Technology Roadmap

smart
advanced manufacturing

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Contents

1. Introduction

Manufacturing forms the backbone of the economy of many countries in the Modern Economy. It creates jobs, drives innovation, supports trade, and promotes sustainability.
Manufacturing is one of the most important sectors in the global economy. It involves the production of goods using raw materials, machinery, and human labor. Almost everything we use in our daily lives—cars, phones, clothes, and household items—comes from manufacturing.

Manufacturing is a vital area, whose role is increasingly seen as fundamental towards European recovery and sustainable growth. It is a relevant Key Enabling Technology for the current shift towards a 'Competitive Sustainable Globalisation', addressing grand socio-economic and environmental challenges of our times. To give some figures:

- **Contribution to Global GDP**: In 2023, the manufacturing sector added approximately $16,18 trillion to the global economy.
- **Leading Manufacturing Countries**: According to World Bank data (2023), the top manufacturing nations by total production value were China, Japan, Germany, South Korea, Italy, Switzerland, Spain, … all of them countries with high technological levels.
- **Impact on Employment**: The manufacturing sector is a major employer worldwide. For example, in 2023, it accounted for approximately 19% of total employment in industrialised countries such as Germany and Japan.
- **Innovation and Research**: Manufacturing drives a significant portion of global investment in research and development (R&D), fostering technological advancements that benefit multiple industries.
- **Multiplier Effect**: Growth in the manufacturing sector stimulates demand across various supply chains, generating positive spillover effects and boosting productivity in service industries.

These facts underscore the strategic importance of manufacturing as a driver of economic development, technological innovation, and global competitiveness.

SMART is a flexible, industry-driven EUREKA Cluster program in Advanced Manufacturing. SMART aim is to promote collaborative, international & close-to-market R&D&I projects. As a EUREKA Cluster, SMART is grounded in Europe and open to worldwide participants from the Eureka Network.

SMART mission is to boost the competitiveness, growth and attractiveness of the European discrete manufacturing industries through the promotion of R&D&I in an open community of industrial organisations: large industries, SMEs, associations; RTOs and academia.

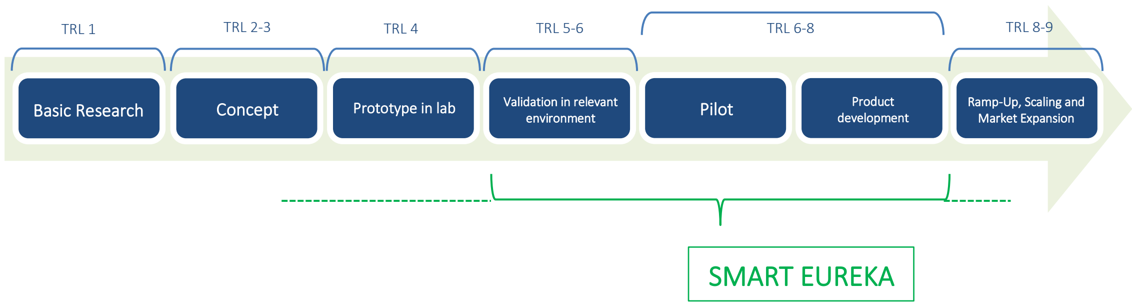
Advanced Manufacturing Technologies are perceived as key players in the new industrial revolution. For example, 3D additive manufacturing permits the production of much smaller batches, making low-cost customised production possible and opens new market niches for innovative SMEs. Tomorrow's companies are expected to use highly efficient processes in terms of energy and raw materials use; they will incorporate recycled and bio-based materials, design products aimed at reuse and disassembly and promote the adoption of sustainable business models based on circular economy, industrial symbiosis and value chain integration.

Furthermore, the new possibilities brought by advances in information technologies and their application in industry, mean that information technologies and knowledge become closely interwoven with industrial equipment and processes, converging towards virtual manufacturing, - or immersive reality. Concepts such as internet of things, cyberphysical systems or cloud computing, are now commonly used in the design and development of new products and services. This will bring important challenges to people involved in manufacturing, who will require an adequate working environment, new tools and lifelong training specifically devised for advanced manufacturing factories.

This **technology roadmap** outlines key areas and developments needed to enhance the competitiveness of Europe's manufacturing industry. It serves as a **guide** rather than an exhaustive list of technologies or domains. The SMART scope covers discrete manufacturing, including any related technologies, challenges, or technical handicaps.

This document is the result of a reflection process carried out within the framework of the SMART Cluster, led by important players from European industry and completed with the contribution from academy and research organisations. The roadmap provides the vision of strategic challenges identified in **several** high impact **industrial sectors**: **Aeronautics, Automotive, Consumer Goods including Pharma and Medical Devices, Capital Goods and Railways, the Energy sector** in which the technologies and new solutions developed within the cluster projects shall be mainly applied as far as MANUFACTURING IS A KEY ISSUE

We also want to emphasize that the SMART Eureka Program focusses on MAINLY Technology Readiness Levels (TRL) from 5 to 8. This means that projects should start with a prototype already validated at a Laboratory level and even in relevant environments and should consider the ramp-up and market exploitation after finishing. Other TRLs might also be considered in certain countries under specific circumstances

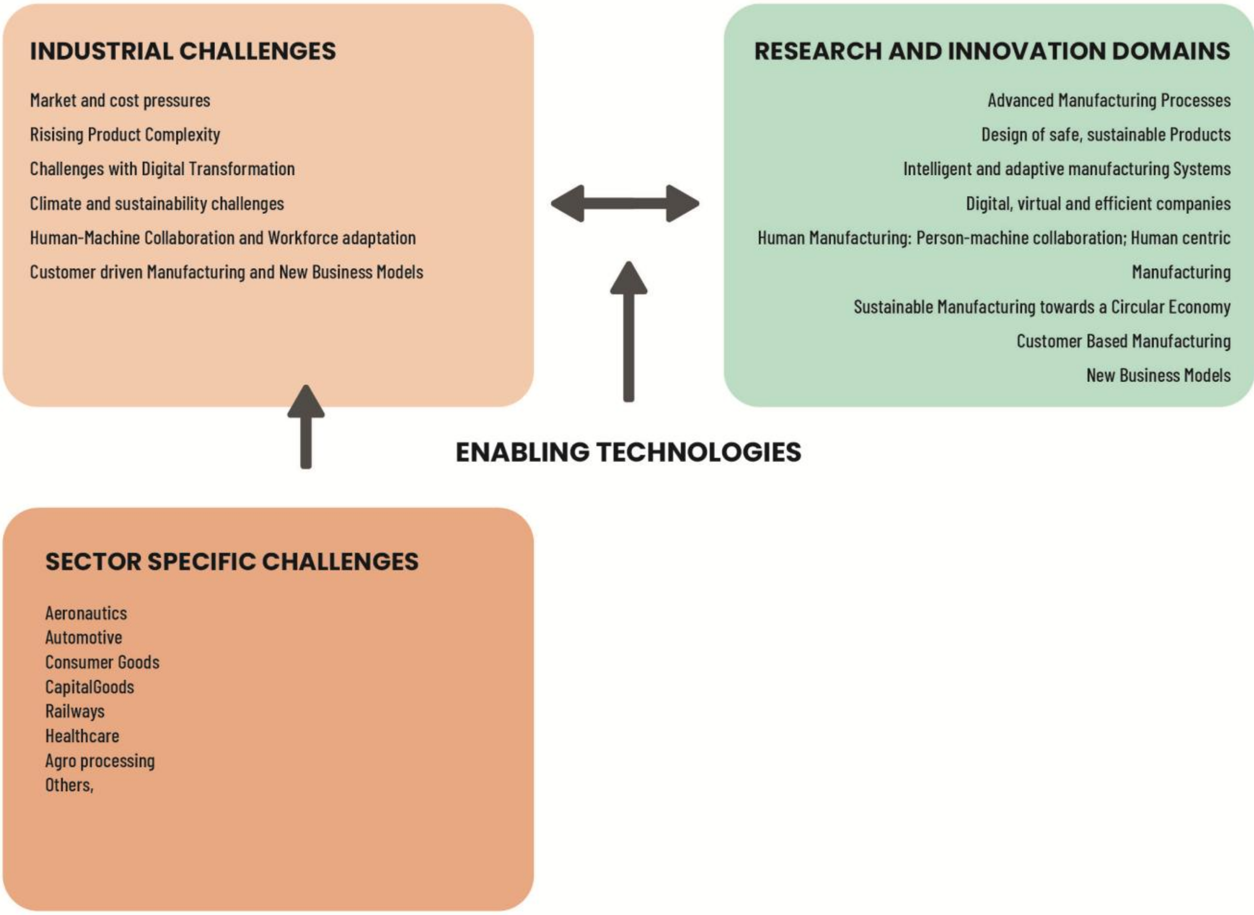


2. Technology Roadmap structure

SMART Technology Roadmap is developed based on two building blocks:

1. The **industrial challenges** which manufacturing companies face, with the gaps, barriers and bottlenecks that they need to overcome in order to improve their competitiveness (Chapter 3)
2. The **research and innovation domains** which should be addressed considering the research topics and impact areas (Chapter 4)

The enabling technologies are some inputs which facilitate the implementation of the **research and innovation domains** which should be approached in order to fulfil the challenges of the different sectors in industry.



3. Industrial challenges to be solved

3.1. Industrial Challenges in Advanced Manufacturing

As SMART is a flexible industry-driven Eureka Cluster program, the technology roadmap must start by analysing what industrial challenges are to be solved.
Industry is facing relevant challenges which we try to analyse and for which technology may have an answer.

The advanced manufacturing sector is evolving rapidly to address the challenges posed by global competition, rising product complexity, digital transformation, and sustainability requirements.
The advanced manufacturing sector keeps on maintaining the challenge of global competition and at the same time faces the need for supply chain resilience and non-equal sustainability requirements globally, creating unlevelled playing field. These challenges can develop contradictory solutions and need to be tackled in a holistic way.

Resilience is crucial when addressing global industrial challenges. Therefore, challenges in the manufacturing sector must be tackled effectively, building upon well-established and proven technological developments.

The digital transformation has become a continuous effort to the manufacturing sector to catch-up with its latest developments. This trend is accelerating particularly with new Artificial Intelligence developments and has created a challenge for advanced manufacturing.
These challenges impact multiple industries, including aeronautics, automotive, consumer goods, capital goods, railways, medical care, energy, agro processing among any others.
These challenges, though nor being exhaustive, are related to:

- Market and Cost Pressures
- Rising product complexity
- Challenges with digital transformation
- Climate and sustainable challenges
- Human-Machine Collaboration and workforce adaptation
- Customer-Driven Manufacturing and New Business Models

3.1.1. Market and Cost Pressures

Manufacturers across all sectors face increasing competition and cost pressures, requiring them to:

- Reduce new product developments cycle time.
- Reduce production costs and lead times.
- Improve supply chain integration and connectivity.
- Implement integrated design and manufacturing processes.
- Develop flexible, adaptive manufacturing and assembly systems.
- Enable mass customisation through modular system integration.
- Develop robust collaborative methodologies for manufacturing systems optimization.
- Create new business models driven by advanced manufacturing.
- Adapt to the production on different physical locations and diverse value chain stakeholders.
- Additional financial pressure due to current tariffs strategy adopted between regions.

3.1.2. Rising Product Complexity

Manufacturing processes must evolve to accommodate increasingly complex products and systems:

- Development of high-precision, zero-defect manufacturing techniques.
- Integration of new materials, including composites, nano-intelligence, and lightweight structures.
- Implementation of advanced metrology and in-process inspection systems.
- Use of simulation, artificial intelligence, and augmented reality in product design.
- The complexity in standardizing and parameterizing methods and tools is a significant challenge.
- Development of new sensors and their integration into the manufacturing processes and products.
- Efficient use of resources and sustainable manufacturing processes.

3.1.3. Challenges with Digital Transformation

The increasing role of digitalisation in manufacturing introduces several challenges:

- Embedding intelligence into product design through data management.
- Ensuring seamless machine connectivity within complex cyber-physical production ecosystems.
- Developing real-time monitoring, auto-tuning, and predictive maintenance systems.
- Enhancing interoperability of equipment and digital twins for virtual manufacturing.
- Data and artificial intelligence intellectual property management.
- Addressing cybersecurity risks associated with data-driven production environments.
- To develop advanced and sustainable production technologies and driving digitized and automated processes.

3.1.4. Climate and Sustainability Challenges

The manufacturing industry must respond to stringent environmental regulations and sustainability goals:

- Harmonizing sustainability challenges with global competition needs.
- Achieving low-carbon, resource-efficient production, to reduce the carbon footprint of manufacturing plants
- Complying with increasingly restrictive CO_2 emissions regulations.
- Enhancing recyclability and reuse of materials.
- Implementing circular economy strategies in production and supply chains.
- Developing sustainable manufacturing systems that reduce energy and material consumption.
- Critical raw materials scarcity
- Energy supply and prices uncertainty

3.1.5. Human-Machine Collaboration and Workforce Adaptation

The increasing role of automation and robotics requires a redefinition of human-machine interaction:

- High costs of implementing digital infrastructure and the lack of standardization on digital platforms
- Enhancing operator roles through intuitive human-machine interfaces.
- Reducing the complexity of reconfiguring and adapting production systems.
- Developing safe and collaborative workspaces with robots and automation systems.
- Integrating artificial intelligence to assist in real-time decision-making.
- Using augmented and virtual reality for operator training and ergonomic improvements.
- Training, re-skilling, up-skilling and retention of workers, engineers and technicians.

3.1.6. Customer-Driven Manufacturing and New Business Models

Modern manufacturing must evolve to incorporate customer-driven innovation:

- Enabling ultra-fast, on-demand production through digital and agile manufacturing systems.
- Enhancing product customisation capabilities through modular and reconfigurable designs.
- Modular product designs and manufacturing means.
- Manufacturing systems adaptation to high variability in throughputs.
- Integrating real-time market intelligence into production decision-making.
- Shifting from product-centric to service-oriented business models.
- Developing manufacturing-as-a-service solutions.

3.2. Some examples of the manufacturing challenges related to specific sectors of application would be:

- Aeronautics:
  - Reduce development cycle time, recurrent costs and lead times through seamless digital design- manufacturing engineering, flexible manufacturing and automation.
  - New materials (composites, ceramics, new light weight metallic alloys, nanocomposites) with concurrent and competitive manufacturing processes. High costs of certification of new materials
  - Transition towards a fully digitalised “virtual factory” model.
  - Lack of recycling solutions applicable to complex products for instance carbon fibre reinforced plastics.
  - Improve operator training through digitalisation and simulation tools.
  - Improve supply chain coordination for increased responsiveness.

- Automotive:
  - Implement energy-efficient production processes and real-time inspection systems.
  - Increase automation and flexibility in production through autonomous robotic networks.
  - Develop image-processing systems for detecting product variations and defects in real-time.
  - Reduce the carbon footprint of production processes through efficient energy management.
  - Implement collaborative robotic networks with embedded intelligence.

    - Implement intelligent systems to optimise planning and scheduling.

- Consumer Goods:
    - Enable high-speed production of customised products with improved value chain integration.
    - Advance CAx systems to integrate geometry, material properties, costs, and manufacturing constraints.
    - Enable adaptable, networked, and knowledge-based digital manufacturing.
    - Incorporate green production chains and sustainable materials.
    - Enhance ergonomic and intuitive interaction between operators and smart manufacturing systems.
    - Improve integration of market feedback into product and process design.

- Capital Goods:
    - Reduce design-to-delivery time while ensuring sustainability and zero-defect production.
    - Implement surface functionalisation techniques for improved performance.
    - Implement cyber-physical systems (CPS) for intelligent decision-making.
    - Adopt "green manufacturing" strategies to minimise waste and energy consumption.
    - Develop symbiotic human-robot collaboration for flexible and efficient production.
    - Develop new business models for manufacturing services and solutions.

- Railways:
    - Increase efficiency in transport-related manufacturing, integrating lightweight materials and modular systems. Use and integration environmentally friendly materials and components reducing noise, track/road damage, ground borne vibrations and similar.
    - Adopt modular manufacturing and automation for cost-effective production
    - Use big data and AI to improve transport efficiency and operational management.
    - Improve lifecycle analysis and recyclability of railway components.
    - Adopt automation for assembly and manufacturing processes, improving safety and efficiency.
    - Increase interoperability to standardise production across different railway networks.

- Healthcare:
    - Scale up production of personalised medical devices and biopharmaceuticals while maintaining cost efficiency.
    - Enable advanced biomanufacturing and 3D printing of medical implants and prosthetics.
    - Integrate AI-driven diagnostics and automated production for pharmaceuticals and medical devices.
    - Reduce waste in pharmaceutical production and transition to biodegradable medical materials.
    - Enable precision robotics in surgery and medical manufacturing to assist human experts.
    - Enable personalised medicine and on-demand biopharmaceutical production.

- **Agro-processing:**
    - Improve production efficiency in food processing, packaging, and machinery for precision farming.
    - Improve precision in agricultural equipment manufacturing and smart farming solution
    - Improve precision farming using IoT, AI, and robotics for enhanced yield prediction and monitoring.
    - Improve sustainable food processing techniques and reduce waste in supply chains.
    - Improve automation in farming machinery and processing plants to optimise labour productivity.
    - Develop smart food supply chain models to enhance traceability and food safety.

3.3. Conclusion

The transformation of the European manufacturing industry is driven by the need for cost efficiency, product complexity, digitalisation, sustainability, and evolving workforce roles. Addressing these industrial challenges requires a coordinated research and innovation effort across multiple enabling technologies, ensuring that manufacturers remain competitive in a rapidly evolving global market.

4. Research and innovation domains

The challenges that the European manufacturing industry faces, as explained in previous chapters, require a coordinated and broad research and development action. The SMART technology roadmap relates to complementary initiatives and agendas at European level focused on advanced manufacturing.

SMART cluster roadmap identifies that the transformation towards more advanced and efficient factories will require a pursuit of a set of research and development priorities along six Research and innovation domains:

1. **Advanced Manufacturing Processes**, including innovative processing techniques for both existing and novel materials or products, with a particular emphasis on digitally driven methods.

2. **Intelligent and Adaptive Manufacturing Systems**, including Innovative Manufacturing equipment at component and system levels, mechatronics, control and monitoring systems

3. **Design safe, sustainable, digital products for** manufacturing Including re-manufacturing.

4. **Digital, Virtual and Efficient Companies**, including Factory design, data collection and management, operation and planning, from real time to long term optimization approaches.

5. **Human Manufacturing,** including:
    a. **Person-Machine Collaboration, including** the enhancement of the role of people in manufacturing
    b. **Human Centric Manufacturing designing systems and processes around workers' needs, safety, and capabilities.**

6. **Sustainable Manufacturing towards a circular economy,** including innovative processes and systems for sustainability in terms of energy and resource consumption and impact on the environment and circular economy business models for the manufacturing industry.

7. **Customer-based Manufacturing**, including involving customers in manufacturing value chain, from product process design to manufacturing associated innovative services, and agile and ultra-fast digitized manufacturing concepts enabling new business models such as manufacturing as a service or on-demand production of custom parts.

8. **New Business Models** taking advantage of the new opportunities for servitization arisen from product´s digitalization and new sustainable related developments.

4.1. Advanced Manufacturing Processes

Advanced manufacturing processes address both conventional and non-conventional production challenges by leveraging cutting-edge technologies. These include fundamental understanding of material-process interactions, intelligent control and automation, additive, subtractive and shaping manufacturing, robotics, photonics, and AI-driven systems.

These technologies enhance productivity, precision, efficiency, and scalability while reducing waste, energy consumption and costs. They enable the zero-defect discrete manufacturing of intricate, high-performance components for many industries and applications such as aerospace, automotive, healthcare, energy, railway, consumer goods and electronics.

There must be a close relationship between advanced manufacturing processes and the production equipment. Manufacturing processes include the production at micro-, meso- and macro- scales, allowing both the creation of microfeatures and high precision components as well as large elements.

Research Topics

The research topics below highlight possible key innovation areas within the SMART Eureka program:

- Advanced material and product processing knowledge-based technologies
  - Precise, science-based material transformation processes with understanding the interactions between materials and process parameters, and the effect on future component's functionality and performance.
  - Understanding process parameters and their impact on material attributes to predict optimal process and product performance.
  - Manufacturing processes that achieve zero defect targets while being resilient to recycled input materials.

- Simulation and modelling, digital twins of manufacturing processes
  - Advanced simulation and modelling techniques providing valuable information on how the material-process-equipment will interact together.

- Mechanisms to structure and modularize the content of digital twins and to extend the content when new kinds of information become available over the entity's lifecycle/complete manufacturing value chain.

- Scalable, reconfigurable, zero-defect and zero-down time manufacturing
  - Zero defect manufacturing solutions for complex, dynamic and variable manufacturing contexts.
  - On-line inspection tools for understanding, monitoring, analysis and real-time fault diagnosis of machine operations and product quality.

- Freeform manufacturing
  - Provide advanced solid freeform fabrication techniques for making cost-effective functional parts and pre-forms.
  - Mass customization and one-of-a-kind production.
  - New inspection technologies for in-line geometric and functional product characterization.

- Less-energy demanding and low environmental impact processes
  - Manufacturing processes with low emissions and optimum use of raw material.
  - Materials combinations and product design for improving assembly and disassembly.
  - Manufacturing processes that minimize the pre- and post-processing needs.

Related Enabling Technologies

- Material Transformation: Involves converting input material into the desired output via thermal, chemical/photochemical, or electrochemical reactions. Processes include heating, cooling, compounding, blending, mixing, straining, dilution, aggregation, annealing, separation, stratification, purification, etc.

- Material Shaping: Covers all processes and equipment used to alter the physical form of the product. This includes forming, casting, molding, pressing, stamping, forging, shearing, extruding, bending, rolling, rotational methods (e.g., spin forming), compression, stretching, cutting, expansion, punching, freeform fabrication, and related techniques.

- Material Removal: Encompasses all processes and equipment used to cut, shape, or refine a product by eliminating excess material. This includes cutting, trimming, shaving, clipping, milling, drilling, grinding, sanding, deburring, punching, and includes micro and nanofabrication as well as traditional material removal techniques.

- Material Addition/Deposition: These methods construct objects in a layer-by-layer fashion, which is recognized for its potential to increase precision, reduce material waste, and minimize the need for extensive post-processing. Includes all additive processes such as Additive Friction Stir Deposition, Laser Direct Energy Deposition, Laser Powder Bed Fusion, Volumetric Additive Manufacturing, and similar techniques.

- Material Finishing & Treatment: Includes all processes and equipment required to prepare the product or component for assembly and/or packaging, and includes cleaning, polishing, painting, coating, lubrication, and like processes. Includes surface treatment and hardening processes such as induction hardening, knurling, shot peening, etc.

Impact areas

Advanced manufacturing processes drive efficiency, innovation, and sustainability but require strategic investments in technology, equipment, skills, and supply chain restructuring. Manufacturing companies that adapt effectively can gain a significant competitive edge, while those that lag risk obsolescence and lower resilience. The adoption of advanced manufacturing processes can significantly transform industrial production across multiple impact areas, including:

- Productivity & Efficiency
  - Higher throughput due to automation, precision, and reduced cycle times.
  - Reduced waste through optimized material usage (e.g., additive manufacturing, laser cutting) and reduction of scraps/reworks.
  - Lower downtime with predictive maintenance and smart manufacturing, through an intensive monitoring and key data acquisition process.

- Cost Structure due to manufacturing processes
  - Initial high investment in advanced machinery (e.g., 3D printing, robotics) but long-term cost savings. At the same time, a reduced labor costs via automation but increased need for skilled technicians.
  - Energy efficiency gains from optimized processes (e.g., smart heating, minimal rework).

- Product Innovation & Customization
  - Complex geometries enabled by additive manufacturing and micro/nano-fabrication.
  - Mass customization through flexible, digital production (e.g., on-demand 3D printing). New surface functionalization through texturing and coating.
  - New material capabilities (e.g., composites, smart materials) due to advanced shaping/removal techniques.
  - Methodologies and strategies for integrating maintenance, production and quality systems into the multi-stage manufacturing processes.

- Quality & Precision
  - Tighter tolerances via laser machining, superfinishing, and AI-driven process control.
  - Fewer defects with real-time monitoring and adaptive machining.
  - Consistent output through closed-loop feedback systems.
  - Quality assurance in the presence of alternative process plans

4.2. Intelligent and Adaptative Manufacturing Systems

Intelligent and Adaptive Manufacturing Systems address innovative manufacturing technologies and equipment with embedded intelligence at the machine, process, and system level. This domain focuses on enhancing manufacturing adaptability, efficiency, reliability, and autonomy through advanced sensing, monitoring, control, and optimization methods.

Research Topics

The following research topics provide examples for key areas for innovation in the SMART Eureka program:

- Real-time Monitoring and Process Control:
  - Advanced sensors and multisensory networks for real-time process monitoring.
  - Algorithms and methods for dynamic process diagnosis and feedback control.
  - Cognitive systems enabling machine self-adaptation and optimization based on real-time data.

- Predictive Maintenance and Machine Lifecycle Optimization:
  - Systems for predictive diagnostics, condition monitoring, and preventive maintenance.
  - AI-based methods for predicting machine component lifetimes and optimizing replacement schedules.
  - Strategies to maximize asset utilization and reliability through lifecycle optimization.

- Intelligent Equipment and Component Integration:
  - Integration of AI-driven cognitive capabilities into manufacturing equipment.
  - Adaptive machinery capable of autonomous adjustments to varying production demands.
  - Development of hybrid models combining theoretical simulations with empirical data.

- Multisensor Fusion and Data-driven Decision Making:
  - Multi-objective optimization algorithms leveraging sensor fusion and real-time analytics.
  - Hybrid models for process adaptation integrating physical simulations and real-time data streams.
  - Self-learning systems that continuously improve operational efficiency through experience-based feedback.

Related Enabling Technologies

- Advanced sensor technology (optical, mechanical, thermal, and acoustic sensors).
- AI and machine learning (especially convolutional neural networks and deep learning).
- Real-time computing, edge processing, and embedded systems.
- Advanced robotics and mechatronics.
- Cyber-physical systems (CPS) and digital twins.
- Cognitive computing and adaptive algorithms.

Impact Areas

- Enhanced Productivity and Efficiency:
  - Increased throughput and reduced cycle times via dynamic real-time optimization.
  - Improved utilization and longevity of manufacturing equipment through predictive maintenance.

- Greater Production Flexibility:
  - Rapid adaptation of production lines to changing market demands and custom orders.
  - Autonomous self-optimization of processes without significant downtime or manual intervention.

- Reduced Operational Costs:
  - Minimized downtime and lower maintenance costs through proactive monitoring and interventions.
  - Optimization of resources leading to reduced waste and improved resource efficiency.

- Improved Quality and Reliability:
  - Reduction in defects and improved consistency in production through precise control and monitoring.
  - Enhanced ability to consistently meet stringent product quality standards.

- Sustainable Manufacturing:
  - Reduced energy consumption and lower environmental impact due to optimized processes and machinery operations.
  - Contribution towards sustainability objectives through efficient resource management and minimized waste.

4.3. Design safe, sustainable and digital products

Research Topics

The following research topics provide examples for key areas for innovation in the SMART Eureka program:

1. **Sustainable product design**
   - Life Cycle Assessment (LCA): Evaluating the environmental impact of a product from cradle to grave.
   - Circular Economy: For example, by designing products for reduce, refurbish, reuse, remanufacturing, recycling, and minimal waste.
   - Eco-friendly Materials: Investigating biodegradable or recyclable materials for product design.
   - Energy Efficiency: Creating products that consume less energy during use and production.

2. **Safe and Sustainable by Product Design**
   - Human Factors and Ergonomics: Ensuring products are safe and comfortable for users.
   - Risk Assessment and Management: Identifying and mitigating potential hazards in product design.
   - Compliance with Safety Standards: Designing products that meet international safety regulations.
   - Cybersecurity: Protecting digital products from cyber threats.

3. **Digital Product Design**
   - User Experience (UX) and User Interface (UI): Enhancing the usability and accessibility of digital products.
   - Digital Sustainability: Reducing the environmental impact of digital products, such as minimizing energy consumption and electronic waste
   - Smart Products and IoT: Designing interconnected devices that improve efficiency and user experience.
   - Data Privacy: Ensuring user data is protected and managed responsibly, reducing challenges while implementing e.g. digital product passports

Related Enabling Technologies

The related enabling technologies would be:

- Advanced Materials: Using materials that are non-toxic, durable, bio based, or recyclable can significantly enhance product safety and sustainability.
- Artificial Intelligence (AI): AI can optimize design processes, identify potential hazards, and suggest improvements to enhance product safety.
- Internet of Things (IoT) can monitor and manage energy usage, track the environmental impact of products, and ensure efficient resource utilization throughout the product lifecycle
- Digital Twin Technology allows designers to simulate and analyze the environmental impact of different design choices before physical production.
- Additive Manufacturing (3D Printing) enables the creation of complex designs with minimal material waste.
- Sustainable Sourcing and Supply Chain Management enhance transparency and traceability in supply chains and ensure that materials are sourced responsibly and sustainably.
- Simulation and Modeling Tools allow designers to predict and analyze the behavior of products under various conditions, helping to identify potential safety issues before production.
- Augmented Reality (AR) and Virtual Reality (VR) allow designers to create more innovative and user-centric designs.
- Lifecycle Assessment (LCA): This method evaluates the environmental impact of a product throughout its lifecycle, from raw material extraction to disposal, ensuring sustainability is considered at every stage.
- Design for Inspectability (DfI): This approach integrates inspection capabilities into the design process, making it easier to detect and address defects during manufacturing.
- Data Analytics: Data-driven design leverages large datasets to inform design decisions, optimize user experiences, and predict future trends. This approach ensures that designs are based on real user needs and behaviors.

Impact areas

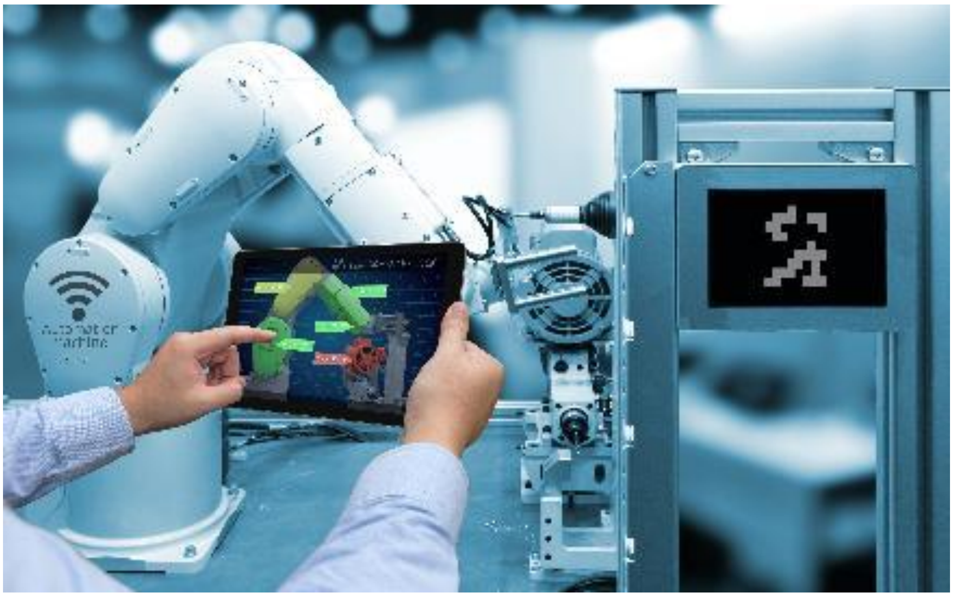
And would have an impact on:

1. Sustainable Product Design:
    - Reduces environmental footprint and operational costs.
    - Enhances market differentiation.
    - Promotes environmental preservation and social responsibility.

2. Safe Product Design:
    - Improves product reliability and user trust.
    - Ensures compliance with safety standards.
    - Enhances public health and ethical considerations.

3. Digital Product Design:
    - Boosts efficiency and innovation through technologies like digital twins.
    - Promotes accessibility and inclusivity.
    - Drives economic growth and cost savings.

4.4. Digital, Virtual and Efficient Companies



The area involves factory design, data collection and management, operation and planning, from real time to long term optimization approaches.

Digital, virtual, and efficient companies leverage industrial IoT, data and AI technologies, digital twins, cloud-edge computing or cybersecurity to support innovation at different levels across their manufacturing ecosystem: the value chain and supply network, the factory and production system, the office and business processes, the factory floor and shop operations, production processes and quality control, the workforce and human-machine collaboration or sustainability management.

Research Topics

The following research topics provide examples for key areas for innovation in the SMART Eureka program:

1. **Smart and data-driven manufacturing**
   - Digital twins and simulation tools for real-time feedback-based design improvements.
   - Automation of inline and offline quality control, predictive maintenance, and production optimization.
   - Self-learning AI models for flexible, demand-driven, and lot-size-one dynamic production scheduling and manufacturing.
   - Integration of industrial and economic data from multiple sources for AI-driven strategy-optimization and decision-making in manufacturing.

2. **Connected and intelligent factory environments**
   - Industrial integration of sensors, edge computing, and digital platforms for factory floor optimization.
   - (interoperable) factory solutions enabling seamless integration of data platforms, production systems and machines, and digital services across manufacturing ecosystems.

3. AI & virtualization for manufacturing operations
   - AI-enhanced virtual twins combining simulation and real-time monitoring for dynamic factory management.
   - Augmented and virtual reality for training, remote supervision, and optimization.
   - AI-based predictive decision-making for resilient and efficient factory operations.
   - AI-driven supply chain intelligence, using (real-time) data for logistics and resource management.

4. Traceable digital manufacturing
   - (near) Real-time end-to-end traceability solutions for tracking tools, production progress, and products within a company and across value chains.
   - Secured solutions ensuring tamper-proof records for product tracking, compliance, and quality control in supply chains.
   - Integration of process monitoring and quality feedback into virtual models or actionable insights for guiding improvements.
   - Solutions and tools for managing increasingly complex and flexible manufacturing systems.

5. Increasing the cybersecurity in manufacturing
   - Industrial cybersecurity supporting the protection manufacturing systems and manufacturing data.
   - AI-powered anomaly detection to support the identification of cyber threats and prevent disruptions.

Related Enabling Technologies

The related enabling technologies woud be:

- Artificial Intelligence & Machine Learning.
- Industrial IoT & Edge Computing.
- Digital Twins & Virtual Simulations.
- Cybersecurity & Blockchain.
- Augmented & Virtual Reality (AR/VR).
- Data and advanced analytics

Impact areas

And would have an impact on:

- Competitivity: enabling manufacturing companies (esp. SMEs) to adopt advanced digital manufacturing technologies with impact on KPIs, e.g.: cost, quality, lead-time, delivery performance, flexibility, sustainability.
- Improved resilience and adaptability of supply chain and manufacturing ecosystems.
- Improved manufacturing operations, sustainability and circular economy integration.
- Agile, demand-driven manufacturing with small lot sizes and mass customization capabilities.
- Ensuring cybersecurity and data-protection in industrial ecosystems.
- Workforce empowerment and support of knowledge intensive activities.
- Enabling "Manufacturing as a Service" business models.

4.5. Human Manufacturing

4.5.1 Person-Machine Collaboration

Research Topics

The following research topics provide examples for key areas for innovation in the SMART Eureka program:

1. **Human-Machine Interaction (HMI) and Interface Design**
   - Improvement on how humans interact with machines, particularly in complex or automated manufacturing settings through intuitive, ergonomic interfaces for operators to control, monitor, and collaborate effectively with machines.
   - Augmented Reality (AR) and Virtual Reality (VR) to provide real-time, immersive feedback to operators, enabling them to visualize complex machine data, maintenance processes, and assembly instructions.
   - Wearables devices, such as exoskeletons, that can assist workers by enhancing their physical capabilities or providing real-time data and communication links.

2. **Collaborative Robotics (Cobots)**
   - Cobots are designed to work alongside human operators, enhancing productivity and safety. Research explores how these robots can assist in assembly, quality control, and complex tasks that require a high degree of dexterity.
   - Safety Systems and Standards to ensure that robots and humans can work safely in close proximity without risking injury.
   - Adaptive Learning and Flexibility allowing robots to learn from human actions and adapt to changes in the manufacturing process or environment.

3. Artificial Intelligence (AI) and Machine Learning
   - Predictive Maintenance: AI algorithms that predict when machines require maintenance, reducing downtime and improving collaboration between operators and machines for efficient workflow.
   - AI-Assisted Decision Making: AI systems that help humans make data-driven decisions by providing insights, recognizing patterns, and offering recommendations.
   - Human-like Perception: Integrating AI into machines to enable them to understand human emotions, gestures, and actions for smoother collaboration.

4. Advanced Manufacturing Systems and Digital Twins
   - Digital Twins are virtual replicas of physical assets, processes, or systems. In manufacturing, they allow real-time simulations and monitoring, helping humans and machines collaborate more effectively.
   - Real-time Process Optimization to continuously monitor and optimize processes, allowing for human operators to intervene only when necessary.
   - Simulation and Training to allow workers to train in safe, controlled environments, improving their interactions with both machines and complex processes.

5. Ergonomics and Human Social Factors
   - Ensuring that the physical interaction between humans and machines is comfortable and sustainable is a significant research area.
   - Task Allocation: Research on which tasks are best suited for humans versus machines to maximize productivity while considering the physical and cognitive capabilities of human workers.
   - Human-Centered Design: Designing machines and robots that are user-friendly, reducing operator fatigue and errors, and ensuring safety.

6. Cyber-Physical Systems (CPS) and Internet of Things (IoT) Integration
   - Integrating IoT with cyber-physical systems enables real-time data sharing between machines and human operators.
   - Edge Computing: Processing data locally on machines rather than relying solely on central servers allows for faster decision-making, which is vital for real-time collaboration.
   - Real-Time Data Analytics: By leveraging data from machines, human operators can get insights to adjust processes, improve quality control, and optimize production.

7. Human-Robot Teaming for Customization and Small-Batch Production
   - Flexible Manufacturing Systems (FMS): Researching systems that allow human-machine teams to easily switch between tasks and adapt to the production of different types of products.
   - Mass Customization: Combining human creativity and expertise with machine precision to create customized products in a cost-effective way.

Related Enabling Technologies

The related enabling technologies would be:

- Robotics Software and Control Systems:
- Force Sensing and Compliance Control for detecting human presence.
- AI algorithms and Machine Learning for Autonomous Operation.
- Augmented & Virtual Reality (AR/VR) and computer vision.
- IoT Sensors and Actuators
- Edge computing
- Digital twins
- Wearable sensors and gadgets

Impact areas

Focus on enhancing the role of people in manufacturing by improving their interaction with software and machines: developing inclusive workplaces, with high interaction capacity, easy to operate and with high personal safety. The research domain includes the following topics:

- Developing functions with cognitive abilities that contribute to a reduction of programming and configuration requirements. There are clear benefits in reducing the time and skill needed to reconfigure and adapt systems to new processes. This includes ICT solutions for the interaction between machines and humans.
- Concepts for smart use of virtual or augmented reality improving operations/process flow visualization systems.
- Friendly and inclusive work environments (noises, emissions, vibrations, loads, repetitive tasks, ergonomics).
- Raising workers' capabilities by means of smart human machine interphase solutions and real time information and analysis.
- Concepts for safe automation of operations and of system integration
- Tools to ease this interaction, such as virtual reality or augmented reality, semantic interfaces adapted to the skills of the momentary operator, and tools to include the knowledge provided by the experience and skills of the operators to the machines will be required. Safety and improved ergonomics will also be critically improved by using these techniques.
- New machine architectures, including collaborative integration of robots for flexibility and multi-processing capabilities.
- Solutions where artificial intelligence is supporting a human to make better decisions in highly controlled environments with low risk tolerance. Improving the understandability of AI decisions is crucial to improve the trust of the human operators on the AI systems.
- Intuitive programming devices, aimed at multimodal tasks and based on new dialogues between humans, machines and robots.
- Ergonomic human-robot collaboration, for human performance improvement and error minimisation. Coexistence of robots integrated with manual processes.
- Human-machine collaboration allows for more personalized products and services that meet individual customer needs.
- Capability to reconfigure industrial robots and their applications with regards to software and hardware. Improvement of usability by the adoption of Intuitive programming

- As manufacturing becomes more automated and integrated with advanced human-machine interactions, industries can scale production, improve quality, and reduce costs, making them more competitive on the global stage.
- Intuitive, effective and safe Interaction with human, other robots and other systems within a production environment.
- One of the fields of improvement required by robots to extend their application beyond handling operations is their kinematics and dynamics, in terms of accuracy, repeatability, dynamic stability, controllability.
- Perception ability adapted to the field of automation, suitable choice of sensing modality, efficient signal and data analysis, as well as generating the maximum information output from the data at hand. Guaranteed safe perception is also a key issue.
- Social implications. While automation and human-machine collaboration may reduce certain jobs, they can create new opportunities for workers to engage in higher-level tasks, leading to a shift in workforce roles. However, there will be a need for reskilling and retraining to prevent job displacement.

4.5.2 Human Centric Manufacturing

Research Topics:

The following research topics provide examples for key areas for innovation in the SMART Eureka program:

- Worker Well-being and Ergonomics:
    - Design of ergonomic and adaptive workstations tailored to individual physical needs.
    - Use of wearable sensors to monitor health, stress, and fatigue levels, ensuring proactive health management.

- Safety Enhancement Technologies:
    - Intelligent systems for real-time hazard identification and proactive risk management.
    - Integration of advanced sensing technologies for accident prevention and worker safety improvements.

- AI-Assisted Decision Support:
    - Systems assisting workers in complex decision-making tasks, balancing human expertise with AI-driven analytics.
    - Transparent AI models to enhance human trust and acceptance.
    - Integration of Large Language Models (LLMs) to facilitate intuitive, context-aware interactions between humans and AI, supporting decision-making processes, troubleshooting, and knowledge retrieval.
    - Exploration of natural language interfaces powered by LLMs to improve worker engagement, reduce cognitive load, and streamline communication within teams.
- Workforce & Skills/Talent
    - Upskilling requirements in robotics, AI, and advanced process control.
    - Human-machine collaboration (cobots, augmented reality-assisted maintenance).

Related Enabling Technologies:

- Wearable health-monitoring technologies.
- Ergonomic simulation and analysis software.
- AI-driven personal assistants for decision support.

Impact Areas:

- Improved worker health, satisfaction, and reduced occupational risks.
- Increased productivity through optimized human-machine interactions.
- Reduced absenteeism and enhanced worker retention.
- Higher quality outputs resulting from improved worker engagement and skill alignment.

4.6. Sustainable Manufacturing Towards a Circular Economy – BOEL, IVO

Implementing circular economy is central to the competitiveness and sustainability of European manufacturing. Circular economy refers to the decoupling of growth from resource consumption through the optimisation of resource flows and recirculation of products, equipment, components and materials in value-chains and production systems.

Further research is required to understand how advanced manufacturing technologies can enable the implementation of circularity and ultimately scale up remanufacturing and recirculation of resources in high impact industrial sectors.

Research Topics

The following research topics provide examples of key areas for innovation in the SMART Eureka program:

1. Digital Material and Product Passports
    - Optimising the recirculation of materials in production systems requires information regarding material composition, optimal productivity, and how-to disassembly and recycle the component or product in question
    - Wide-spread implementation of digital material passports would enable manufacturers to more easily recover, re-use and recycle valuable resources.

2. Scaling up Industrial Symbiosis
    - Real-time digital marketplaces for production waste could enable diverse forms of industrial symbiosis (by-product exchanges and resource sharing) across industries
    - Linking up Industry 4.0 systems and connected technologies is central to creating real-time digital marketplaces for waste
    - Scaling up implementation of real-time digital marketplaces for waste requires overcoming challenges associated with inter-operability, standardisation, and cyber security.

3. **Circular Metrics and Mapping Tools for Manufacturers**
   - Sector-overarching methods to gauge and compare the actual progress made in implementing circularity across companies within an industry and between industries
   - Measuring progress in the circular economy requires standardised frameworks and indicators based on life-cycle analysis, which takes into consideration resource flows from raw material extraction, design, distribution and multiple use-phases to ultimate disposal at end of life
   - New measurement frameworks and digital tools, including AI, are needed which can be seamlessly integrated into manufacturers' existing reporting and monitoring frameworks.

4. **Innovative processes and systems for circularity and resource efficiency in terms of energy and resources**
   - Design aimed at manufacturing, assembly, disassembly, remanufacturing, reuse and recycling
   - Operational excellence in all layers of the organisation.
   - Recyclability of new materials
   - Reduction of the carbon footprint of production processes based on complete life cycle information
   - Lower consumption of materials, water, energy, lubricants, etc. and reduction of generated waste.

Enabling Technologies

From digitisation including AI and automation to IoT and additive manufacturing - advanced manufacturing technologies are key enablers of circular value chains. Implementing circularity is a central pillar of sustainable manufacturing alongside industrial energy efficiency, which together can deliver low emissions and clean growth.

Circular economy enablers include, but are not limited to:

- product-service systems
- eco-design and life cycle optimisation
- re-use, repair and remanufacturing
- resource recovery and recycling
- industrial symbiosis
- operational and cyber security

Expected Impact

Development in this area will lead to:

- Circular value chains that reduce waste, increase resilience, and promote manufacturing competitiveness
- Near net zero emissions from the manufacturing industry
- Clean growth decoupled from increased use of primary resources.

4.7. Customer-based Manufacturing

Involving customers in the manufacturing value chain will increase in importance, from product process design to manufacturing associated innovative services.

Customer-based Manufacturing involves integrating customers as active participants throughout the manufacturing value chain, from product and process design and real-time feedback loops to on-demand and modular production, leveraging digital tools, data analytics, and sustainable design to deliver personalized, high-value products and services.

Research Topics

The following research topics provide examples for key areas for innovation in the SMART Eureka program:

- Flexible and adaptive manufacturing systems (demand driven manufacturing) that can quickly adjust production to changing customer demands and market preferences.
- Personalized manufacturing through data-driven and AI customization/personalization of products by customers, enabling mass customization with high efficiency.
- Tools and frameworks to ensure quality and reliability in mass-manufacturing of bespoke products.
- Platforms and solutions supporting on-demand, decentralized, and connected manufacturing models that enable localized production with short lead times (Manufacturing as a Service).
- Modular production systems enabling to reconfigure machines and processes for efficient adaptation to customer demands.
- Scalable manufacturing services for maintenance, upgrades, and sustainable end-of-life solutions for personalized products.

Related Enabling Technologies

The related enabling technologies would be:

- Additive manufacturing and digital manufacturing technologies
- Cloud-based Manufacturing Platforms
- AI-enabled services and tools
- Product configurators and design applications integrating design and application knowledge with the capabilities of the manufacturing system.

Impact areas

And it would have an impact on:

- Increased customization and market responsiveness by tailored products and agile production to meet dynamic customer needs.
- Improved production efficiency and flexibility for bespoke products.
- Stronger customer engagement and value creation.
- Resilient, decentralized local production networks.

4.8. New Business Models

The evolution of manufacturing is not solely driven by technological advancements but also by the transformation of business models that leverage digitalization, servitization, and sustainability. As global markets demand greater flexibility, efficiency, and customer-centricity, manufacturers are shifting towards new paradigms that redefine value creation, operational strategies, and competitive differentiation.

Research Topics

The following research topics provide examples for key areas for innovation in the SMART Eureka program:

1. **Servitization and Manufacturing-as-a-Service (MaaS)**
    - Transition from product-centric to service-based models, focusing on delivering value through long-term service agreements.
    - Development of digital platforms for remote monitoring, predictive maintenance, and lifecycle management.
    - Research on pay-per-use and subscription-based manufacturing models.

2. **Mass Customization and On-Demand Production**
    - AI-driven personalization and agile production strategies for customised products.
    - Distributed and decentralized manufacturing networks enabling local, real-time production.
    - Integration of additive manufacturing and modular design for flexible production.

3. Circular Economy and Sustainable Business Models
   - Development of closed-loop manufacturing systems and remanufacturing strategies.
   - Implementation of digital passports for tracking product lifecycle and recyclability.
   - Research on sustainable supply chain models and resource-efficient production.

Related Enabling Technologies

- **Artificial Intelligence & Machine Learning**: Enabling predictive maintenance, demand forecasting, and process optimisation.
- **Industrial IoT & Edge Computing**: Facilitating real-time data collection and decision-making.
- **Digital Twins & Virtual Simulations:** Supporting lifecycle management and adaptive manufacturing.
- **Additive Manufacturing & Advanced Robotics:** Enabling mass customisation and decentralised production.
- **Blockchain & Smart Contracts:** Enhancing transparency, traceability, and secure transactions.
- **Cloud-Based Manufacturing Platforms:** Supporting Manufacturing-as-a-Service (MaaS) and digital collaboration.

Impact Areas

- **Increased Customization and Market Responsiveness**: Accelerating adaptation to changing customer demands through real-time production strategies.
- **Operational Efficiency and Sustainability:** Reducing waste, energy consumption, and material costs while increasing lifecycle value.
- **New Revenue Streams and Business Growth:** Enabling manufacturers to shift from single-product sales to long-term service-driven revenue models.
- **Resilient and Agile Manufacturing Ecosystems**: Strengthening supply chains with digital integration and decentralised production capabilities.
- **Enhanced Workforce Productivity**: AI-driven automation reducing complexity in operations while supporting workforce adaptation and upskilling.

Conclusion

The transformation of business models in manufacturing is integral to maintaining competitiveness in an increasingly digitalized and customer-driven landscape. Companies that embrace servitization, sustainability, and AI-driven decision-making will not only enhance operational efficiency but also create new revenue streams and market opportunities. As manufacturing ecosystems continue to evolve, collaborative and agile business models will define the future of industrial success.

Annex 1 - Enabling Technologies –

The achievement of the transformations planned for the European Manufacturing Sector requires a coordinated research and innovation effort, integrating technological developments from different areas, with a collaborative and complementary vision.

This table provides a structured mapping between core enabling technologies and the Research & Innovation (R&D) domains defined in the SMART Technology Roadmap. It aims to reduce redundancy in descriptions across the document and clarify which technologies support which innovation areas. A check mark (✓) indicates a primary role for the enabling technology within that R&D domain.

	4.1 Advanced Manufacturing Processes	4.2 Intelligent Systems	4.3 Design Digital Products	4.4 Digital Companies	4.5 Human Manufacturing	4.6 Circular Economy	4.7 Customer-based	4.8 New Business Models
AI & Machine Learning	✓	✓	✓	✓	✓	✓	✓	✓
Digital Twins	✓	✓	✓	✓	✓	✓		✓
Additive Manufacturing	✓		✓		✓	✓	✓	✓
Advanced Sensors / IoT	✓	✓		✓	✓	✓	✓	✓
AR / VR / XR			✓	✓	✓			
Cyber-physical Systems		✓	✓	✓	✓			
Edge/Cloud Computing	✓	✓		✓	✓	✓	✓	✓
Blockchain				✓		✓		✓

Some tips to clarify the meaning and scope of the core enabling technologies:

- **AI & Machine Learning:** Supports predictive maintenance, autonomous control, quality prediction, decision-making support, and demand-driven customization.
- **Digital Twins:** Used for simulating and monitoring processes, equipment, and product lifecycles. Enables real-time process adaptation and operator training.
- **Additive Manufacturing:** Enables freeform fabrication, personalized parts, decentralized production, and resource-efficient manufacturing.
- **Advanced Sensors / IoT:** Provide real-time data acquisition for control, monitoring, diagnostics, and traceability across production systems.
- **AR / VR / XR:** Enhance human-machine interaction, support remote maintenance, and improve training in virtual environments.
- **Cyber-physical Systems:** Combine physical processes and digital control layers for adaptive, intelligent systems.
- **Edge / Cloud Computing:** Facilitates real-time processing, data management, and distributed decision-making.
- **Blockchain:** Enables secure data exchange, traceability, and smart contracts, especially in distributed or service-based models.