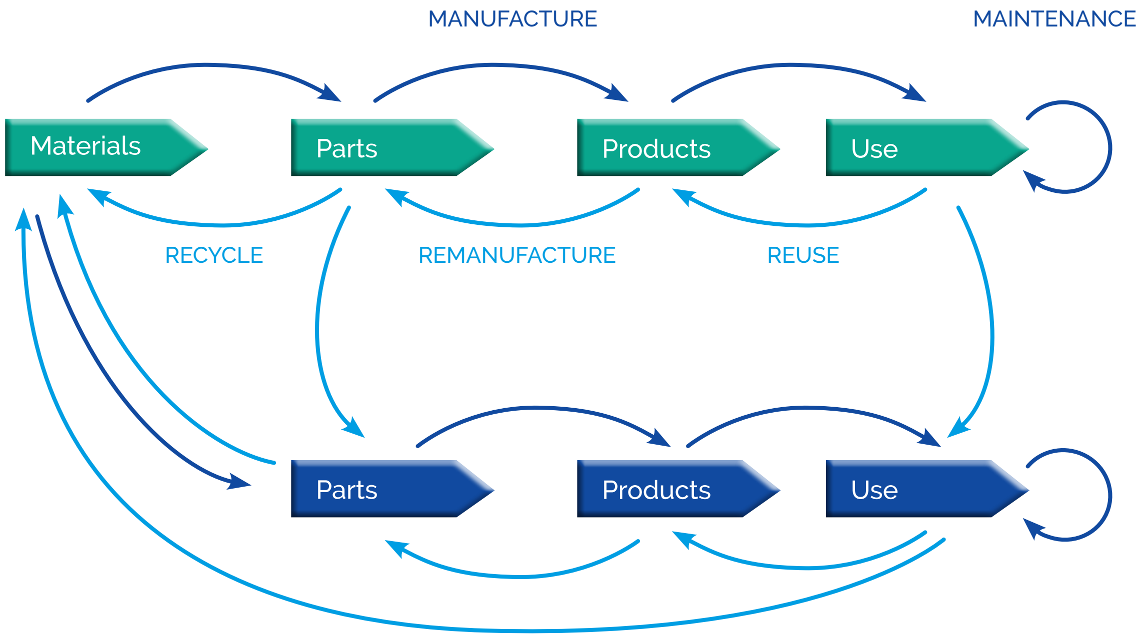


Figure 14 – Circular economy scheme for reuse, remanufacture and recycle.

Research and Innovation priority domains in the circular economy:

MATERIALS AND ENERGY (recovery, recycle, efficiency)

SECONDARY MATERIAL MANAGEMENT (F/A)

Recycled materials are aimed at providing a reduced environmental footprint, although their characteristics, chemical composition and behaviour, could be affected by uncertainty due to the complexity of the separation, collection and recycling processes. Secondary materials have to provide sufficient quality for industry and re-users, as well as safety of toxic residues. New approaches, methodologies and technologies must be addressed to support the qualification, quality control, handling, tracking of recycled materials.

RESILIENT APPROACHES FOR RAW MATERIALS (F/A)

The expected availability of critical materials cannot be guaranteed in the future. For this reason, new technologies must be investigated for sustainable mining as well as for the replacement, using different materials. During mining, challenges are related to equipment, and their respective materials, with higher strength and corrosion resistance to enable operations at higher depths and extreme environments.

MATERIAL RESOURCE EFFICIENCY (F/A/P)

In the future, bioeconomy is important to reduce the amount of materials used, including raw materials and intermediate products, under the paradigm of "doing more or the same with less". Research is required for more efficient manufacturing systems with a lower environmental impact. In this context, new technologies must be explored for sustainable exploitation, use of raw materials and improve sustainability of the supply chains.

NEW SUSTAINABLE MATERIALS, PROCESSES AND BIO-PRODUCTS (A)

The introduction of new sustainable raw materials resulting from other industrial processes and the adaptation of industrial processes and equipment allows them to carry out an intelligent management of materials and waste, enabling their future valuation elsewhere in the value chain. In this context, further research is required to promote industrial symbiosis, consisting in the physical exchanges of materials, energy, water and by-products between industrial facilities, in a way that the waste/byproduct of one facility is used as a resource by another.

Promote the production and use of bio-based products, in alternative to synthetic and non-renewable products. Research needs to rethink the product and process design in order to use biological feedstocks. Also, it requires more sustainable and efficient supply chains, capable of making a better use of the raw materials.

ENERGY-EFFICIENT APPROACHES IN MANUFACTURING (A/P)

Development of manufacturing systems (lines, cells, etc.) and tailored industrial control processes aimed at intelligent management of energy use, efficiency, energy balance and integration of multiple production processes. Manufacturing systems and energy supply systems should be adapted to use energy from renewable sources.

INDUSTRIAL SYMBIOSIS AND ECO-EFFICIENCY OF PRODUCTION PROCESSES (F/A)

Significant technical and methodological breakthroughs and coordinated R&D effort are still required to bring the environmental footprint of the manufacturing industry to a radically deep minimum, ideally at a symbiotic level. Advanced technologies and procedures should be developed and properly combined to provide for:

- minimum inefficiencies of the production systems
- improved efficiency of the industrial processes, designed to maximise the preservation of natural resources
- integration of renewable energy sources in the industrial manufacturing processes
- balanced flows of resources and integration of waste streams as input materials
- valorisation of waste
- rational thermal energy consumption
- recovery of waste heat/cold, thermal energy storage
- energy management

Research and Innovation priority domains in the circular economy:

Design, Refurbish and Remanufacture

PRODUCT AND PROCESS DESIGN FOR MATERIAL REUSE AND RECYCLING (A/P)

The design of a product and the associated process is a fundamental phase to ensure longer lifespan and to define many of the future reuse and recycling options. With this aim in view, new approaches for the design of processes and products (metal, plastics, composites and multi-material) have to be developed in order to provide an easy reuse and recycle of the materials and extend the product lifecycle. The following aspects have to be taken into account:

- design for repair and disassembly
- products can be easily repaired and upgraded for a long-term use
- recycling options for the product, with regulations and recycling guidelines
- energy and resource footprint of the products and the associated manufacturing processes
- energy and resource footprint of the manufacturing system

PROCESS MODELLING AND CONTROL IN DEMANUFACTURING AND REMANUFACTURING (F/A)

The research aims at increasing the knowledge about demanufacturing and remanufacturing process modelling and about cyber-physical systems for process control in circular economy businesses.

The research will develop new knowledge based on an extensive study of the existing research on systems, methods and tools for process modelling and control in the recovery, reuse, and upgrade of functions and materials from industrial waste and post-consumer products.

ADDITIVE-SUBTRACTIVE PROCESSES AND SURFACE TREATMENTS FOR IN-LINE PRODUCT REPAIR AND REMANUFACTURING (A/P)

New methods and tools to enable combined additive-subtractive processes and surface treatments for in-line product repair and remanufacturing. The objective is to significantly increase resource efficiency and to reduce costs. The results of this research are relevant and applicable in many industrial sectors and companies, namely those dealing with a large product portfolio or customisation.

VARIANT PRODUCTION TECHNOLOGIES FOR MANUFACTURING/ REMANUFACTURING SYSTEMS (A/F)

The need to cope with production systems playing different role in the manufacturing/ remanufacturing process chain and the use of alternative technologies must be considered for the production of a given part/product. In this perspective, additive or subtractive processes as well as different technologies within these classes will be interchangeable to cope with the fraction of products to manufacture and remanufacture, the dimension of the lots, etc. Besides process characterisation, assessment and management approaches, the role standards and regulations must also be addressed.

MANUFACTURING SYSTEMS FOR THE RE-USE OF SECONDARY RAW MATERIALS (A/P)

Secondary raw materials are an important source but entails the need of manufacturing processes and systems to be tolerant in terms of some characteristics, e.g., chemical behaviour, mechanical behaviour, chemical composition, purity, among others. The aim of the research is to design manufacturing systems and processes capable of managing material-related uncertainty through robust design or robust control of the process and system parameters. The impact is to reduce waste and costs and to significantly increase resource efficiency. The results of this research are relevant and applicable in many industrial sectors and companies, particularly those dealing with the manufacturing of textiles, electrical and electronic equipment, furniture, vehicles, and buildings and building components.

DIGITALISING AND AUTOMATING DE- AND REMANUFACTURING PROCESSES AND SYSTEMS (A/P)

This research will develop, implement and evaluate highly digitalised, automated and optimised de-manufacturing and remanufacturing technologies that enable the recovery of value, functions and materials of scrapped defective parts and of end of life products.

The objective is to unlock the potential of remanufacturing and make it a viable proposition for many more companies, thus helping to expand the remanufacturing industry and to spread the benefits of remanufacturing across Europe.

NEW TECHNOLOGIES FOR REMANUFACTURING, REFURBISHMENT AND RECYCLING OF PRODUCTS AND COMPONENTS (F/A/P)

This research priority stems from the need to design high-performance processes, machines and robots for the remanufacturing, refurbishment and recycling of products and components. The research will focus on new concepts and technologies as well as cross-fertilisation from other sectors and/or applications. Process-monitoring solutions are relevant to developed adaptive systems that are able to cope with the intrinsic uncertainty of the products to process. The activities can range from the development of advanced physical models to small and large-scale prototypes and pilot plants.

MONITORING OF THE ENERGY FOOTPRINT OF THE PRODUCTS (A/P)

The energy impact of the products is influenced by numerous factors, some of which grounds on the design and engineering phase and have an impact on the production process and technologies and the way they are used. The capability of recovering high-energy materials (e.g. aluminium or semi-conductors) has a significant impact on the overall balance from the energy point of view and therefore requires new methods for the recycling of these materials.

The research will address the development of Cyber Physical Systems (CPSs) capable of gathering and centralising data on energy consumption in general (production of raw materials, production cycle, distribution logistics, conditions of use, disposal and recycle), considering the specific characteristics of the context (monitoring the boundary conditions that may have an impact (e.g., climate, type of use, maintenance, etc.) and characterising of the products in terms of their energy footprint.

TECHNOLOGIES AND TOOLS FOR INTELLIGENT REMANUFACTURING AND RECYCLING SYSTEMS (F/A/P)

The development of technologies, methods and tools to support remanufacturing and recycling systems for products and the recovery of critical materials is essential in the high-tech product manufacturing industry in Europe. The main aim of this research is the development of an integrated and interoperable platform to efficiently design, operate and control advanced remanufacturing and recycling systems for the recovery of components with high added value, such as electronic and mechatronic components of automotive and aeronautical applications.

A multilevel approach should be pursued including both the process level and the system level as well as the possibility to be reconfigured throughout its life cycle to match the requirements of the products and processes. The platform should also be integrated with field data acquisition tools for a continuous improvement of the technologies and the systems.

INNOVATIVE SOLUTIONS FOR SUSTAINABLE AND FLEXIBLE PRODUCT PACKAGING (A/P)

Reducing the environmental footprint of the packaging material is a key aspect of the circular economy. New packaging solutions are necessary for helping to reduce the amount of waste, increase the products shelf life and process efficiency, while providing valuable traceability information for the consumer. Research in this field should focus on new packaging materials and technologies, packaging design as well as adapting the product design, manufacturing process and logistics to cope with the new packaging solutions.

Research and Innovation priority domains in the circular economy:

Maintenance and Reuse

ORGANISATIONAL AND BUSINESS RELATED MODELS FOR MAINTENANCE AND REUSE AND IN A CIRCULAR ECONOMY SCHEME (F/A)

Business models for the “Circular Economy”, based on innovative technologies for the management of the end of life of products and materials within close-loop supply chains. The collection of products at the end of their life has to be considered as well as the associated generation of waste, to maximise their residual value through maintenance, reuse, remanufacturing and recycling. With these approaches, the recovered systems, products, components and materials will re-enter the production cycle. New business models also have to address new architectures for the relationships in the supply chain, aggregation of skills and technologies to improve efficiency, distribution of value among the various actors, aiming at encouraging to close the loop within the supply chain and promoting the new paradigms of the sharing economy.

LIFECYCLE MANAGEMENT TECHNOLOGIES AND APPROACHES FOR PRODUCT MAINTENANCE AND REUSE (A/P)

Models and techniques for the economic, environmental and social performances of product services, production processes and systems based on Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Lifecycle Assessment (S-LCA). These models must embrace the entire lifecycle of the products (from design to production and end of life) to manage the network of actors involved and the associated risks. Supply sustainability metrics have to be addressed to support the decisions for the different product's lifecycle phases and may be used both at the corporate and public policy level, including changes to consumer behaviour from privileging more sustainable products.

The collaboration between private companies and public authorities have to be investigated to improve and optimise the production, maintenance, reuse as well as remanufacturing and recycling flows. The enrichment of LCA and LCC systems based on data shared by different companies must also be considered as well as the use big-data approaches to make these systems more reliable. The social impact of the related job creation in Europe should also be evaluated.

These technologies and approaches are aimed at improving the traceability of the products and components in working conditions and their actual status to estimate the expected "remaining useful life"" (RUL). These calculations should be supported by accelerated tests, simulating the work conditions of the materials in relevant use environments. The knowledge and tools will also support the analysis and identification of viable "second lives" of a product or component (re-use/remanufacture or recycling).

Legend: F – Fundamental Research, A – Applied Research and Technological Development, P – Pilot implementation and Demonstration.

4.10. New business models and logistics networks

Economies and industries permanently search for new business opportunities and new ways of doing business. After the trends of vertical integration of the 70s and 80s and the outsourcing and focus on the core business of the 90s, the pattern has been changing, as the increasingly complex service-product systems require integration of knowledge of a variety of value network actors.

This means that many companies outsourced manufacturing of non-critical components (give up earlier stakes in the value chain), while establishing a more strategic cooperation with components suppliers. These component suppliers are becoming more involved in the actual design and engineering of the component, rather than just supplying the components against specifications. The suppliers hence provide more services to the EOMs rather than just supplying components, such as design, engineering packaging, and recycling services.

On the other hand, manufacturers are also moving closer to their customers, providing not only the finished products but also many services that are associated to the full lifecycle of the product. Companies that used to be suppliers, increasingly become "system-partner". As a result, complex supply networks emerged, aiming at innovation, cost-efficiency and better service. In addition to this, the logistics and supply chains, more specifically distribution and service networks, play an important role as they provide the existing link to the end customers.

At the same time, over the past decades, digitalisation increased in importance, thus enabling new opportunities. All kind of new business models are emerging around "Data" itself as the valuable good. Digitalisation provides the means for complex real-time management and enhances the emergence of data markets in the crossroads of manufacturing value networks and operators of global data flows. Here, digital data platforms and the application programming interfaces (APIs) that integrate data flows have been identified as significant change drivers.

In the future, circular economy will change the currently relatively linear business models of manufacturing industry (as discussed in the section 3.3). The aim of circular economy is to maximise the time span of products, components and materials that are kept in use. It is an endless cycle instead of the traditional take-make-dispose value chain. Manufacturing companies need to rethink their solution designs, and continuously engage with their customers and ecosystem partners in order to move towards circular economy.

To sum up, the need for designing new business models can have several reasons:

- Desire to create new offerings, enter new product and service segments;
- The need to differentiate from the competition;
- The need to react to customer demand and foresee market changes;
- The sudden availability of new technologies, be they digital technologies or others;
- The need to adapt to legislation (e.g., the need to recycle or to ban a specific material);
- The emergence of databased businesses that can have higher impact on GDP growth than the traditional trade in goods. (due to industrial internet solutions and other digital technologies)
- Transition towards circular economy
- Better integration between manufacturing companies and logistics providers.
- A shift away from proprietary solutions to more open solutions.

New industrial ecosystems and dynamic networks will be needed in all sectors of manufacturing. These are efficiently orchestrated by highly integrated IT-Systems that synchronise and optimise all operations and resources for low inventory and delivery in real-time ("just in time", "just in sequence", …), supporting the transition towards the outcome economy. Increase productivity and added value can be achieved by:

- Looking at the full lifecycle of products from customers' demand to end of life including immaterial services in usage phase
- Usage of true data (round about 30 % of data used in the logistic systems are incorrect)
- Learning elements in the models with sensor-based learning (AI) from reality and environment
- Operation with reliable processes (Defects and Quality Deviations make process chains instable)

- Fast reaction on downtime of resources and strategies for maintenance
- Reduction of bureaucratic operations in the administration of supply chains for customised solutions and flexible automation
- Reliability and Resilience in the business models for customised logistics

These points require research for future development of the logistics and supply networks in Europe to support industrial manufacturing. Models of future logistics should be adaptable and should have learning features for self-organisation, optimisation and control as basics for Industry 4.0 and for the exchange of products. In the coming years, these reasons will be drivers for change and for search for new business logics and models. New technologies will offer huge opportunities to adapt and improve the way companies work. Customers and consumers show openness to interact with suppliers and service providers, but they will also become more demanding, especially in terms of delivery times and specific needs. The above-mentioned trends like outcome, sharing and circular economy will become more mainstream.

With new business logics, industrial actors search for increased added value and exploit new technology, including digital knowledge-intensive solutions. It can even be stated that in the novel data-driven business models it is a question of race between industrial and digital companies (IoT, platform or other software companies): which ones will be the first actors in the markets with appropriate market value. This is also a paradigm change: whether smartness is added to physical products or physical products are part of digital solutions.

Research and Innovation priority domains in new business models and logistics networks

INDUSTRIAL PRODUCT-SERVICE SYSTEMS (IPSS) (P/F)

In order to improve competitiveness and sustainability, industries shift their business models, by providing Industrial Product-Service Systems (PPS) increasing the added value of their products. There is a need to develop new approaches that will enable new and existing products to be upgraded to PSS. Developing solutions adaptable to customers' requirements is a major challenge. The results are applicable in many industrial sectors, with the main purpose of increasing their competitiveness and profit. Furthermore, there is a need for paradigm shift of industrial companies. In other words, research should build roadmaps for digital knowledge of intensive product-service-systems. The roadmap would explore whether smartness is added to physical products or physical products are part of digital solutions. Digital platforms and data-driven business models are crucial elements for these novel product-service systems within Industry 4.0.

INNOVATIVE PRODUCT DESIGN AND MANUFACTURING BASED ON THE FRUGAL CONCEPTS, (FUNCTIONAL – ROBUST – USER FRIENDLY – GROWING – AFFORDABLE – LOCAL) SUPPORTED BY ADVANCED ICT PLATFORMS (P)

Modern manufacturing companies are heading towards a new era of frugal innovation. Frugal innovation introduces a new business model, in which low cost and high customer value solutions should be designed and provided taking into consideration the regional customer's requirements. Mobile applications and advanced ICT tools that will support manufacturing companies to capture the needs and preferences of the customers and markets need to be developed.

DEVELOPMENT OF SUSTAINABLE BUSINESS MODELS FOR INDUSTRY 4.0 TECHNOLOGIES (A)

In order to achieve a systematic change in pursuit of sustainable I4.0 manufacturing, a strategic long-term perspective (looking for new techs) and a concrete implementation of the knowledge acquired in practical sustainable business models are needed. Given the opportunities brought forward by the fourth industrial revolution and the challenges that current modes of production and consumption place on nature and society, it is necessary to pursue a new way of conducting business. It is indeed a challenge transforming business models into I4.0 empowered sustainable business models and creating pathways for sustainable technology development. Indeed, no application is viable without identification and assessment of the value for customers, producers and society in general created by the new application of technology and the corresponding production systems.

MANUFACTURING STRATEGIES AND BUSINESS MODELS FOR CIRCULAR ECONOMY (F/A/P)

New manufacturing strategies and business models for circular economy will be implemented, tested and validated in relevant manufacturing environments. Research should also study how to implement and monitor sustainable Closed-loop supply chains that include the returns processes in order to capture additional value and further integrating all supply chain activities. Moreover, the interaction within international supply and production networks will be taken into consideration.

BUSINESS MODELS FOR DISTRIBUTED (DE-CENTRALISED) PRODUCTION AND PRODUCTION AS SERVICE, AIMING AT COMMERCIAL AVAILABILITY OF PILOT LINES AND SPECIFIC MACHINERY (A)

Distributed production of different components of a product followed by an efficient assembly provide opportunities to meet consumers' expectations in terms of product diversity and personalisation in an efficient way. Novel business models are necessary to engage and involve SMEs in the production of large businesses. Suppliers not only provide raw materials and finished products but also transportation, energy, packaging, design, and recycling services. This include telemaintenance, rapid repair at breakdowns, upgrading existing machinery with new sensors, controls, replacement of specific parts of the processing lines. In different industries, including food, high variability and seasonality allow network operators to benefit from sharing, specific equipment between different companies and geographical locations.

AN OPPORTUNISTIC MODEL FOR INTEGRATED MAINTENANCE, QUALITY AND INVENTORY CONTROL (A/P)

The research will aim at increasing the knowledge on dynamic and opportunistic maintenance models, which integrate maintenance, quality and inventory control decisions, to mitigate the impact of maintenance actions on the target service level. Here, data-driven business approaches could provide new opportunities for integrated maintenance, when maintenance planning is done, using market data to schedule maintenance breaks. Adaptive lifecycle management aim at developing methods and tools for business-driven upkeep, maintenance and renewal, and re-use of production assets.

FLEXIBLE PLATFORMS FOR BUSINESS PROCESS MANAGEMENT (A/P)

Business models and logics are largely based on the business process management that is realised using dedicated platforms. The existing solutions for business process management platforms have major shortcomings: (i) aren't flexible nor efficient enough to provide a response (composite service/process) in a near real time; (ii) difficulty in composing a new service using existing services that come from different applications / vendors; (iii) high cost; not affordable for a vast majority of SMEs. The research and technological development should address the above-mentioned limitations, including an improved service-oriented architecture (SOA), to provide an efficient and flexible environment to compose services/ processes from heterogeneous applications in a near real time, and to enable plugand-play process/service capability. These platforms should be prepared to be offered as a service (Platform as a service – PaaS). The results should be relevant for various industrial sectors and companies, especially for manufacturing SMEs that strive towards business process agility in the sharing and the outcome economy. In addition to the platform's technical solution, there is a need to explore cooperative boundary resources, i.e. operation models and practices enabling connected platforms and information flow (smart contracts, block chain technologies, APIs, cybersecurity).

END-TO-END BUSINESS PROCESS AND BUSINESS MODEL OPTIMISATION (A/P)

New methods and approaches for the modelling of (i) business processes sequence at the enterprise level, and (ii) business model (for example. end-to-end dynamic business process) at the enterprise network level, using digital twins, AI, machine learning techniques (e.g., deep neural networks). Based on the above, new methods and approaches for optimising end-to-end business process behaviour and sequence using AI optimisation techniques (e.g., swarm-based algorithms) in terms of an improved match-making, simplified business model and logic ("the shortest path" approach), etc. There is a need for research to address the above-mentioned tasks, followed by the pilot implementation and demonstration on the enterprise network level. The results are relevant for several industrial sectors and manufacturing companies that strive towards a business process agility in the sharing and the outcome economy.

Legend: F – Fundamental Research, A – Applied Research and Technological Development, P – Pilot implementation and Demonstration.

5.

Innovation and Entrepre-neurship

5. INNOVATION AND ENTREPRENEURSHIP

Challenge

Products become more complex and resulting value networks require high levels of digitalisation and interaction between actors. The necessary technology is complex and expensive, especially for SMEs, which generally lack financial resources for high investments in technology. At present, only 36% of the European SMEs use industrial robots, when compared to 74% of larger companies (>1,000 employees). Manufacturing companies, including SMEs, face critical cybersecurity risks, including intellectual property protection, personal data and privacy, and interoperability of systems. Start-ups and SMEs are often not well integrated in the value chain and struggle to survive. The importance of SMEs lies in the fact that they account for 58% of the total employment and 42% of the total value added by the manufacturing sector and that are a key source of innovation. SMEs naturally include start-ups seeking growth and venture capital. According to the last Annual European Venture Capital Report, in 2017, the amount of venture capital investments in manufacturing was of EUR 1.8 billion. This value is two times smaller than the value invested in Fintech or Healthcare. Scaling up manufacturing business requires higher investments, due to required capital intensity of physical machinery.

Thus, a network of ecosystems is required in Europe, in which ideas and enabling technologies can be refined and connected to the markets and where innovators are able to attract investors and acquire venture capital.

Objective

The primary objective is to provide a fruitful environment to create start-ups, accelerate technology uptake in SMEs and to support companies with their transformation focusing on enabling technologies with high manufacturing application potential. This objective is fully in line with the goals of the EU Start-Up and Scale-Up Initiative, the United Nations Sustainable Development Goals, etc.

The aim should be to create ecosystems where manufacturing companies of all sizes can emerge, accelerate, transform, innovate, and produce customised products and services. A relevant target group for business creation, acceleration, and transformation in Europe are the “gazelles”, i.e. companies with >20% annual growth, that account for 60% to 90% of new job creation. These ecosystems should also include organisations such as regional authorities, clusters and industry associations, capital investors, accelerators or incubators, as well as digital innovation hubs.

Sub-objectives include:

- Foster high-growth manufacturing businesses
- Create jobs and value across the manufacturing business
- Unlock new business models and growth in the manufacturing industry

Approach

In order to exploit the full innovation potential in a systematic way, we need to put tools and processes in place to identify and launch the most promising ideas and technologies. Complementing similar activities of the European Commission, a manufacturing dedicated technology radar can be a powerful digital tool for technology foresight and business intelligence. It will help to identify future trends, emerging technologies or disruptive technology combinations that have strong potential to create new added value in EU manufacturing, to bring novel solutions to the market and to foster new value systems.

On top of that, innovation and entrepreneurship programmes should be deployed to create value from this potential. Synergies with manufacturing stakeholders including start-ups and SMEs are required as well as mechanisms to facilitate access to appropriate infrastructures and funding. Essential ingredients to accelerate value creation include:

- enabling people, by providing SMEs and Start-ups with the expertise and skills to deploy new business models and grow,
- enabling innovation, by providing people with knowledge on customer needs and local support to adapt technologies and competencies when capturing new markets, and
- enabling business, by providing SMEs and Start-ups with the financial leverage to deploy ambitious business plans, allowing them to capitalise on knowledge and market access.

A portfolio of relevant activities would include:

Mature & cross-fertilise technologies

- Assessing current maturity and evolving it to integration into a predefined product, process or service, supported by a solid business case
- Combining validated technologies from manufacturing players and applying them to industrial processes to achieve a new innovative product or service

Diffuse and replicate applications

- Disseminating technologies and products over an extended network of industrial partners, innovation hubs and stakeholders
- Replicating innovations throughout Europe and in different business and societal backgrounds

Support Start-ups

- Better exploit knowledge and technologies available in innovation hubs and local ecosystems to create new start-ups
- Incubate new promising manufacturing start-ups to scale up materials and manufacturing processes
- Link start-ups to customers and investors. Help to scale up, by connecting them with larger, established industrial companies that become first users and customers

Support companies to develop faster

- Provide support (finance, skills and business related) to cross the valley of death
- Provide access to industrial platforms and pilot lines to penetrate the market faster

Help companies to transform

- Support the transformation of manufacturing operations and business with new technology
- Pilot new technologies and manufacturing business models, and link to finance to deploy and scale up
- Provide access to technology, industrial platforms and finance

Activate technology transfers centres

- To support the transfer of new manufacturing technologies towards industries and markets and accelerate the innovation value chain
- Support the industrial scale up of new manufacturing technologies by means of dedicated initiatives, well focused on a very few technologies and specific products/services
- Such infrastructures should be linked to other initiatives at regional/ national levels and to specific actions, including EIT manufacturing

In order to have a significant impact on European manufacturing, we need to leverage the existing networks in Europe. Technology providers should play a key role on that, so their transformation through access to knowledge, technologies, customers and finance should be a priority.

6.

Education and Training

Challenge

Talented people are crucial to the future leadership of global high-value manufacturing, but our manufacturing industries face both a lack of available employees and increasing skill gaps. European industry therefore quickly needs to accelerate its ability to engage and empower its best people, regardless of age and background. Adapting the competences of people to the future needs of manufacturing industry and society will be the overarching challenge in the years to come. To handle new, emerging and enabling technologies, lifelong learning and frequent knowledge and skill updates will be the norm, – a challenge as well as an opportunity for many European citizens.

Objective

The primary objective is to develop, across Europe, a skilled workforce through education, reskilling and upskilling people of all ages, gender and origin to ensure that the required competences for future manufacturing are available. Educational programmes must incorporate hands-on activities related to workplace learning, practice-oriented training in learning and teaching factories and innovative digital education solutions, to enable businesses to emerge and grow, while contributing to the major initiatives, such as the New Skills Agenda for Europe, the United Nations Sustainable Development Goals etc. Integral part of this objective is to raise public awareness on future opportunities in the European manufacturing sector and its importance in general in order to attract the best (entrepreneurial) talents in manufacturing.

Sub-Objectives include:

- Societal Awareness
- Industry Involvement
- European focused Skills
- Identification of competences
- Application-driven qualification
- Life-long Learning
- Education On-and Off-the-Job

Approach

The introduction of new technologies into Manufacturing requires always new qualifications and skills. To leverage new solutions and drive the industry forward, reskilling, retraining and developing new qualifications that can be broadly used and recognised are all of paramount importance. The workforce profile is changing fast and companies, universities, training institutions and governments must work together, at a European level and not just at a national level. It is necessary to align formal and informal qualifications, adding flexibility to the curriculums, allowing lifelong learning in all its dimensions, and, more importantly, implementing all of this at the European level. Ensuring that Europe develops its workforce as a whole.

Advanced manufacturing education and training should consider all relevant target groups and their different needs, such as the students at schools, vocational training centers or universities, the already employed technicians, engineers and managers, the engineering trainers themselves, as well as dropouts, unskilled and unemployed people.

Addressing all ages, occupations, cultural origin, gender diversity and levels of qualification. Such a diversity will be catered for with close-to-reality education and training supported by latest technologies, training and educational methods and interactive learning experiences in realistic industrial environments.

Modern, advanced education, training and learning schemes for a continuous delivery of engineering competences are expected to be the necessary vehicles not only for remaining competitive but also for accomplishing sustainable manufacturing and gaining from the added-value created. Innovative education methods, novel knowledge delivery mechanisms and e-learning tools will need to be utilized enabling the long-life education and training of skilled workforce and overcoming the emerging gaps of skills.

The adaptation of the educational content and its delivery mechanisms to the new requirements of knowledge-based manufacturing, the provision of integrated engineering competencies, including a variety of soft skills, as well as the promotion of the innovation and entrepreneurship spirits, need to be pursued in order to achieve innovative and sustainable manufacturing in the future. Accordingly, modern techniques, methods and tools for knowledge communication and skills delivery are required.

Manufacturing education programs should empower European companies with people that are capable of driving manufacturing innovation in the future. Innovative, personalised and industry-driven education solutions for manufacturing are required. Activities should include skilling, upskilling and reskilling, developing tools and systems to make knowledge accessible for everyone, attracting and involving people of all societal levels into manufacturing:

- Development of European Qualification and Training programmes for Manufacturing. These should be led by industry, developed at European level and introduced and adapted to national and regional needs/requirements, ensuring that the future manufacturing workforce is prepared, across Europe, for the challenges ahead.
- Skilling young pupils and students, promoting distributed degree programmes for improved knowledge exchange between countries and talent mobility

- Upskilling professionals as well as reskilling people for the latest technologies and applications, new tasks and professions in future manufacturing.
- Providing senior management courses that equip business professionals in industry with leadership skills and tools needed to cope with more agile and distributed manufacturing organisations.
- Implementing advanced on-the-job learning and qualification systems within the real workplaces or in an environment, which very closely matches that of the workplace, using digital technologies such as VR/AR, real-time shop floor dashboards 8to support rapid learning
- Complementing classroom and digital learning modules with hands-on experience and intense practice-oriented learning opportunities
- Building upon existing experience and accelerate the implementation of emerging training paradigms, such as the Teaching Factory and modular/flexible training, and the use of advanced learning facilities, such as the Learning Factories, at a European level (training networks etc.)
- Developing manufacturing dedicated learning platforms that can combine learning-related facilities, open access to digital learning content and tailor-made learning paths, so connecting learners with each other and linking the learning facilities and content
- Attracting bright people of all backgrounds into manufacturing addressing different target groups to engage society and actively draw top talents to the manufacturing industry
- Develop, in collaboration with Industry, European Qualifications in Manufacturing, that can be easily adapted and transferred to the national and regional level
- Ensure alignment/collaboration between the developed new manufacturing skills and the requirements from Standardisation
- Align industry qualifications and needs with the European Qualifications Framework, hence ensuring a more qualified and mobile workforce within the EU;
- Ensure that the skills development is done before industry needs those skills.

7.

Cooperation with Other Initiatives

7. COOPERATION WITH OTHER INITIATIVES

Background: Manufacturing as a multipurpose enabler for strategic value chains and sectors

Manu*FUTURE* ETP is mainly addressing horizontal, crosscutting and pre-competitive challenges of manufacturing. It does not focus explicitly on the specific manufacturing needs of individual sectors. The objective is to identify and develop multipurpose manufacturing technologies that generate crosscutting impact and spillovers. The focus is on those challenges, which are common to several sectors, and require the payback from more than one application to justify the groundbreaking effort and substantial investments. Manu*FUTURE* ETP's competence and expertise relies on the mastery of upscaling to volume production, whilst ensuring a high-level of quality, flexibility, affordability and regulatory compliance.

These deliverables of advanced manufacturing technologies are needed in a wide range of industrial sectors where they enable product innovation, cost and resource efficiency, quality and volume production. This is obvious for traditional sectors such as automotive, construction, food, packaging or textile. In addition to this, in particular in emerging and future value chains where upscaling and costefficient production is a critical success factor, manufacturing competence is essential to ensure affordability, deployment, safety and impact. For example, this has been the case for photovoltaics and will be the case for battery production. Manufacturing technologies is therefore not only a strategic value chain itself, but is part of future strategic value chains such as clean and connected vehicles and new value networks, e.g., as required by the Circular Economy.

In order to identify the common and crosscutting challenges to be addressed by Manu*FUTURE*, a continuous strategic dialogue with sector-oriented platforms, initiatives and networks is essential and has been promoted by Manu*FUTURE* since the beginning of its activities. In addition, when there is a need for a more intensive exchange, joint actions such as common road mapping, piloting and demonstration actions could help to align priorities, validate the results of manufacturing research in sectorial settings and accelerate the production of innovative products.

Outlook: Manufacturing across clusters and intervention areas in Horizon Europe

With regard to Horizon Europe, Manufacturing is therefore of high relevance for other intervention areas and clusters and share challenges and objectives with them. A close exchange and even strategic cooperation will be necessary with the following areas:

Intervention Area	Manufacturing is a..	Relevance	Potential actions:
4.2 Key Digital Technologies	Manufacturing provides technologies for key components; manufacturing integrates IT components and IT solutions	High	Continuous dialogue on priorities and results, demonstrators and pilot lines, where appropriate
4.3 Advanced Materials	Manufacturing provides industrial process technologies for new materials; manufacturing needs new materials (lightweight, high performance, secondary materials)	High	Continuous dialogue on priorities and results, common action for upscaling of processes for new materials
4.4 Emerging Technologies	Potential user of emerging technologies	Medium	Continuous dialogue on results
4.5 AI and Robotics	Manufacturing uses and deploys AI technologies, partially same community	High	Strategic dialogue on priorities common projects
4.8 Space	Provider of high-performance manufacturing solutions	Low	Dialogue on priorities, potentially validation/ piloting activities
4.9 Circular Industries	Addressing the same challenge; manufacturing complements CE activities of 4.9 beyond materials streams, manufacturing is a user recycled materials	High	Strategic coordination / sharing of activities
4.10 Low-carbon and clean industries	Addressing partially the same challenge, manufacturing is a user of products of energy-intensive industries	Medium	Dialogue on priorities, potentially validation/ piloting activities

Cluster/ Intervention area	Manufacturing is a..	Relevance	Potential actions:
Health			
4.2 Living and working in a health-promoting environment	User of results Provider of improved manufacturing technologies	Low	Dialogue on priorities, results; Validation
Cluster 5: Climate, Mobility, Energy	Provider of scalable manufacturing technologies	High	Dialogue on priorities, pilot lines & demonstrators
4.2.1 Establish a competitive and sustainable European battery value chain	Provider of scalable manufacturing technologies	High	Dialogue on priorities, pilot lines & demonstrators
4.3.1 Achieve global leadership in renewable energy	Provider of scalable manufacturing technologies	High	Dialogue on priorities, pilot lines & demonstrators
4.5 Develop low-carbon and competitive transport solutions	Provider of scalable manufacturing technologies	High	Dialogue on priorities, pilot lines & demonstrators
4.5.4 Enable low-carbon, smart, clean and competitive waterborne transport	Provider of scalable manufacturing technologies	Medium	Dialogue on priorities, pilot lines & demonstrators

Existing strategic cooperation and common challenges with relevant sectors and value chains

It has always been a strategic task of Manu*FUTURE* ETP to maintain fruitful collaboration with several other ETPs. In particular, through the sub-platforms, some specific to sectors, others focused on technology, the cooperation has been established and materialised in joint roadmap activities, projects and other initiatives. The development of the Manu*FUTURE* VISION 2030 document and, naturally, this SRIA follows this approach and relies on the relevant contribution of most of these initiatives. This is crucial to ensure a broad sectorial and technological relevance and impact of the results and also the necessary geographical coverage of Europe's industrial landscape. Therefore, despite the fact that the Manu*FUTURE*'s Platform addresses mainly horizontal challenges and technologies, this SRIA also accommodates some actions and areas identified as appropriate for collaboration and joint developments, such as strategic research and innovation priorities and future of solutions for some key industrial value chains, resulting from the close collaboration between Manu*FUTURE* and the respective initiatives and/or their contribution to relevant societal challenges.

Food for life

1. Developing concepts and demonstration projects on the application of advanced manufacturing systems and industry 4.0 in the food factory, particularly in food processing
A system approach shall be applied, including the multilevel system approach from technical processes on the factory floor to networking and business operations in the upper level, the internal communication between the different levels of the system, the data capture with sensors, the data analyses and visualisation, the planning and simulation, the control and monitoring of food processing operations by using actuators and robots, and collection and transfer of knowledge.

Typical pilot and demonstration actions shall be targeted to the following topics:

- Flexible, efficient, sustainable production of customised food products at costs approaching those of mass production, to meet the diverse and rapidly changing needs of customers and consumers.
- Reduction of unnecessary costs in food processing and supplying through efficient use of resources.
- Reduction of the environmental impact of food processing and packaging.
- More reliable food safety and hygiene and more uniform food quality through better process control and more efficient detection and removal of foreign bodies and other contaminations through smart sensor systems and robotics.
- Simulation, better design and optimisation of food manufacturing and supply processes and plants using concepts such as 'digital twins'
- Identification of the jobs, activities and their limitations and constraints, which can be automated and robotised, leading to the reduction of shortage of labour force, increasing the efficiency of controls, and improved analyses of data and trends.
- More efficient maintenance, prevention of breakdowns, reduction of the down time.

2. *Establishing pilot plant/living lab facilities where food industry applications of advanced manufacturing solutions, systems, mechatronics, robotics, industry 4.0 solutions can be tested.*

The perishable nature of the food material and the need to ensure the compliance to food safety and hygiene requirements represent a specific challenge.

3. *To develop new business models, to make the access of food businesses, particularly SMEs to new machinery, equipment, manufacturing systems easier, to reduce the limitations represented by the cost of investment.*

4. *Establishing a systematic and regular dialogue between the manufacturing and food production, processing communities to enhance better mutual understanding and joint activities.*

5. *Developing training and education programs to enable the adoption of Industry4.0 in the food industry.*

This shall include training and education modules for food industry professionals, management, staff and students of food-related subjects on the basics necessary for the adoption of industry 4.0 in the food chain particularly focus on the food factories. The training shall include the explanation of the enabling functions of the mechatronics, sensors, robots, IoT, Digital Twins, Virtual and Augmented reality, Big Data analyses, Artificial intelligence, Learning Machines, additive manufacturing and other Industry4.0 solutions and the necessary knowledge and skills for using equipment, manufacturing solutions having these functions to manage the current lack of skills and shortage of trained workforce on this area.

Another part of the training program shall be targeted to manufacturing personal and on the typical needs, challenges and problems of the food industry for which advanced manufacturing, mechatronics, industry 4.0, and robotics solutions can be adapted. This part shall include the explanation of the specific nature of food, the consumer requirements and the constraints represented by the perishable nature of food, the need for compliance to food safety and quality requirements, legislation, retailer standards.

6. *Exploring the opportunities for fostering innovations and entrepreneurship by transdisciplinary collaborations.*

Linking manufacturing start-ups to food SMEs. Organising transdisciplinary innovation contests, hackathons by involving food technologists and manufacturing specialists.

Fibres textiles and clothing

Developing joint applied research and demonstration projects in the following areas:

- Flexible, digital and small foot-print manufacturing systems for fashion (micro)factories, design-ateliers and in-store production of personalised fashion goods
- Manufacturing systems for smart textiles and wearables focusing on automation and efficiency in the production and assembly of materials and final products
- Complete manufacturing chain for high-performance fibre-to-composite production focusing on speed, energy-efficiency and flexibility to compete with traditional materials in the transport and construction sectors
- Industry-scale technologies for disassembly, recycling and re-manufacturing of end of life textile and clothing products linked to supply chain solutions supporting traceability and circularity.

Artemis-ia

The Strategic Research Agenda for Electronic Components & Systems, prepared on behalf of Aeneas, ARTEMIS-IA and EPoSS, identified several topics suitable for collaboration with Manu*FUTURE*, especially the ones related with the Challenges identified in the Digital Industry domain:

- Major Challenge 1: Developing digital twins, simulation models for the evaluation of industrial assets at all factory levels and over system or product lifecycles
- Major Challenge 2: Implementing AI and machine learning to detect anomalies or similarities and to optimise parameters
- Major challenge 3: Generalising condition monitoring, to pre-damage warning on-line decisionmaking support and standardisation of communication scenarios to enable big data collection across huge (remote) sites
- Major challenge 4: Developing digital platforms, application development frameworks that integrate sensors/actuators and systems.

Photonics[21]

Industrial photonics is part of Europe's leadership in industrial technology, including machine tools and robotics. It was identified potential for developing joint applied research and demonstration in the following areas:

- Highly versatile tool technology for light-based manufacturing
- Sensors and data integration for prediction and control in digital light-based production
- Materials for photonic production and photon induced material modification

European Construction, built environment and energy efficient building Technology Platform (ECTP)

The ECTP SRIA (is still under development) provides a good source of topics and areas for joint work and collaboration. The following were considered as the most pertinent.

1. *Cost-effective multi-functional and/or prefabricated retrofitting technological packages, integrating RES.*

- Certified, industrialised and market-ready multifunctional (passive & active) prefabricated turnkey package for retrofitting, including RES.
- Lean construction tools, protocols and methodologies for deep energy renovation, including prefabrication or 3D printing allowing both mass production and customisation, with a focus on suitable also for SMEs.

2. *Integration of construction and demolition waste in new constructions and industrial symbiosis.*

- Innovative routes to recycle/upcycle waste and residue streams from one industry to raw material for the others, e.g., use of other sectors' by-products (e.g., steel slag) for the production of new construction materials (e.g., cement or other eco-materials (e.g. geopolimers).
- Validation at real scale of the industrial symbiosis strategies to be applied in the construction sector.

3. *Automation and mass-customisation of design and manufacturing processes.*

- Develop, test and scale up new smart manufacturing processes such as modular off-site construction or prefabrication, 3D printing, generative design, automated Lean measurement

4. *Predictive and integrated maintenance solutions and processes*

- Integration of IoT, sensors, automation systems for smart monitoring and automated maintenance in manufacturing processes and in the built environment.

5. *Bio-based materials and materials capturing CO2*

- New design and manufacturing techniques for innovative prefabs and multifunctional materials (including recycled materials such as CDW), with large-scale demonstration of performance (energy, durability, protection against fire).
- New routes for the (low energy) production of traditional materials (e.g., glass, steel, cement, ceramics), with energy auditing of production processes as part of the overall energy performance assessment.

6. *Multi-modal transport hubs and urban mobility infrastructures*

- Industrialised construction processes for the development of new multimodal transport hubs, minimising the disruptions and impacts to the urban activity and environment.

Industrial value chain for battery production

The EC has identified batteries as one of the strategic value chain. It is evident that competitive and successful set-up of a battery value chains requires state-of-the-art manufacturing technologies to ensure quality improvements, reduce costs, increase throughput, ensure process stability and, finally, deliver sustainable recycling/remanufacturing solutions. In terms of specific challenges, the Roadmap of VDMA Battery production WG identifies handling, automation and joining/connection technologies as urgent research needs. Also "Roadmap for Battery 2030+" has identified manufacturability and recyclability as important areas, which require more attention due to cost, quality and circularity aspects. The following areas were identified at this stage as the most relevant for joint collaboration between the two initiatives and related communities.

1. *Manufacturing technologies for the production of next-generation rechargeable lithium battery cells*

The rechargeable lithium battery market is experiencing a rapid growth and is forecasted to reach the TWh scale between 2025 and 2030. During the same period, some important changes in terms of cell production processes or cell technologies are expected to occur, such as, for example, organic solvent-free electrode coating processes, or the transition from Generation 3 (liquid-electrolyte lithium-ion cells) to Generation 4 (all-solid-state lithium-ion or lithium-metal cells). Such evolutions will have a strong impact on the way lithium battery cells are manufactured, hence new or adapted manufacturing technologies (e.g., process automation, process monitoring and process control) will have to be developed. This will provide the European battery cell industry with competitive advantages in order to upscale cell production capacities in a rapidly evolving market.

2. *Versatile and safe manufacturing technologies for the assembly of rechargeable lithium battery pack*

Electric vehicles (EV) are expected to be the main driver for the development of the rechargeable lithium battery market. For EV applications, battery cells are assembled into modules and then packs. Battery packs are optimised according to the targeted automotive platform and powertrain technology (hybrid, plug-in hybrid, fully electric). One of the challenges for the mass production of battery modules and packs is hence the development of versatile, flexible, modular and safe manufacturing technologies, which can be adapted to several platforms and vehicle designs.

3. *Recycling of batteries*

Developing automated units for sorting, dismantling, recycling end-of-life energy devices such as solar panels or batteries could be another field of interest. Based on an integrated approach of novel materials designed for recycling and sensoring technologies, the ambition would be to trend to a new recycling model based on the health check of devices and components through data collection and analysis, automated device disassembly to components level, investigating the reuse and re-purposing of components whenever possible, automated component cell disassembly to maximise individualised components, development of selective powder recovery technologies and reconditioning processes to active materials that as such are useable again in the same or similar applications.

4. *Automotive Powertrain production*

A CO2 neutral mobility and power generation is essential to achieve the climate goals as signed in the Paris agreement without compromising the needs of the society in terms of affordable mobility and power supply. The affected industries face the need for a significant change in structure and business models. Millions of well-qualified and well-paid jobs depend on a successful transition of these industries. Manufacturing and mechanical industry need to transform to service provider for drivetrain solutions.

Vanguard Initiative 3DP Pilot

The Vanguard 3DP Pilot is a structural and cross-regional (more than 25 EU regions) partnership that aims at accelerating market uptake of 3DP applications in the EU through the development of industryled, transregional demonstration platforms that connect 3DP capabilities and actors (companies, facility centres, universities etc.) that were operating in largely disconnected and fragmented value chains in Europe. The 3DP Pilot supports the emergence and implementation of industry-driven cross-regional demonstration project*s*

Generally speaking, the linkages and complementarities between the 3DP Pilot and ManuFUTURE could be materialised, among others, as follows:

1. Part of the specific 'Research and Innovation Priority domains' listed in the chapter 5 (in the section 'Manufacturing technology and processes') can inspire/ will be directly linked to demonstration and pilot lines currently under development and/or investigation within the 3DP Pilot. This 'uptake' of Manu*FUTURE* Priority domains would be made possible and strengthened by the strong ties that exist between the pilot and the regional authorities as well as with the regional industrial basis (including a particular attention devoted to SMEs). For example, the following aspects are already potentially under investigation in the demo cases (i.e. collaborations areas for technology co-development and deployment):

    - Advancement in Additive Manufacturing (A/P)
    - Added-value Additive Manufacturing (F/A/P)
    - Hybrid processes (A/P)
    - Optimised joining for new materials, structures and manufacturing processes (A)

   For illustrative purposes, in the '3D-Printed large parts and complex shapes (mono-material) through emerging 3DP technologies' demo case, which aims at offering to industrial actors several solutions for investigating/printing large components with complex shapes, one of the solution offered to the network is directly linked to the Kraken Project (H2020 funded project). One of the outcome of this project was a ALL IN ONE 3D, a printing Machine that will develop a disruptive hybrid manufacturing concept. To equip SME and large industries with affordable ALL-IN-ONE machines for the customised design, production/reparation and quality control of functional parts (made in aluminium, thermoset or both materials combined from 0,1m till 20m) through subtractive and novel additive technologies in vast working areas without floor space requirements. This emerging solution will be further elaborated and made for industrial uptake in one of the node of the 3DP Pilot Network (Aitiip, Aragon) with contribution (in terms of design, monitoring) from other nodes of the network (a mapping of the expertise of each facility centre has been conducted).

2. 3DP Pilot activities allow further specification of the industrial needs and the (possible lack of) availability of the requested expertise and equipment to address these needs. On the supply side (facility centres), extensive identification of current and upcoming missing expertise/equipment could help (in the future) feeding into discussions on industrial bottlenecks to be addressed (including in the identification of possible specific topics within the Priority Domains).

2. 3DP Pilot activities allow further specification of the industrial needs and the (possible lack of) availability of the requested expertise and equipment to address these needs. On the supply side (facility centres), extensive identification of current and upcoming missing expertise/equipment could help (in the future) feeding into discussions on industrial bottlenecks to be addressed (including in the identification of possible specific topics within the Priority Domains).

3. Finally, collaborations on aspects such as Education and training (chapter 7) or certification/standards could also be fruitful, relying upon the structural network of the 3DP Pilot and the linkages among facility centres (training providers), SMEs and regional authorities.

Vanguard Initiative Efficient and Sustainable Manufacturing (ESM) Pilot

Within the Vanguard "Efficient and Sustainable Manufacturing (ESM)" pilot project, the "De- and Remanufacturing for Circular Economy Pilot Plant has been conceived and designed, addressing some of the 'Research and Innovation Priority domains' listed in paragraph 5.9 Circular economy and 5.10 New business models and logistics network.

The main concept of the De- and Remanufacturing pilot network is defining the most suitable combination of technologies to retrieve the highest residual value from the post-use phase of products in different industrial areas. The output of this process will be a set of demonstrated integrated technological solutions and circular economy business models to support the implementation of the specific business cases at industrial level.

The cross-regional architecture of the "De- and Remanufacturing" pilot plant currently includes eight Regional Nodes, each of them specialised in a specific testing and demonstration domain acting as an *access point* for manufacturing end-users in the same or in other regions, depending on the specific capabilities and target sectors. According to regional specialisation, pilot nodes will include a set of advanced technologies to support companies' uptake in specific domains, e.g., the remanufacturing of electronics products, recycling of composites, re-use and recycling of batteries.

Currently, the definition of the pilot concept is supported by more than 80 private companies (both SMEs and large companies) at a European level with a cumulative turnover of EUR 27 billion and with some 150,000 employees, 68 universities and RTOs distributed among the involved regions. These actors also declared their intention to co-fund the development of the pilot network.

SusChem - Technology Platform for Sustainable Chemistry

Moving towards 2030, SusChem (www.suschem.org) recognises three overarching and interconnected challenge areas: Circular economy and resource efficiency, low carbon economy towards mitigating climate change, as well as protecting environmental and human health. This requires aligning all actors of the innovation ecosystem on priorities, across value chains, spanning from the most fundamental to the most advanced technological readiness levels and includes several areas suitable for collaboration with ManuFUTURE.

The main research and innovation areas covered within the SusChem SIRA are:

1) Advanced Materials
2) Advanced Processes
3) Enabling Digital Technologies

Horizontal topics essential for the deployment of sustainable chemistry and its contribution to solving global challenges are also addressed (Sustainability assessment innovation; Safe by design approach for chemicals and materials; Building on education and skills capacity in Europe.

THESE PRELIMINARY RESULTS WILL BE FURTHER DEVELOPED WITH THE RESPECTIVE PLATFORMS AND Manu*FUTURE* ETP WILL CHALLENGE OTHER INITIATIVES TO ESTABLISH SIMILAR PROCESSES.

Appendix A.

APPENDIX A

Appendix A. Shortcuts, acceleration lanes and trans-disciplinarity linking basic science and applied research[6]

A.1 Preamble

A.1.1 The best controller is no controller

In 2006, Microsoft hired a former Electronic Arts' employee, Don Mattrick, to lead the division working on the Xbox system, in an attempt to cope with the unexpected success of Nintendo's Wii in that same year, mainly driven by an innovative sensitive controller. In fact, Mattrick had been focusing, for a large part of his professional career, on innovative game controllers. About one year after, Mattrick proposed a challenge to the Xbox team: getting rid of the controller completely! A small team was established within the Xbox division, aiming at exploring technology requirements. Getting rid of the controller would have required being aware of what a user was doing, in a very broad sense.

The main requirements were referring to the motion sensing technologies, thus computer vision was the main addressed target and led to the adoption of a technology developed by the Israeli start-up, PrimeSense. They had been able to use infrared light to sense the environment around the camera and used a second camera to detect colours. Moreover, they had managed to put all these functionalities and technology in a single chip able to sit just behind the camera. Microsoft acquired the license for PrimeSense chip design in 2008 and later bought two more companies working in 3D sensing technology.

Once the technology was there, the work was just about to start. Two Microsoft's researchers, Andrew Blake and Jamie Shotton led a group of researchers (from both basic science and applied research) working on algorithms to recognise the human body without being puzzled by multiple players and rapid movements. Speech recognition was already a topic in Microsoft's fundamental research portfolio, and a game development company, RareStudios, was acquired to deliver a sport game ready to take advantage of the new controller.

Microsoft launched the Kinect in November of 2010, selling 5 millions of units by the end of 2010. Besides being a commercial success for

[6] *Tullio Tolio and Marcello Urgo, 2019*

Microsoft, the Kinect ecosystem of programmers, hackers, researchers and practitioners that started taking advantage of the associated technology, had a disruptive impact on a whole scientific and technical community working in computer vision and interaction. The launch and hacking of the Kinect reduced the cost of motion sensing technology by an order of magnitude, from multiple thousands of dollars to approximately $150. Many scientists were forced to modify and diversify their research fields since the performance of a low-cost device like the Kinect was able to supersede all their pre-existing approaches and methodologies, both theoretical and heuristic. Today, the Kinect has been dismissed as a game controller and has become the central sensor of the Microsoft's Kinect Azure SDK, devoted to building advanced computer vision and speech models[7], leveraging on the cloud and AI infrastructure of the Microsoft Azure Platform.

A.1.2 Fibre lasers grow up for industry

Since Elias Snitzer firstly developed the fibre laser in 1963[8], it needed another 20 years of development to reach its first commercial device entering the market in the late 1980s, based on single-mode diode pumping and capable of emitting a few tens of milliwatts. Nevertheless, besides optics and metrology, the vast majority of laser applications was in the size of watts of optical power, rather than milliwatts. The main factor limiting the development of fibre lasers with higher power was mainly related to the singlemode diode pumping and to the difficulty of composing multiple sources in a single one.

The jump to watt-level fibre-laser output occurred in 1990, when a 4-W Erbium-doped fibre laser was reported exploiting a multi-diode pumping and using the fibre for carry the laser emission[9]. The achievement was due to Valentin P. Gapontsev and Igor Samartsev, two Russian physicists who funded IPG Photonics, one of the main players today in the fibre laser market. Using a side-pumping technique, Gapontsev and Samartsev's unique fibre laser architecture enabled many semiconductor laser diodes to pump through one single-mode fibre, thus exploiting a concept that was first proposed in the 70s[10]. The rush towards higher power was pushed by the advancement in electronics and semiconductors. Modern high-power fibre lasers are pumped by high-power multimode diodes, or by a broad-stripe semiconductor laser diode, or an array of laser diodes.

A further step towards the availability of high-power fibre laser was due to IPG, which was able to develop the first 100-W-class diffraction-limited fibre laser in 2000, by using its basic multifibre side-coupling technology, thus overcoming the previous overheating issues and paving the way for a wide range of industrial applications reaching today up to 2-kW[11]. Since then, many machine tool suppliers started embedding fibre laser sources

[7]https://azure.microsoft.com/en-us/services/kinect-dk/

[8]E. Snitzer and C. J. Koester in Optical Processing of Information, Spartan Books, Baltimore, Md., 1963.

[9] V. Gapontsev et al, Adv. Solid State Lasers Topical Meeting, Tech. Digest, 258, Salt Lake City (1990).

[10]Maurer, U.S Patent 3,808,549 (April 30, 1974).

[11] Valentin Gapontsev, William Krupke. Lasers grow in power, 2002, https://www.laserfocusworld.com/fiber-optics/article/16552610/fiber-lasers-grow-in-power

in their machines, for example Salvagnini in the late 2000s. In a very short time, fibre lasers entered and dominated the market pulling research both fundamental and applied research, supporting the application of fibre laser in multiple and heterogeneous areas. The result were machine tools requiring no warm-up, no laser gases, no mirror realignments and capable of cutting highly reflective materials such as copper, brass, aluminium, and galvanised steel.

A.1.3 A nice theoretical construction

Elliptic curves arose in mathematics in the 19th century, supporting the calculation of elliptic integrals. Today they are among the NSA's recommended cryptographic algorithms and protocols, known as 'Suite B', believed to be the best of the unclassified schemes. The first use of elliptic curves in cryptography was H. W. Lenstra's elliptic curve factoring algorithm, developed in 1984 (but published in 1987[12]) and later on by N. Koblitz[13] and V. Miller in 1984, independently proposing a similar approach based on elliptic curves for discrete log cryptosystems.

Neal Koblitz didn't immediately recognise the commercial potential of his discovery in cryptography, considering it as a nice theoretical construction to study[14]. In fact, the research of a number of theoretic questions concerning elliptic curves was originally pursued mainly for aesthetic reasons, although several concrete applications had been proposed in pseudorandom number generation and cryptography.

A company called Certicom Corporation was the first to commercialise the Elliptic Curve Cryptography (ECC) in March 1997, also offering a consultancy position to Koblitz which he accepted but donated the money to charity organisations. In 2003, the U.S. National Security Agency (NSA) paid Certicom a $25 million licensing fee for 26 patents related to ECC, also encouraging others to use the system by including a key agreement and a signature scheme based on ECC in its 'Suite B' list of recommendations[15].

Since its commercialisation in 1997, the interest of researchers in ECC raised, resulting increased papers published, moving from less than 15 per year (before 1997) to about 50 in 1998, 200 in 2004, more than 300 in 2009 and more than 500 in 2004. Among these, a significant number come from mathematics: less than five before 1992, more than 30 in 1998 (76% of the total), 100 in 2004 (50% of the total), and about 150 in 2018 (28% of the total). Hence, the adoption of ECC pulled a considerable amount of theoretical research addressing algorithms to manage the implementation of ECC, analysis of privacy and security-related issues, further developments to cope with the rapid advances of calculation technologies and computational power.

[12] Lenstra,Jr.,H.W.,Factoringin-tegerswithellipticcurves,Annal-sofMathematics,126(3),649âA S 673,1987

[13] Koblitz, N., Random Curves: Journeys of a Mathematician, Springer, Berlin, 2008

[14] Bauer, Craig P. Secret History: The Story of Cryptology, Boca Raton, FL: CRC Press, 2013

[15] Cryptography, National Security Agency/Central Security Service, http://www.nsa.gov/ia/programs/suiteb_cryptography/index.shtml

A.2 Motivation

A.2.1 New paths for the production of knowledge

The production of knowledge, i.e., the mechanism leading to the synthesis of a complex of ideas, methods, values and norms has been historically structured in terms of a linear process. This process, stemming from the Newtonian approach and being extended to almost all the fields of the scientific practice, defines a phase where the cognitive and theoretical hypotheses are formulated and validated, and a following one where this knowledge is exploited in applications. This traditional research and innovation scheme, labelled as the scientific approach, also led to the dichotomy between basic science and applied research. Applied research is driven by the need of innovation towards a clear and concrete result, while basic science recognises as its only genuine goal the advancement of knowledge for its own sake.

The fast and significant changes affecting research and technology in the last decades has brought this model into significant question[16]. These changes are strictly linked to the transformation that our societal and economic environment are undergoing, and the consequent impact on science and technology:

1. A large part of research activities carried out today are organised and motivated with respect to an application context. The associated results are expected to be useful to someone (industry, government or society)
2. The current dimension and extent of valuable application contexts are such to require trans-disciplinarity, i.e., entailing the need of putting together many specialists coming from different disciplines (mathematics, physics, material science, engineering, etc.) to work in teams in a complex application-oriented environment.
3. Significant research is carried out in a public-private partnership involving funding from both institutional bodies and private companies and investors, whose capability in research spending has significantly increased, when compared to the past decades.
4. The value and accountability of research activities and funding has become more and more relevant, thus public institutions are in need of clear messages to support their decision with respect to recognisable social needs.

[16] *Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., Trow, M. (1994). The new production of knowledge: The dynamics of science and research in contemporary societies. London: Sage.*

A.2.2 Poaching moves to universities

In 2015, when Uber moved to the field of autonomous driving, they were in a desperate look for the right people to establish research and development activities within the company and to boost the development of Uber's autonomous driving system entering the challenge where many others tech giants were already playing. The approach pursued by Uber was not new for a company, it is called *poaching*, i.e., hiring skilled employees from another company, usually a competitor. Companies all over the world behave this way, and the only effective limitations are non-competitive agreements and the level of the salaries. Nevertheless, rather than hiring employees from a competitor, Uber turned its attention to universities. In fact, they just settled a new research centres sharing the same parking lot with the Carnegie Mellon University's Robotics Center (NREC) and hired about 50 people of its staff: technicians, programmers and professors, about one third of the NREC personnel.[17].

Moving from academia to industry is common to many researchers and professors Alexander J. Smola, studied physics at the TUM - Technische Universität München and received a PhD at the Technische Universität Berlin, before entering into a research career working, among others, at the Fraunhofer Geselschaft, Google, and Yahoo Research. In 2014, he was hired as a Professor at the Carnegie Mellon University but, not later than 2017, he joined Amazon where he is now appointed as the Director for Machine Learning.[18].

Also Facebook is acting in a similar but more structured way, through its double affiliation programme, in which allows scientists to continue publishing and avoiding the freezing of their academic career while working at Facebook's research labs. Yaser Ajmal Sheikh, Associate Professor at the Robotic Institute of the Carnegie Mellon University[19], is also the director of the Oculus Research Pittsburgh, a Facebook lab focused on Social VR. Yann LeCun, one of the pioneers in machine learning approaches, is appointed as Silver Professor at the Courant Institute of Mathematical Sciences at New York University but he is also the Vice President and Chief AI Scientist at Facebook.

This phenomenon is significantly increasing in the computer science area, an area in which the US detain the leadership and major tech companies, being enough large to run their own research centres. The scheme is however also moving towards Europe and other research fields.

Similar career stories are those of Zoubin Ghahramani, professor of information engineering at the Cam-bridge University, and today at Uber, Murray Shanahan, professor of cognitive robotics at the Imperial College London, now working at Google's DeepMind unit, and Neil Lawrence, professor of machine learning at the Sheffield University, recruited by Amazon [20].

[17] https://techcrunch com/2015/02/02/uber-opening-robotics-research-facility-in-pitts-burgh-to-build-self-driving-cars/

[18] http://alex.smola.org/

[19] http://www.cs.cmu.edu/ yaser/

[20] https://www.ft.com/con-tent/895caede-4fad-11e8-a7a9-37318e776bab

Besides the decisions related to personal careers and more competitive salaries, the unifying scheme behind these stories is that large companies pursuing research and innovation are extending their R&D teams to involve researchers in basic science. This is a consequence of the transformation research and innovation has undergone in the last years and often matches the need to leverage on basic science to achieve a challenging objective or to bring an emerging technology to maturity. Moreover, they need to move in this direction rapidly, thus, they are looking at hiring basic science researchers from universities.

Despite of the dificulty in applying to public research and funding, this scheme entails some interesting characteristics, specifically the need to facilitate and accelerate the connection between basic science and applied research, which could be implemented in public research policies.

A.2.3 What an impact

Funding agencies from all over the world are increasingly asking for the immediate commercial impact on science grant applications. This is clearly affecting the way research is carried out and research projects are organised.

Winning research projects often consist of very large consortia, involving large corporate groups and focusing on applied research pilots. They are a good approach towards the delivery of impact, i.e., the addressed research is very close to the market uptake, and the involvement of large industrial groups makes the possibility of actually moving towards a real application or implementation more realistic.

This trend is also shifting the focus of researchers on universities towards applications close to be reached and, thus, reasonable rather than innovative. Moreover, this shift is also increasing the gap between basic science and applied research, rather than decreasing it; thus, making the delivery of research results to concrete applications even more difficult.

A fundamental aspect to be considered is that grant applications are requested to demonstrate direct impact of the research they intend to carry out. Although this could be reasonable for innovation actions, when referring to research activities more far away from the application, asking for an identification of a direct impact is the equivalent of asking researchers to concentrate on something different and far from their focus.

The scope of a researcher is focusing on technical aspects relevant within his/her scientific and technological area. Research funding should ask researchers to do their job at best, rather than spreading their time and effort on something different. In fact, grants for this class of research activities should ask a clear and sound description of the scientific and technical scope of the research, rather than asking for figuring out possible future impact of it.

Because of this, paragraphs addressing the impact in grant applications are more and more similar to each other, in a stereotyped scheme showing that, somehow, many sectors and areas will be impacted. At the same time, measuring the real impact is increasingly difficult, since it often refers to a time horizon far beyond the completion of the research project.

To overcome this, **a workprogramme has to define a set of impact regions,** i.e., areas strategic for the EC, and general objectives supporting the declaration of the impact. The workprogramme also **has to provide a set of scientific and technological objectives,** relevant in the perspective of achieving the impact. Given an overall impact direction that addresses energy saving in a specific industrial sector, example objectives could be: designing advanced materials for improving the isolation properties of current equipment complying with the specific requirements of the process/technology; improving the stability of a process through advanced mathematical models supporting its control; concept-proofing new technological principles able to reduce the energy consumption in a specific process of x% compared to the ones currently used.

A general framework for the definition of impact's requirements for research could be:

1. A workprogramme defines a set of impact regions together with a set of scientific and technological desired objectives;
2. Applied research very close to the implementation (high TRL) has to clearly show direct impact within the declared impact regions, both in terms of addressed areas/sectors and quantitative assessment.
3. Cross basic-science/applied-research, less close to the effective implementation, has to declare its impact through a direct connection with one or more of the scientific and technological objectives defined by the workprogramme.
4. The measurements of the achieved impact is provided, for high TLR research, through a review of the pilot implementations developed within the projects; for cross basic-science/applied-research, in terms of the achievement of the scientific and technological objectives.

A.2.4 Supporting cross basic-science/applied-research to accelerate the delivery of innovation

The previous paragraphs highlighted some of the constraints, changes and threats affecting the path leading from basic science to applied research, and to the actual adoption of innovative product/processes/approaches.

Specifically, a summary of the relevant points to be taken into consideration is:

1. The link between basic science and applied research does not stick to the traditional scheme anymore. Thus, the path leading from new theories and ideas to their concrete applications has become more erratic and unpredictable, requiring different framework schemes to be pursued.
2. Private companies, as well as research agencies (e.g., NSF, DARPA), ground their research programmes (or research funding programmes) on very clear objectives to be reached, or on the advancement of an emerging technology. This approach resulted to be successful and effective. Europe, as a collaborative research space, is missing this scheme due to the lack of specific research funding agencies (e.g., linked to the military area). The EC could address this weakness by defining workprogrammes entailing some of these characteristics.
3. In the proposed examples, the acceleration of the delivery of innovation is due to a direct contact between basic science and applied research.
4. The role of private companies at the border between basic science and applied research is becoming more and more relevant. As emergent actors with significant financial capability, these companies are creating research teams mixing basic science and applied researches to control and accelerate the complete research pipeline. Some of the underlying principles beyond this approach could be beneficial if adopted in the EC's research policies.
5. The structuring of research funding programmes is looking at basic science and applied research as two separate entities, leading researchers to work at the border between the two to find difficulty in getting the proper financial support pushing researchers towards more mature research or to stay in basic science. Funding cross basic-science/applied-research endeavours could be beneficial to support this critical phase in the delivery of innovation.

Starting from the three cases presented in the preamble, we describe an informal and not exhaustive set of proposal schemes, linking together basic science and applied research and delivering innovation to the society. We label them as **objective-driven** research (Section A.3), **technology-driven** research (Section A.4) and **upstream-swimming** research (Section A.5).

These sections also contain examples of areas, in which these innovation-delivery schemes are already in place or about to start, driving the way research communities work together and evolve to meet the new characteristics and requirements of the research and innovation ecosystem.

Starting from this listing we also derive a proposal for the implementation of research-policy pilot initiatives to facilitate the link between basic science and applied research, thus supporting, accelerating and ensuring the delivery of the result coming from basic science to concrete results and applications (Sections A.3.1, A.4.1 and A.5.1).

A.3 Objective-driven Research

"BASIC SCIENCE AT THE INTERFACE BETWEEN DIFFERENT DISCIPLINES JOINS APPLIED RESEARCH TO PROPOSE NEW SOLUTIONS AND NEW DEVICES"

The move towards research with an impact has been a significant trend in the last 20 years. Research policies within the EU have moved step-by-step towards the definition of easy-communicable research objectives clearly linked with social and economic needs. This has been implemented in terms of challenges first, lately, missions.

Challenges usually address very general objectives, e.g., effective treatments for cancer, the reduction of environmental impact of human activities, etc. Driven by the need to be easily communicable and understandable by the public opinion, challenges are typically very broad and naturally multidisciplinary, requiring the joint work of different research communities involving both basic science and applied research.

Nevertheless, the definition of challenges doesn't usually provide the structure of complex and interlinked intermediate steps to be addressed by research and innovation, towards the reaching of the overall objectives. Hence, a clear and well-recognisable general objective is not paired with as much as clear structuring of the associated research and innovation objectives. Therefore, the capability to measure the effectiveness of the results and the associated impact is rather difficult.

Missions need to be recognisable and understandable by the public opinion. Unlike challenges, missions are designed to be focused on a much more concrete result and the achievement or failure of a mission should be clear to everybody without detailed explanations.

Current European 'missions' do not have these characteristics since a) they transformed the idea of 'understandable objective', to 'socially relevant objectives', therefore moving the focus from a technical to a social achievement, with more emphasis on the impact than on the quality of the scientific and technological leap, and b) they enlarge the scope of the 'mission' to so broad topics that it becomes difficult to assess the real achievement.

As a consequence of this last point, much emphasis is placed on the measurement of the results of a mission whereas mission achievements should be more on-off and easy to understand and measure. The need to deliver clear and concrete results within broad objectives often drives the research to concentrate on reliable and partially developed approaches and methodologies, causing the pursuing of innovative but risky options less attractive.

As a result, basic science is only partially engaged in this scheme, due to discouraging of the investigation of new solutions or fields, as it would be expected from fundamental research. Thus, in the effort of driving research initiatives towards more accountable and concrete results entails a less significant engagement of fundamental research and the discouraging of possible breakthrough but risky research paths.

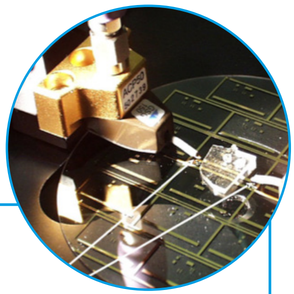
The current definition of both challenges and mission defines the final achievement, but leaves everything else undefined. There is a need to create a structure of steps required to address challenges. Objective- driven research could allow to define these steps and to make explicit the European approach to fulfil the challenges (and the missions). Objective-driven research should strengthen the focus on the scientific and technological achievements, and this is possible since these objectives are introduced within the framework of a challenge or a mission, which has a social impact. Hence, being focused on scientific and technological achievements, it becomes the perfect playground to integrate basic science and applied research.

A.3.1 A proposal for Object-driven Research

The structuring of research and innovation programmes through clear and measurable objectives has a strong and shareable motivation. In particular outlining detailed and concrete objectives to be pursued would increase the effectiveness in the implementation of the research policy as well as its measurability in terms of results and impact.

With this aim, given a high-level result (such as a research challenge or a mission), scientific and techno- logical objectives should be defined in terms of clear scientific and technological advances supporting the achievement of the high-level result. Scientific and technological goals defined in this way tend to be multidisciplinary, since typically different research areas must be involved towards their achievement.

Being very focused when compared to the current definition of challenges and missions, they allow a more significant engagement of basic science. Nevertheless, due to the need of bringing a concrete result at the end of the research and innovation programme, basic science is likely to have the role of addressing the border between different disciplines or across them. Thus, basic science addresses transdisciplinarity, focusing on the development of theories and methodologies to bring together and link results coming from different areas towards the achievement of the objective. In this framework, applied research tries to push in the direction of solutions that have the potential of being scaled up in the future.



Picture 1

EXAMPLE: PERSONALISED, UBIQUITOUS AND AFFORDABLE DIAGNOSES

Following the technological advances in electronics, micro-nano fabrication and the emergence of new materials, the concept of lab-on-a-chip (LOC) and micro total analysis systems (microTAS) has become a concrete objective.

Pilot applications of LOC and microTAS have used in the biomedical, food and environmental sectors and lately in the synthesis of chemicals and nanostructures involving transdisciplinary research in the field of electronics, power sources, sensors, data transmission, microfluidic, micro and nanomanufacturing, ranging from theoretical to pure engineering problems.

The effective adoption of these devices entails the need to solve the current limitations in terms of reliability, integration of multiple analyses on the same device, resistance to environmental conditions, user-friendliness, low consumption and low cost.

The real goal would be to create pilot devices that can be produced at large scale and low costs. This requirement is typical of an object driven research. Basic research is required to work on the integration the various disciplines (biology, electronics and manufacturing) and should work side by side with applied research and engineering to guarantee the possibility of a future scale up.

Many specific object-driven research initiatives could be defined in this area and they have the need of addressing various scientific and technological objectives such as:

1. Improve current techniques and technologies for cell separation, DNA sequencing through nanopores, micro qPCR and micro reactors to enable lower detection levels, increase the efficiency in terms micro-droplets and energy consumption, reduce false positives and negatives.
2. Increase the number of biological operations able to be operated on the same through parallelisation to achieve the detection of hundreds of pathogens in the same microfluidic cartridge.
3. Design devices capable of integrating multiple types of microelectrode and electronics on the same chip.
4. Micro-manufacturing processes able to cope with the required materials and matching the required accuracy of the microfluidic portion of the LOC.
5. Materials and surface treatments to improve the reliability of the LOC and its resistance to environmental disturbances.

Picture 2

EXAMPLE: AUGMENTED HUMANS

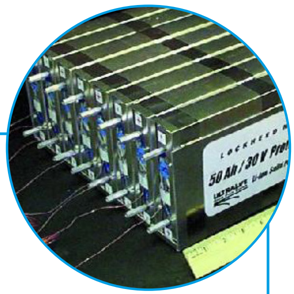
Exoskeletons are one of the key technologies to assist humans in a wide range of applications, such as rehabilitation, daily activities, and industrial operations. Its development as an assistive technology have been very promising, with applications in the restoring of lost limb functions resulting from brain damage, thus allowing injured people to walk again.

The current effective adoption of exoskeletons as an established as- sistive technology for human in different classes of tasks as well as in rehabilitation has to cope with some limitations in the field of comfort, easiness of use, power consumption and adaptability to the specific characteristics of a human being.

Many specific object driven research initiatives could be defined in this area and they have the need of addressing various scientific and technological objectives such as :

1. New actuating devices based on the concept of artificial muscles able to reduce weight, noise, energy consumption and maintenance needs.
2. Models for the prediction of human intention partially indepen- dent from the environmental conditions (e.g., from the payload).
3. Effective control approaches exploiting direct information exchange between the nervous system of the human wearing the exoskeleton and the wearable device.
4. Provide extreme personalisation of the wearable device to improve comfort and effectiveness exploiting 3D scans, multi-physic models and rapid fabrication processes.
5. Predict and take into consideration the neurological and psychological effect of wearing a device that enhance the individual capabilities.

As it can be seen, there is a very strong need to integrate basic science results coming from different disciplines (medicine, neurology, mechanics, manufacturing) in order to create prototype exoskeletons that are compatible with the human nature, with the human feelings and at the same time able to satisfy the need of empowering the individual. Basic science is needed in particular at the interface between medicine and device engineering, neurology and control, physiology and material science, etc.



Picture 3

EXAMPLE: RECONDITIONED POWER

Batteries have a central role to play in Europe's transition from fossil fuels to renewable energy.

In the transport sector, Europe's position as a global leader in the automotive market is being seriously challenged by the transition to electro-mobility in which batteries are estimated to count for up to 40% of the value of the car.

Although supporting the adoption of green energy for mobility, batteries requires a considerable effort (in terms of materials and energy) for their production and, today, have an expected life that is significantly shorter than the cars they are assembled onto.

In this perspective, important research efforts are required to address the monitoring, diagnosis, reconditioning and recycling of the batteries.

With this aim in view, the following scientific and technological objectives need to be addressed:

1. Manufacturing and recycling technologies for Li-Ion batteries.
2. New materials supporting reconditioning and recyclability.
3. Electro-chemical models to assess the aging of batteries and estimate their remaining life and residual performance.
4. Self-healing models and treatments.

All these objective-driven research efforts require the combination of theories and results coming from different disciplines, chemistry, material science, electrical sciences, manufacturing sciences, information sciences but at the same time require applied research to guarantee that the solution proposed will be applicable to millions of cars.

A.4 Technology-driven Research

"NEW ENABLING TECHNOLOGIES START TO GROW EXPONENTIALLY AND ATTRACT BASIC SCIENCE, APPLIED RESEARCH, CAPITAL, APPLICATIONS"

Recent advances in science and technology highlight that game changing research frequently has a specific enabling technology as a core. In the traditional framework, enabling technologies are considered as a transversal enabler affecting different disciplines. Thus, specific initiatives are addressed within a given areas, e.g., manufacturing, health care, energy, etc., addressing the development and application of the required enabling technology in that field.

Nevertheless, the push for the development of **enabling technologies,** mainly supported by large companies, has become a significant driver **aggregating researchers** from different scientific areas, **companies and investors,** around emerging disruptive technologies whose evolution is able to bring very high impact and dramatically change the research and innovation scenario.

The very fast advancement of a technology is able to fill the gap between basic science and applied research, rapidly overcoming the years-long limitation of traditional approaches and short cutting the available theoretical advances with a wide range of effective applications.

Traditional approaches lagging behind for years struggling to achieve the desired maturity, completeness, and effectiveness to move to real applications suddenly become ready and fire a multitude of branches for applied research, patents and final applications. Research communities rapidly grow aggregating researchers from different disciplines and application areas, both fundamental and applied.

In this context, traditional research schemes and institutions are exposed to serious threats:

1. Established basic science communities are disrupted by the fast development of these enabling technologies. Related research becomes less relevant, since the effectiveness of the new technologies is largely more satisfiying than the results coming from existing research achievable in similar time frames.

2. Applied research communities are forced to rapidly move towards the adoption of these new technologies, entailing the need to acquire new knowledge, skill, competences and equipment.

3. The leadership in innovation moves from researchers to the owner of the new technology.

A.4.1 A proposal for Technology-driven Research

Enabling technologies can constitute a concrete and effective criterion in the definition of the targeted research and innovation initiatives, involving all the relevant actors from basic science to applied researchers as well as end users and investors.

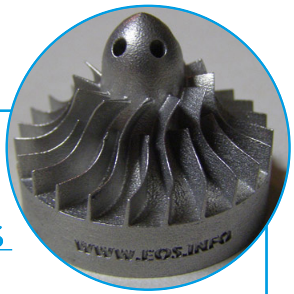
Research policies have to be able to take advantage from these new trends, fostering the creation of aggregations around specific enabling technologies, thus guaranteeing the possibility for basic science and applied researchers belonging to different disciplines and fields to find a new common research space to work together, activating new fast-growing research communities also involving investors and private companies with a significant increase of the expected impact and innovation potential.

Once the ride has started, it is normally self-sustaining, therefore the real goal is to identify in advance the potential new enabling technologies that should be supported in order to initiate the process and to guarantee that this process starts and is developed in Europe.

With this aim, a set of enabling technologies experiencing a rapid and promising development have to be identified. Then specific technology gaps must be identified, limiting the adoption of each technology in one or more application areas. These gaps have to be very concrete in terms of requirements and engagement of research areas. In this scheme, basic science is engaged in the development of theories and methodologies supporting the closing of the identified gaps.

Multidisciplinary is a possibility but not necessarily mandatory. Impact is not to be sought in the medium term because enabling technologies are far reaching and the impact can be immense and diversified in many fields. Therefore, in the medium term the goals should be more related to the improvement of the enabling technology per se. In turn, the improvements in the technology make new and unforeseen applications possible and bring more impact than any reasonable forecast could have identified at the beginning.

EXAMPLE: ADDITIVE MANUFACTURING OF METAL PARTS



Picture 4

Additive manufacturing (AM) processes have been gaining a continuously increasing industrial attention.

Additive produced parts exhibit innovative shapes, complex features and lightweight structures, advanced multi-material products, difficult or even impossible to obtain through conventional technologies.

Nevertheless, ensuring quality and repeatability is a fundamental need to cope with the requirements in sectors like health-care and aerospace.

As a relatively new process, metal AM requires basic science to establish (or re-establish) knowledge supporting the design of products and materials, the modeling of the production process from the mechanical, chemical and thermal point of view, the inter-dependencies and interactions between the part and the process during the fabrication, etc.

To this aim, for example, the following scientific and technological objectives need to be addressed:

1. Modeling of the laser/electron-beam and material interaction.
2. Characterization and mechanical/thermal/chemical behavior of alloys with variable composition in the same part.
3. Process control and prediction approaches exploiting multiple set of in-process observation and theoretical models.

To answer to most of these questions there is a need of combining new basic research together with applied research. The motivation for this endeavor comes from the fact that additive manufacturing is getting now the attention of important users and producers of machines and the self reinforcing mechanism that drives more investment, more research, more results, more applications has started.

The enabling technology therefore moves now very quickly and tend to attract all the researchers that have something to say in the field towards a common goal of making the technology grow and become mature.

A.5 Upstream-swimming Research

"APPLIED RESEARCH IDENTIFIES THE KNOWLEDGE BOTTLENECKS THAT HINDER FOR FUTURE DEVELOPMENTS AND JOINS EFFORT WITH BASIC SCIENCE TO ADDRESS THE PROBLEMATIC AREAS"

The traditional scheme for research and innovation follows the hypothesis that applied research will, sooner or later, take advantage of existing results developed by basic science. The time lapse between the availability of basic science results and their exploitation cannot be estimated and often depends on random events. Although interesting from an epistemological and bizarre perspective, this is probably one of the main sources of delay and risk in the effective exploitation of research results.

Modern information technologies are partially closing this gap, by providing researchers more visibility and powerful search tools. Nevertheless, the knowledge of specific research sub-areas and their classification, typical of a given discipline, is usually not known and difficult to understand even for researchers from different areas. As a matter of fact, matching the requirements of applied research with the offer in terms of results coming from basic science is a complex process often resulting in a failure.

Upstream-swimming research addresses this mechanism, i.e., the propagation of requirements from applied research, backwards (upstream), when compared to the typical research stream, aiming at supporting the matching with existing research results or pulling the development of new results addressing these requirements.

A.5.1 A proposal for Upstream-swimming Research

Swimming upstream in the research flow requires the definition of existing and/or missing connections between an applied research area and basic science capable of providing useful and exploitable results in that area. Existing connections derives from clear affinity in the research topics, e.g., fundamental research in fluid dynamics has a clear match with processes or products exploiting the behaviour of fluids as well as chemistry and thermodynamic is naturally connected with material-related processes like casting and thermal-treatments.

Nevertheless, the extreme specialisation of basic science requires the definition of exact matches between the specific research sub-areas. Missing connections, on the contrary, rely on the concept of cross-fertilisation, i.e., identifying basic science areas (e.g., in mathematics or physics) not directly connected to an applied research field.

For the definition of these connections, the contribution of both basic science and applied researchers is required, aiming at the assessment of detailed links (existing, partially established or only potential) between research fields.

Once these matchings have been mapped and defined, then specific research activities can be carried out with the aim at exploiting these matchings through the development of new theoretical results by replaying to specific requirements or by fitting existing theoretical corpus.

EXAMPLE: MICRO WATERJET TECHNOLOGIES

Picture 5

High precision water-jet cutting has some peculiar characteristics that make it suitable for biomedical applications, e.g., the absence of thermal effects on the target part that is particularly important for materials like Nitinol. Furthermore, the reduction of the water-jet diameter will enable the capability to manufacture new small medical devices in a fast and affordable way.

Today, 0.2 mm is the smallest water-jet diameter achievable in industrial applications while smaller diameters (down to 0.13 mm) are achievable in research laboratories only. Fundamental research is required to support the achievement of a diameter of 0.1 mm in order to extend the use of this technology to implantable devices, stents, etc.

With this aim, the following scientific and technological objectives need to be addressed:

1. Design of new fluid dynamics of the waterjet cutting head abrasive-feeding system for feeding the jetwith finer abrasive powders
2. Mechanical and fluid-dynamic models of multiphase flows with micro particles.
3. Electro-Discharge Machining (EDM) models to support the manufacturing of micro parts.

All these needs cannot be fulfilled by a simple advancement in technology by means of applied research. As the dimension goes to the sub-millimeter the need of understanding of the basic laws regulating the process becomes a critical bottleneck, which cannot be overcome by applied research. Therefore, basic science and applied research should join efforts in this case. However, it is very difficult that basic science researchers come to know that indeed this is an important problem. This way, the probability to come up with a solution in reasonable times is very low. Swimming upstream in this case would allow to work to find a link, to define the problems in the language of basic science of specific fields, to get interest and eventually solutions.

A.6 Pilot Initiatives

A.6.1 Object-driven research

Pilot initiatives aiming at funding object-driven research have to consider the following requirements:

1. Select a challenge socially and/or economically recognisable.
2. Define a structure of specific scientific and technological goals, identifying the path(s) towards reaching the general objective. The achievement of these technological goals must be easily measurable and verifiable.
3. Involve both basic science and applied research in a transdisciplinary approach, thus bringing together theoretical perspective and practical methodologies in a holistic point of view.

The implementation of Object-driven basic science and applied research efforts grounds on the definition of multi-stage calls for proposals consisting of the following:

Step 1

The European Commission, together with existing co-program partnerships, defines a set of concrete and sound scientific and technological goals linked to the selected challenge. These goals could be a prototype demonstrating a given performance, or the viability of a technology, or an approach to be tested in a laboratory experiment, etc. Together with the setting of the goals, the methodologies to measure and validate the achievements are also identified.

Step 2

A call for proposals is published, addressing the identified scientific and technological goals. The requirements for the consortia are to involve both basic science and applied researchers and to provide evidence of the achieved results using the tests and metrics declared by the call for proposals. A multi-stage approach could be considered in the implementation of this step, through a mid-term audit of the results. This could give the possibility to pursue innovative approaches but, at the same time, to provide a clear milestone where only effective approaches can go further in the research and development activities.

A.6.2 Technology-driven research

Pilot initiative aiming at funding technology-driven research have to consider the following requirements:

1. Identify a relevant and strategic enabling technology.
2. Identify a set of constraining gaps for the selected technology.
3. Define a call for proposal addressing one of more of these gaps.
4. Involve basic science to work on theoretical advances to close the existing gaps.

The implementation of Technology-driven basic science and applied research efforts grounds on the definition of multi-stage calls for proposals consisting of the following:

Step 1

The European Commission, together with existing co-program partnerships, defines a set of strategic technologies to be addressed. For each technology, the specific gaps are identified limiting the adoption, the effectiveness or the affordability of the technology. Together with the identification of the gaps, also the methodologies to measure and validate the achievements are identified.

Step 2

A call for proposals is published, addressing the identified technology gaps to be addressed. The requirements for the consortia are to involve both basic science and applied researchers and provide evidence of the achieved results using the tests and metrics declared by the call for proposals. A multi-stage approach could be considered in the implementation of this step, through a mid-term audit of the results. This could give the possibility to pursue innovative approaches but, at the same time, provide a clear milestone where only effective approaches can go further in the research and development activities.

A.6.3 Upstream-Swimming research

Pilot initiatives aiming at funding upstream-swimming research have to consider the following requirements:

1. For a given application area, identify possible existing matching as well as promising overlapping where matching can be pursued. These matchings have to address concrete requirements in the considered application area.
2. The definition of the matchings has to involve experts coming from both applied research in the selected application area and basic science in different connected disciplines.
3. Define an open call for proposal supporting mixed research groups (basic science plus applied research) working on the identified matches.

The implementation of Upstream-swimming basic science and applied research efforts grounds on the definition of multi-stage calls for proposals consisting of the following:

Step 1

A call for proposal is published asking for consortia working on a mapping of the links between basic science and applied research in a given application areas. The requirement for the consortia is to involve experts in the selected application area (applied research) and linked basic science areas. The duration of these initiatives must be short (1 year). The delivered result is a mapping of the matching between applied research in the considered area and basic science. This matching could be existing or showing high potential, i.e., reasonable from the perspective of the research although not yet exploited.

Step 2

Starting from the matching defined in Step 1, an open call for proposals is published funding research addressing the matches. Consortia applying to the open call are free to select the specific set of matches they want to work on. They must involve at least two research groups from two different countries and involve both basic science and applied researchers in relevant areas with respect to the selected matches.

Image directory

Picture 1 – Photograph of the NIST micro microwave oven, National Institute of Standards and Technology, 2011, https://commons.wikimedia.org/wiki/File:Lab-on-a-chip:_Micro_Microwave_(5941045094).jpg

Picture 2 – Apparatus for facilitating walking, running and jumping, patented in 1890, Nicholas Yagn, https://patents.google.com/patent/US420179A/en

Picture 3 – NASA Prototype Lithium-Ion Polymer Battery, NASA Glenn Research Center / Electrochemistry Branch, 2001, https://commons.wikimedia.org/wiki/File:NASA_Lithium_Ion_Polymer_Battery.jpg

Picture 4 – Miniature turbine 3D print from Rapid 2006 in Chicago, Illinois, Bcn0209, https://commons.wikimedia.org/wiki/File:Turbine_(3D_printing).jpg

Picture 5 – Component made by a micro water jet cutter, Andyheißter, 2011, https://commons.wikimedia.org/wiki/File:Werkstueck_Mikrowasserstrahlschneidemaschine.jpg

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