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Intelligent Motion Control under Industry 4.E

D2.2 Needs for future smart production in Europe from the mechatronics and robotics point of view

Due Date: **08 – 2022-04-30**

Abstract:

This deliverable is a result of WP2 task in IMOCO4.E as described in grant agreement:

"Future needs and requirements for European (smart) manufacturing and Industry 4.0 will be collected and summarized based on the many perspective projects and initiatives that the European Commission has supported to this end in recent years (i.e. ECSEL, Artemis, IMS2020, Manufacture, EFFRA, I-MECH). This review and analysis will be assessed by the industrial partners of the consortium for defining the strategic directions within the IMOCO4.E project. Results are reported in this deliverable.

Based on inputs from D2.1, knowledge among consortium partners and market knowledge, this deliverable identifies the solutions required to expedite the introduction of smart production in Europe, e.g. by addressing existing bottlenecks. The report will provide the key technologies that IMOCO4.E should focus on to benefit a competitive European manufacturing ecosystem."

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BUT	Section 2.8 (electric drives)
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TUE	Section 2.1.2 (cross-cutting), 2.1.6 (IMS), 2.1.7 (national)
UWB	Section 2.9 (Project analysis)
All building block owners	Chapter 4 (identification of relevant needs for building block and supporting technologies)
All pilot, use case, and demonstration owners	Chapter 3 (Needs assessment)
All partners	Building block needs analysis workshop and technology content

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Abbreviations

Abbreviation	Explanation
AGV	Automated guided vehicle
AI	Artificial intelligence
AM	Additive manufacturing
API	Application programming interface
AR	Augmented reality
ASIC	Application-specific integrated circuit
BB	Building block
BLE	Bluetooth low energy
B2B	Business to business
COTS	Commercial off-the-shelf
CMOS	Complementary metal-oxide-semiconductor
CNC	Computer numerical control
CNN	Convolutional neural network
CPS	Cyber-physical system
DNN	Deep neural network
DVS	Dynamic vision sensor
Dx.x	Deliverable x.x
ECS	Electronics, components and systems
ECSEL	Electronic components and systems for European leadership
EDM	Electrical discharge machining
EFFRA	European factories of the future research association
EPoSS	European association on smart systems integration
FMU	Functional mock-up unit
FPGA	Field programmable gate array
GAN	Generative adversarial network
GDP	Gross domestic product
GDPR	General data protection regulation
GPGPU	General purpose graphical processing unit
gPTP	Generalized precision time protocol
GPU	Graphical processing unit
HeSoC	Heterogenous scalable platform
HMI	Human-machine interaction
HPC	High-performance computing
HW	Hardware
IA	Innovation action
ICT	Information and communications technology
IDS	Industrial data spaces
IEEE	Institute of electrical and electronics engineers
ILC	Iterative learning control
IMS	Intelligent manufacturing systems
IMU	Inertial measurement unit
IoT	Internet-of-Things
ISO	International standardization organization
I2C	Inter-integrated circuit

I-MECH	Intelligent motion control platform for smart mechatronics systems
LCA	Lifecycle assessment
LED	Light emitting diode
MBSE	Model-based systems engineering
MIMO	Multi-input multi-output
ML	Machine learning
MR	Mixed reality
M2M	Machine-to-machine
NDI	Non-destructive inspection
NDT	Non-destructive testing
NFC	Near field communication
NWO	Dutch research council
OPC-UA	Open platform communications unified architecture
PCIe	Peripheral component interconnect express
PLC	Programmable logic controller
POSIX	Portable operating system interface
PTP	Precision time protocol
QoS	Quality-of-Service
RFID	Radio frequency identification
RGB	Red green blue
RIA	Research and innovation action
ROS	Robot operating system
RTOS	Real-time operating system
SAT	Satisfiability
SISO	Single input single output
SMT	Satisfiability modulo theory
SoC	System-on-chip
SotA	State-of-the-art
SPI	Serial peripheral interface
SRIA	Strategic research and innovation agenda
SRDIA	Strategic research, deployment and innovation agenda
SW	Software
ToF	Time of Flight
TSN	Time-sensitive network
VAE	Variational auto encoder
VR	Virtual reality
WPx	Work Package x
xIL	x-in-the-loop

Executive Summary

In this deliverable, future needs and requirements for European (smart) manufacturing and Industry 4.0 are collected and summarized based on the many perspective projects and initiatives that the European Commission has supported to this end in recent years (i.e. ECSEL, Artemis, IMS2020, Manufacture, EFFRA, I-MECH). Review and analysis will be assessed by the industrial partners of the consortium for defining the strategic directions within the IMOCO4.E project.

Future needs are collected from several European roadmaps. The main focus is on two recent roadmaps that cover the scope of IMOCO4.E related needs in more detail, namely Manufuture 2030 and AI, Robotics and Data SRDIA. Based on the identified needs, the main needs from European roadmaps are categorised into several topics and presented in this deliverable.

These needs are then further assessed by the IMOCO4.E pilot, use case and demonstration owners. The assessment serves as a link to how IMOCO4.E cases are positioned compared to the strategic needs identified in the European roadmaps, addressing currently relevant needs and needs that are likely to become relevant after the IMOCO4.E.

Based on the inputs from IMOCO4.E deliverable D2.1 "State-of-the-art methods in Digital Twinning for motion-driven high-tech applications" and partner inputs for each IMOCO4.E solution, i.e. building block, this deliverable provides key technologies that IMOCO4.E should focus on to benefit competitive European manufacturing ecosystem.

Keywords: Future needs, needs assessment, IMOCO4.E, mechatronics and robotics

1. Introduction

1.1 Purpose of the Document

In this deliverable, future needs and requirements for European (smart) manufacturing and Industry 4.0 are collected and summarized based on the many perspective projects and initiatives that the European Commission has supported to this end in recent years (i.e. ECSEL, Artemis, IMS2020, Manufuture, EFFRA, I-MECH). Review and analysis will be assessed by the industrial partners of the consortium for defining the strategic directions within the IMOCO4.E project.

Based on the inputs from IMOCO4.E deliverable D2.1 "State-of-the-art methods in Digital Twinning for motion-driven high-tech applications" and partner inputs for each IMOCO4.E solution, i.e. building block, this deliverable provides key technologies that IMOCO4.E should focus on to benefit competitive European manufacturing ecosystem.

This deliverable is related to three main objectives of IMOCO4.E:

1) To assess the demands placed on future smart manufacturing in Europe from mechatronics and service-oriented point of view.

2) To identify the shortcomings of existing solutions in meeting European manufacturing and production challenges in the future

3) To link the IMOCO4.E challenges with technological and business requirements arising from pilot applications and use-cases defined by the industrial end-users from WP7.

Compared to D2.3 "Overall requirements on IMOCO4.E reference framework", which is done in parallel with this deliverable and focuses on a requirements-based view, this deliverable offers a needs-based view on European smart manufacturing and its relationship to IMOCO4.E and related technologies. The results from both deliverables will be used when making the D2.4 "General specification and design of IMOCO4.E reference framework" deliverable.

1.2 Structure of the Document

First chapter is an introduction chapter and provides an introduction to the deliverable.

Second chapter in this deliverable summarises future research topics and needs identified from different roadmaps and projects from the mechatronics and robotics point of view.

Third chapter summarises needs identified from the roadmaps and projects and contains the assessment of the needs by IMOCO4.E industrial end users.

In the fourth chapter, we take a look at IMOCO4.E solutions, i.e. building blocks and key technologies they should focus on to benefit European smart manufacturing.

1.3 Intended readership

This deliverable is intended for two user groups. For the IMOCO4.E consortium, this deliverable describes the smart manufacturing needs collected from several roadmaps and projects, identifying the main needs from IMOCO4.E cases in the context of roadmaps, and provides a list of key technologies IMOCO4.E should focus on to benefit European ecosystem. These results will be further progressed in D2.4 when defining a reference architecture.

For readers outside the IMOCO4.E consortium, this deliverable provides information on how needs for smart manufacturing and industry4.0 are seen from the mechatronics and robotics point of view and which technologies and technology topics are relevant and becoming relevant within the context of solutions provided by IMOCO4.E.

2. Future needs and requirements

Future needs and requirements are collected from several European roadmaps and projects, main focus is on two recent roadmaps that cover the scope of IMOCO4.E related challenges and needs in more detail, namely Manufuture 2030 and AI, Robotics and Data SRDIA. Based on the identified needs, the main needs from European roadmaps are categorised into several main topics and presented in this deliverable in chapter 3.

2.1 ECS SRA 2022

Electronic systems and components strategic research and innovation agenda 2022 (ECS SRIA) describes the main research and innovation directions under ECS in forthcoming years. It is done as a collaborative work of three industry associations, namely Aeneas, Inside and EPoSS.

The digital industry is most closely related to mechatronics and robotics in the application areas identified in the ECS SRA. The following section describes the digital industry and its main topics.

2.1.1 Digital industry

According to the ECS SRA [1], industry4.0 has profoundly impacted how digital solutions are used and needed in the different layers and ecosystems. The digital industry addresses both discrete manufacturing and process industries as well as production services, connected machines and robots. Digitalisation is the key enabler. Training and standards are seen as essential means for the deployment of novel technologies.

The European industry needs an open source based, stable and extensible 3D internet to overcome user interface, networking and communication challenges. 3D here refers to the concept of the industrial internet of things, augmented reality and virtual reality. [1]

ECS SRA [1] identifies six major challenges in the digital industry domain, namely:

- Major Challenge 1: responsive and smart production.
- Major Challenge 2: sustainable production.
- Major Challenge 3: artificial intelligence in digital industry.
- Major Challenge 4: industrial service business, lifecycles, remote operations and teleoperation.
- Major Challenge 5: digital twins, mixed or augmented reality, telepresence.
- Major Challenge 6: autonomous systems, robotics.

Key focus areas in major challenge 1 “responsive and smart production include” [1]:

- Robust optimal production that requires advances in self-healing and redundant automation systems, first-time-right, zero-defect manufacturing and predictive maintenance
- Mass customization and personalised manufacturing, customer-driven manufacturing
- Resilient and adaptive production, shortening of supply chains and modular factories
- Cognitive production, deploying both natural and artificial cognition
- Manufacturing as a service

- Embedded/edge/cloud architectures, architecture consists of three layers: embedded, near computing and cloud. 5G acts as a boost in communications technology.
- Standardisation: focus should be in bridging the standards

In major challenge 2 “sustainable production”, the following key focus areas are addressed [1] :

- Monitoring flows of energy, materials, waste and lifecycle assessment
- Virtual AI assistants helping on optimization and providing advice
- Human machine interfaces and machine-to-machine communication with support of VR and AR for many tasks.
- Human operators in more autonomous plants and in remote operations i.e. “skills 4.0”.
- Human safety including situation-aware safety.
- Competence and quality of work in a human-centred manufacturing
- Green deal and other policy initiatives

Major challenge 3 - “artificial Intelligence in digital industry” - addresses the following focus areas in manufacturing AI [1]:

- AI for dynamic production planning and management
- AI for green and sustainable manufacturing
- AI in supply chain management
- AI for adaptive and smart manufacturing devices, components and machines, cognitive functions for supporting use the use of machines and robot systems in changing environments

For decision-making AI following areas are addressed

- Complex-decision making or hybrid-decision making for semi-autonomous systems
- Human decision-making, machine decision-making and mixed
- Decision making dealing with uncertainty
- AI for human interaction with machines

Major challenge 4 - industrial service business, lifecycles, remote operations and teleoperation - identifies the following focus areas [1]:

- remote operations, teleoperation
- AI services for monitoring and collaboration including collaborative product-service engineering, training and simulation and condition monitoring, condition-based maintenance, anomaly detection and performance monitoring
- Fleet management, edge and local/global decision-making and operations support
- business service integration both locally and globally and full lifecycle tutoring

Major challenge 5 deals with “digital twins, mixed or augmented reality and telepresence”, and addresses the following key focus areas [1]:

- Digital Twin, design process digitalization, telepresence
    - Heterogeneity of systems, information sharing and standards, interoperability of digital twins
    - Industrial robotics immersive telepresence from design toward production lines and other operational scopes
    - Digital twins applied to sustainability and circular economy

- Virtual commissioning to bring collaboration between different disciplines and models in the same environment and interoperability to use applications across platforms
- Simulators
  - Tracking mode simulation: model adoption based on measurements
  - Simulator-based design: continuous design improvement utilizing digital twins and virtual models
- Digital twins as a combination of physics and knowledge-based models
- Humans and knowledge integration, human in the loop simulations and networked simulations

Major challenge 6 deals with "autonomous systems and robotics". The main aims are oriented toward production efficiency, speed and cost, higher precision and quality and safety in working conditions.

ECS SRIA 2022 [1] presents Figure 1 on required technologies and functionalities:

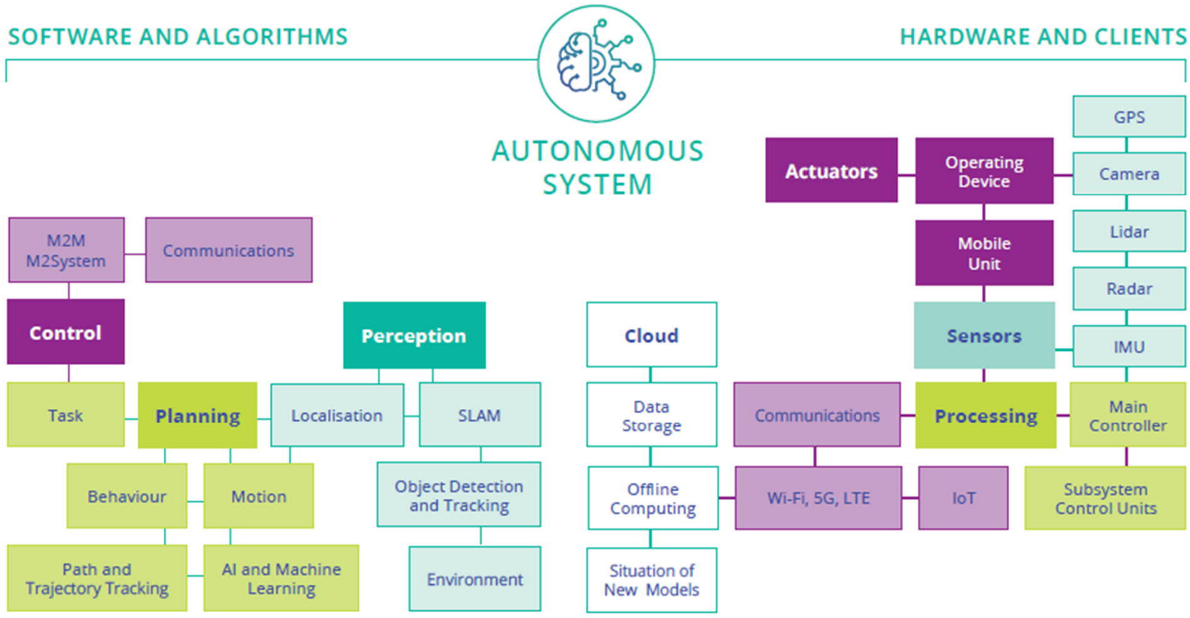

Figure 1. A generalised overview of autonomous system technologies and functionalities (from [1]). [1]

Key focus areas are [1]:

- Autonomous functions of systems
  - Fully autonomous vehicles and autonomous robots in shopfloors.
- Safety and security in autonomous systems
  - on-board sensors and safety systems operating indoors
  - isolated autonomous machines that work in separated working areas, typically intensive outdoor environment
  - machine perception and forecast of expected and unexpected human activities
  - Reaction to hazardous situations encountered by the autonomous machine

[1] Adapted from Pendleton, S.D., Andersen, A., Du, X., Shen, X., Meghjani, M., Eng, Y.H., Rus, D., Ang, M.H.Jr. (2017). "Perception, Planning, Control, and Coordination for Autonomous Vehicles. Machines", 2017

- Requirements management and conceptual modelling
    - Autonomous systems are expected to handle a near endless variety of possible scenarios
- Human-machine interaction (human-robot or human-machine)
    - Transparency of operations in uncertain conditions
    - Remote operation and advanced perception
    - Autonomy to enhance human capabilities
    - Natural human interaction
    - Assisted, safety-oriented and proactive robot interaction
- Verification and validation is automatic or semi-automatic
- Digital design: sub-task automation development, machine state estimation
- Simulators
    - 3D models with solid bodies, environment and object models and simulation tools
    - Early design phase simulators
    - Robotic test environments
    - Empirical or semi-empirical simulators (both real and simulated data)
    - off-road environments
- Autonomous capabilities development in digital environment

In addition to focus areas, the digital industry section notes that the digital twin's role will become broader, and the software will control more and more tasks in the factories. Trust, security, cybersecurity, safety, and privacy should be built or integrated with every lifecycle stage.

Following gaps are identified in the area of digital platforms: [1]

- Moving the focus to industrial and engineering applications. It is important to win the global platform game in various application sectors (which are strong today), and to effectively develop high-level outperforming applications and systems for actual industrial and business requirements.
- Preparing for the coming 5G era in communications technology, especially for its manufacturing and implementation within the edge-to-cloud continuum.
- Long-range communication technologies optimised for machine-to-machine (M2M) communication and large numbers of devices. For instance, low bit rates are key elements in smart farming.
- Solving the IoT cybersecurity and safety problems, attestation and security-by-design. Only safe, secure and trusted platforms will survive in the industry.
- Next-generation IoT devices with higher levels of integration, low power consumption, more embedded functionalities (including AI capabilities) and at a lower cost.
- Interoperability-by-design at component, semantic and application levels.
- IoT configuration and orchestration management allowing for (semi)autonomous deployment and operation of large numbers of devices.
- Decision support for AI, modelling and analytics, in the cloud but also in edge/fog settings.

2.1.2 Cross-cutting technologies

In cross-cutting technologies, edge computing and embedded artificial intelligence sections identify needs relevant to mechatronics and robotics.

According to the ECS SRA [1], the use of digital technologies enables us to provide higher performance and autonomy to existing and new applications with a constant or reduced cost while it poses challenges concerning energy consumption. Distributed computing has diverse architectures, including edge and cloud computing. The trend is to process raw data close to the source to identify the insight data as early as possible. This brings several benefits, including lower latency, higher bandwidth, lower power consumption, and lower memory footprint. The overview of the computing spectrum is shown in Figure 2.

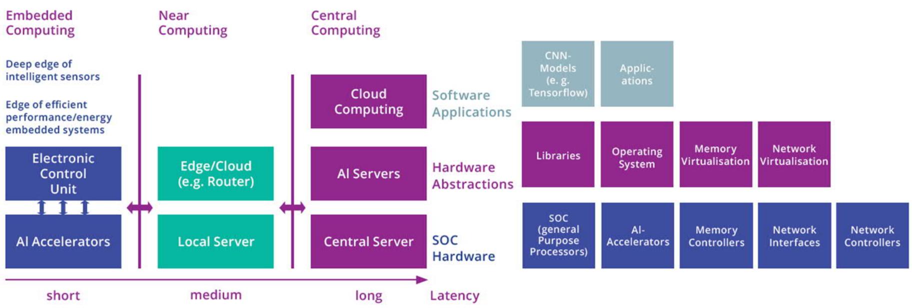

Figure 2. Computing spectrum overview. (from [1])

The above poses the following major challenges:

- Major Challenge 1: ensuring hardware quality and reliability

  The key focuses in this context are the following

  - in situ and real-time assessments
  - Reliability: tests and modelling
  - Design for reliability: virtual reliability assessment prior to the fabrication of physical HW
  - Prognostics health management: increase in functional safety and system availability

- Major Challenge 2: ensuring dependability in connected software

  The key focuses in this context are the following

  - Dependable connected software architectures
  - Dependable softwarisation and virtualisation technologies
  - Combined SW/HW test strategies

- Major Challenge 3: ensuring cyber-security and privacy

  The key focuses in this context are the following.

- Trustworthiness
- Security and privacy-by-design
- Ensuring both safety and security properties

- Major Challenge 4: ensuring safety and resilience

  The key focuses in this context are the following.

  - Safety and resilience of (autonomous AI) systems in dynamic environments
  - Modular certification of trustable systems and liability
  - Dynamic adaptation and configuration, self-repair capabilities, (decentralised instrumentation and control for) resilience of complex and heterogeneous systems
  - Safety aspects related to the human/system interaction

2.2 Manufuture 2030 SRIA

Manufuture 2030 [2] is a joint effort of Manufuture high-level group to describe a roadmap for the European manufacturing industry. SRIA document describes the strategic research and innovation area and has been updated in December 2019.

In Manufuture 2030 SRIA, the manufacturing system is seen as an overall lifecycle covering manufacturing from inputs to outputs and including circular aspects of the manufacturing, as seen in Figure 3.

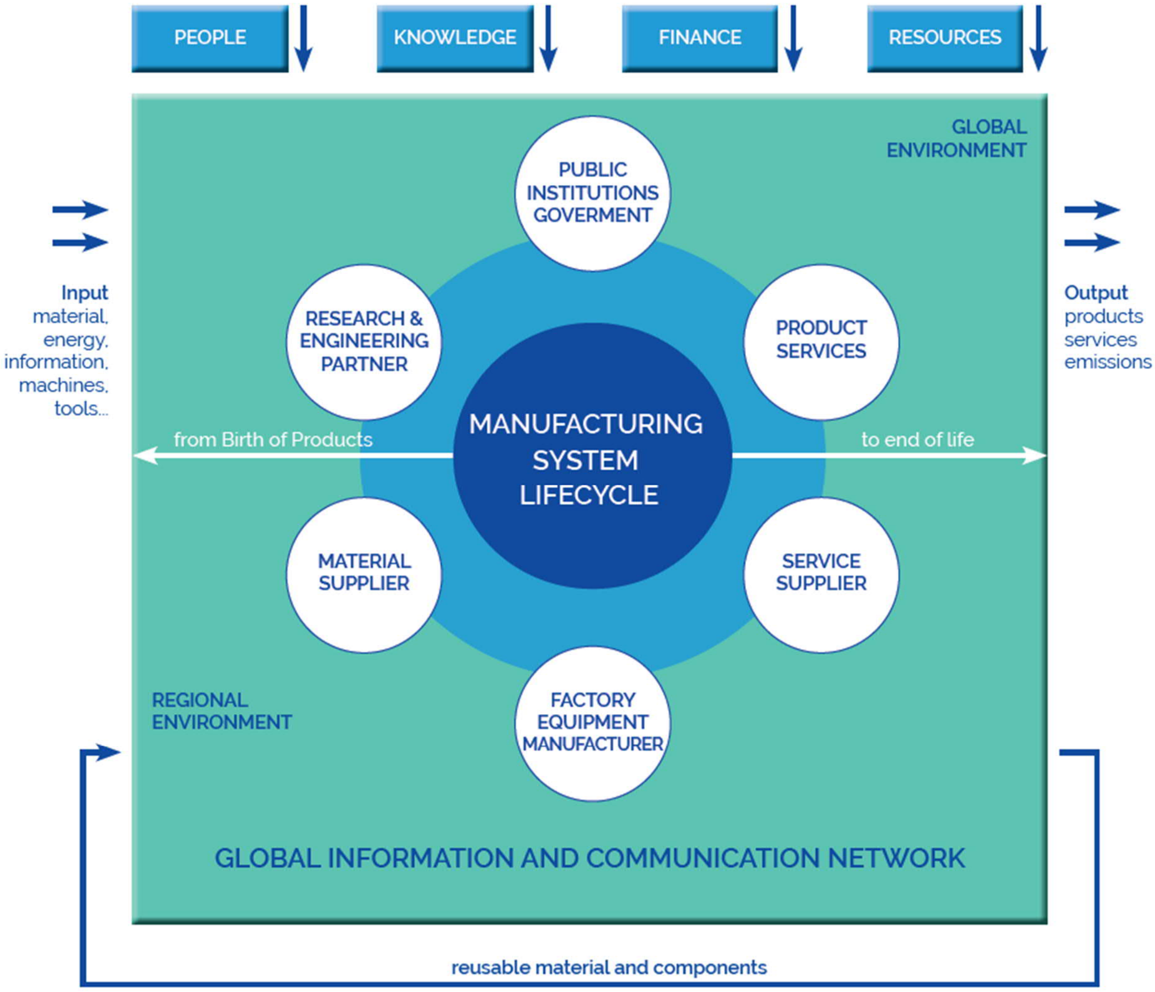

Figure 3. Manufacturing system lifecycle (from [2])

Decentralised technical intelligence, shown in Figure 4, is seen as a core of the manufacturing system.

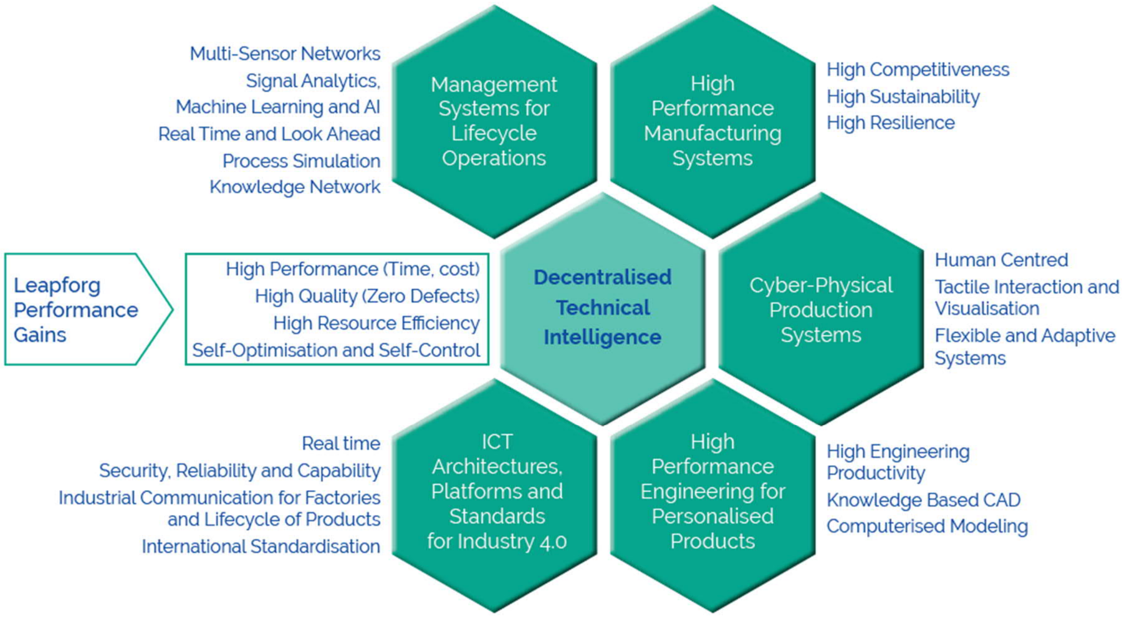

Figure 4. Decentralised technical intelligence (from [2])

The Manufuture 2030 SRIA also defines a matrix for research and innovation priorities, as shown in Figure 5.

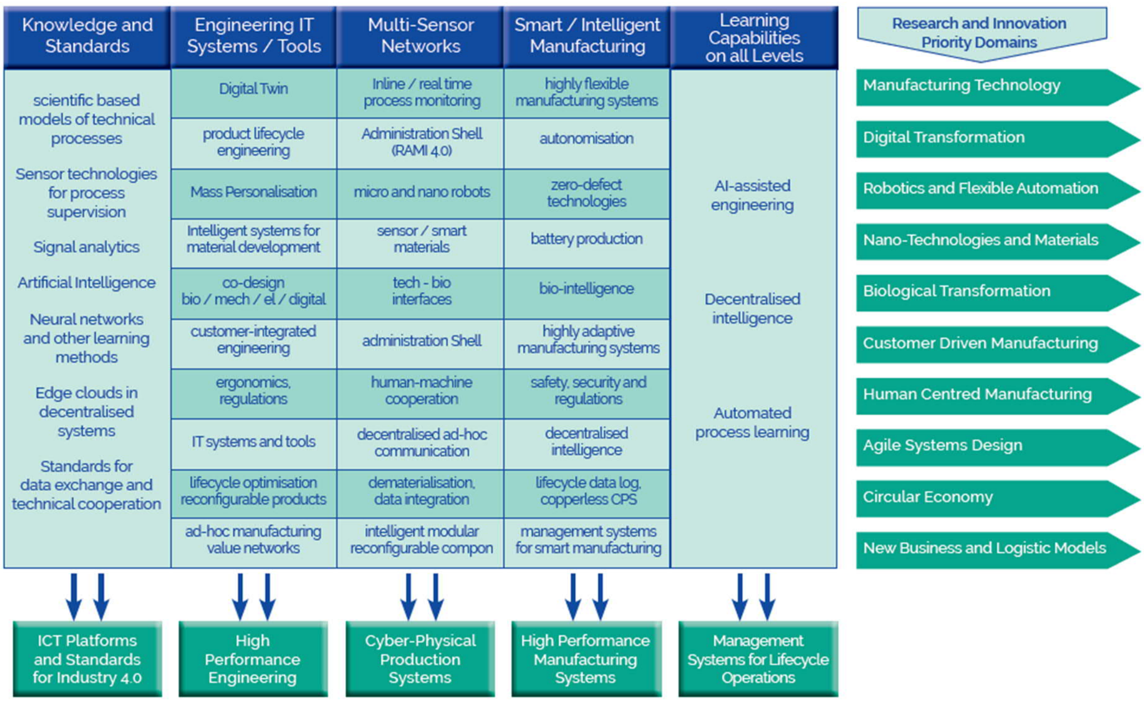

Figure 5. Research and innovation priorities (from [2])

Based on the research and innovation priorities, Manufuture 2030 defines a set of research and innovation priority domains according to which more detailed activities are defined, as shown in Figure 6.

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 6. Research and innovation priorities (from [2])

Following sections present needs obtained in relevant research and innovation priority domains. The more detailed description of needs and related observations in the sections 2.2.1-2.2.6 have been cited and adopted where feasible from Manufuture 2030 document [2].

2.2.1 Manufacturing technology and industrial equipment

Manufacturing processes are constantly evolving and improving but are often relying on appropriate process parameters. Manufacturing systems that are slow to respond are not flexible. 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.

2.2.2 Digital transformation[2]

The digital transition is seen as a key enabler in manufacturing, affecting it at all levels, not just in providing key technology but also affecting value networks, business models and workers. Key priority domains in

[2] Original content from [2], cited and adopted where feasible.

Manufuture 2030 SRIA digital transformation are quality of processes, dynamic and flexible production systems and digital-real convergence.

Quality of processes

The aim for zero-defect manufacturing requires cyber-physical systems that are able to deal with root-cause analyses of complex high added-value products.

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.

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.

In factories, there is still the need to assess if deep learning or other machine learning techniques 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 based on vision systems offer the possibility to deliver an enhanced digital image of the actual product, to identify defects and to monitor compliance. Combining the signals with simulation models and linking different data sources (through AI-based approaches) will offer a digital representation of product and processes reliable enough and constantly updated.

Dynamic and flexible production systems

Digitalisation enables the manufacture of customised and smart products (with embedded software, sensors, connectivity and AI). However, manufacturing systems for these kinds 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.

Multidisciplinary approaches help shaping next generation knowledge-based and system engineering tools and improve understanding of system behaviour, modelling and simulation, delivering easy-to-use solutions.

AI methods and tools are expected in the future to enable CPS systems to optimise both defects minimisation and dynamic adaptation to market needs. Data sharing in production and network requires necessary security and privacy methods. Self-optimisation of manufacturing networks requires historical data and process modelling digital twins utilising AI. Neurocognitive manufacturing systems are expected to make smart decisions in real-time, optimising the operations and enhancing the workforce. Human-driven manufacturing requires process analytics to identify good and bad practices.

The use of AI in real processes will have to meet the highest standards concerning safety, reliability, quality and precision. The ability to work with rather small data sets is required that need 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.

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.

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 also positively affect the manufacturing processes through the technology development of augmented and virtual reality on 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.

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, and 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.

Digital-real convergence

Understanding and modelling the manufacturing processes is crucial to further enhance the productivity of each single process step and the whole process chain. To fully exploit the potential of such understanding, sophisticated models of existing processes (ranging from flexible materials behaviour and properties 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 system's performance).

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 are necessary for effective decision-making.

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, 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.

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.

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.

There is a need to develop a systematic approach to support industrial/ manufacturing companies in deploying 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.

It is clear that connecting the internet to the shop floor has the potential to bring 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 reliable, fast and secure connectivity solutions and 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 can bring substantial advantages. Then the question of how to tackle the security issue in such a heterogeneous real-life environment without blocking the production arises.

When new technologies are introduced to enhance work productivity, research is needed to consider human factors and social aspects related to factory work.

2.2.3 Robotics and flexible automation[3]

Suppose robots are to become more flexibly applicable for manipulation tasks. In that case, 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 interacts with, thereby taking into account events happening in its environment. This requires many actors and sensors to make the robot 'soft' and aware of its environment.

The full autonomy of the robot is still utopic. The human must supervise the robot's actions, intervene and correct when necessary. Therefore, humans are 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 domain-specific 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.

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, and if the user does not trust them, there is a problem (cf. airplanes).

Mobile manipulators are a promising technology for factory environments designed for human use due to 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, requires 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.

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. Such algorithms allow for easy scalability and reconfigurability and lead to resilient/robust systems.

[3] Original content from [2], cited and adopted where feasible.

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'.

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 infrastructures, 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 require considerable research to guarantee the 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 repairing drilling rigs and erection of offshore wind turbines.

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.

Cooperation between humans and robots requires sharing autonomy between both actors. This can be physical, 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 done 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).

Making robots more autonomous requires a training phase during which the skill must 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.

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 are needed in many aspects: hardware, software, and shared autonomy to obtain usable products that can benefit humankind.

Handling soft and limp materials is relatively easy for humans but is a real challenge for robots. These handling tasks frequently occur 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.

The inroads of robots and other flexible automation into the manufacture of homes, buildings 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 a 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 offer high automation potential.

Flexible automation

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 the single source of truth at any time, allows short-term predictions of the system's 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.

The reference architecture allows incorporating the human as a system resource smoothly. 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 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 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 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.

The increasing involvement of humans in flexible automation systems, particularly in multi-plant manufacturing systems, makes it necessary to include trust considerations into the manufacturing execution systems and 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.

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 with the recent emergence and success of the hybrid-manufacturing concept by which several manufacturing processes are combined into 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.

2.2.4 Customer-driven manufacturing[4]

Generative design and personalised solutions need design platforms that collect customers' requirements for individual and specific products. Co-design activities should be developed to involve customers in design.

Co-operation between man and machine needs to be considered based on artificial intelligence and data-driven approaches. New technologies that enable to capture customer opinion and feedback throughout the product’s life cycle are important. New models and approaches considering customer involvement through social networks need to be considered.

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.

[4] Original content from [2], cited and adopted where feasible.

Customised processes are seen as the next step made possible by Industry4.0. This includes personalised manufacturing, novel solutions for efficient mass customisation via additive manufacturing, mass personalisation, mass customisation of composite structures and new rapid tooling technologies.

Data-augmented customization needs include process qualification via industry4.0 for mass customization, learning transfer and scaling up for zero-defect customisation, new solutions and approaches for zero-defect in personalised production and industry4.0 for customised manufacturing systems (such as self-adjusting plug and produce devices, self-adaptive and autonomous technologies etc.)

2.2.5 Human-centred manufacturing[5]

Advanced behavioural and cognitive models for humans in manufacturing are needed. For human-machine interaction, research is needed to fuse human and artificial sensing and operating capabilities in order to make real-time smart decisions in collaborations and interactions. Continuous improvement of manufacturing skills and know-how is needed, and new technology acceptance and adaptation are required. Legal frameworks and multidisciplinary research on humans and knowledge are required. New materials and technologies for safety may be developed, and workplaces should address health and safety issues. Safety should be addressed in both design and operational phases.

New equipment, interfaces and devices such as smart devices, virtual, mixed or augmented reality, or intelligent assistants require new methodologies to assess their safety with respect to different classes of workers. Existing learning environments do not fit the needs of future manufacturing workplaces. The workers on the shop floor need to be trained with contextualised learning technologies (e.g., augmented and virtual reality). Hybrid digital informational content and immersive environments can also be explored to provide human workers with more efficient interaction with data and information on the shop floor.

In the next years, development in advanced soft materials, artificial intelligence, and mechatronics will lead to the creation of natural-to-use and smart skin-tight suits. Wearable and multimode interaction technologies will boost the convergence between the physical and digital world and enable a more seamless workflow, translating into greater productivity.

The increasing degree of interaction between workers and the automatic machine requires new methodologies supporting the design of production systems as well as the flexible assignment of tasks.

2.2.6 Agile manufacturing systems design and management[6]

Agile manufacturing systems address the need for new methods to control autonomous production units, enabling the shop floor reconfiguring for smaller series. It should enable the introduction of flexible production resources such as autonomous mobile manipulators, capable of repositioning themselves on the line and allowing the exchange of both parts and grippers between robots. In addition, new decision-making methods should support the generation of safe and efficient reconfiguration plans.

[5] Original content from [2], cited and adopted where feasible.
[6] Original content from [2], cited and adopted where feasible.

Data-driven algorithms that enable autonomous control will improve decision support in adaptive control. 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 the main challenge.

Sensor-based reconfiguration of flexible robotic cells integrating multiple sensors such as vision, tactile, RFID, and presence sensors is needed to adjust the operation to part types and dimensional variations and assume complete autonomous robotic systems. Cooperating robots and investigating approaches to control autonomous and mobile robotic production units can change tasks and positions on the shop floor to enable random production flow.

Wearable or smart devices augment operators’ abilities in cooperation with robot systems. Augmented reality applications for human operators superimposing information while enhancing operator safety and acceptance. Interaction and collaboration with human operators will be critical for production flexibility while maintaining cost-effectiveness.

Autonomous manufacturing systems are enabled by incorporating AI methods for decision-making at the planning and execution stage. Robotic systems will achieve local autonomy, relying on data from their sensors and the Industrial Internet. They will also contribute to a collective perception, sharing these data with all other production resources.

The introduction of the equipment and production lines is expected to integrate self-monitoring, self-assessment, self-learning, and self-adjusting concepts with artificial intelligence technologies for production systems at the shop floor level.

2.2.7 Circular economy (manufacturing)[7]

The primary aspect of the circular economy from manufacturing perspective is material use and energy consumption. Energy recovery, material recycling and reuse have become essential.

Manufacturing systems aim 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.

Reuse and recycling address design for repair and assembly and energy and resource footprint of the manufacturing system. Production systems' ability to cope with the manufacturing/remanufacturing process and alternate technologies should be considered.

Design, refurbish and remanufacturing research 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.

Lifecycle management technologies and approaches for product maintenance should be addressed. There are models and techniques for the economic, environmental and social performances of product services, production processes and systems based on Life Cycle Assessment, Life Cycle Costing and Social Lifecycle Assessment.

[7] Original content from [2], cited and adopted where feasible.

2.3AI, data and robotics SRDIA

European AI, data and robotics partnership has created strategic research, innovation and deployment agenda (SRDIA) [3] on September 2020 and addresses so-called deep dives in each of the areas, namely AI, data and robotics. The SRIDA was built on the work of BDVA, euRobotics, ELLIS, CLAIRE and EurAI organizations.

As stated in the SRDIA: "While each discipline will continue to develop its own strengths and focus on its individual challenges and priorities, the focus of the Partnership is to define and develop common ground between AI, Data and Robotics. In particular, the Partnership is based on the knowledge that the greatest value will be developed in promoting the appropriate convergence of these disciplines."

AI, data and robotics SRDIA addresses both cross-technological enablers, as seen in Figure 7 and so-called deep dives into each topic separately.

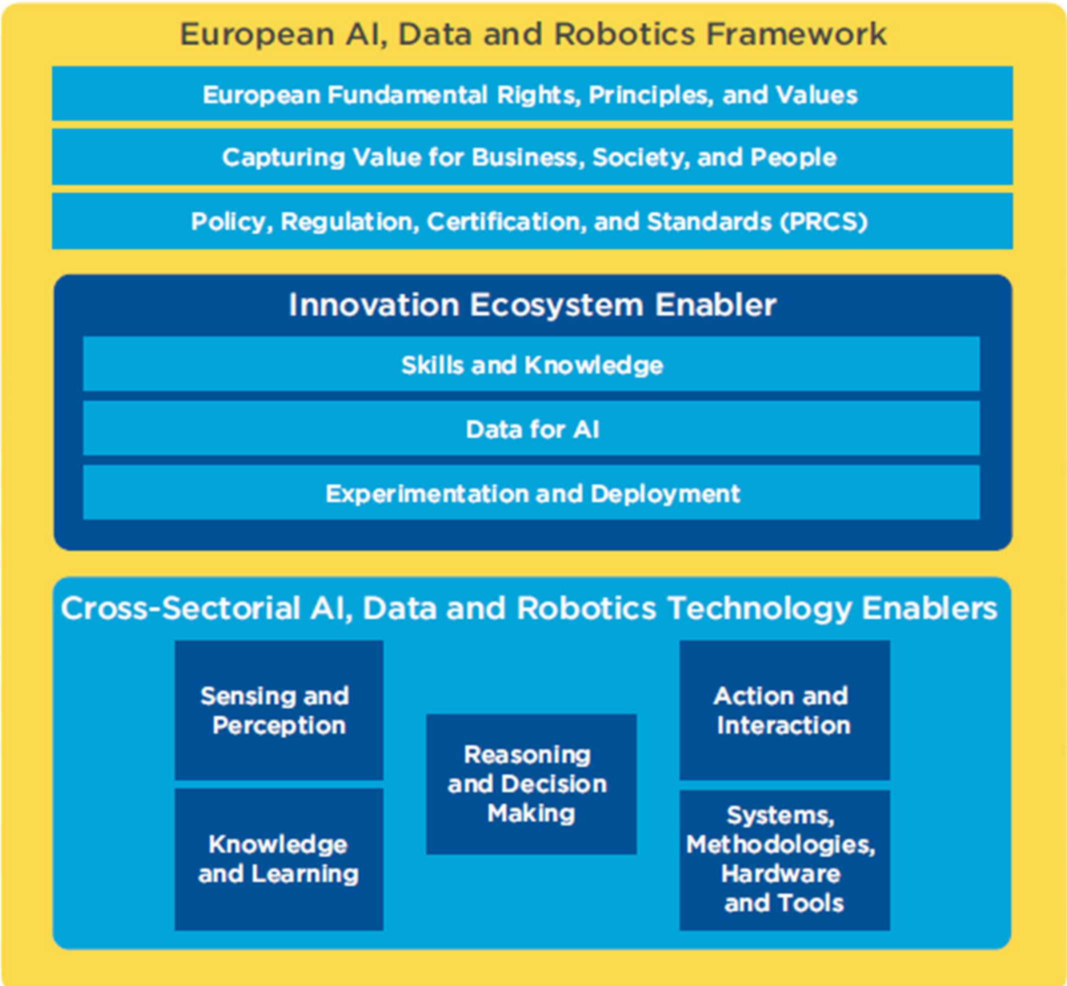

Figure 7. European AI, data and robotics framework enablers (from [3])

2.3.1 Cross-Sectorial AI, Data and Robotics Technology Enablers

The SRDIA states that the core characteristic of AI is trustworthiness. There are, however, certain critical AI applications that expect a high level of trustworthiness. In contrast, all applications do require to be trustable. Trustworthiness must be addressed between the building blocks and requires several system characteristics such as reliability, dependability, safety etc.

AI, data and robotics SRDIA defines several technology enablers that are cross-sectorial in nature.

<u>Sensing and perception</u>

The following challenges/needs exist in this technology enabler: [3]

- The development of faster, more accurate methods of perception that cover all types of data modalities (text, video, image, sound, sensor, etc.) and that can operate across a wide range of environmental conditions; different weather, diverse everyday objects, different human emotions and ages, different behaviours and diverse human interactions.
- The development of active perception technologies that use cognition to guide the perceptual process; for example, prior knowledge and expectations can be used to focus sensing, for example, image interpretation may support text understanding, and video may contextualize sound processing.
- The modularization and standardization of sensor interfaces, meta-information models and data flows; for example, interfaces that can adapt to the balance between processing within the sensor (e.g., edge) and processing centrally (e.g. cloud); or handle both local and distributed data capture; or adapt processing methods to changing operating conditions or dynamics.
- The development of novel sensing and sensor systems for AI, Data and Robotics applications; for example, in challenging environments; low and high temperature, pressure or in corrosive and explosive atmospheres, bio and chemical sensing, biocompatible sensors and low cost, low energy, high accuracy sensors.
- The development of methods to validate and certify sensor systems for safety, privacy, trustworthiness, etc.; for example, safety certifiable sensors for human-robot interaction, body pose detection or in-vivo physical interfaces.
- The development of advanced sensors able to adapt and self-calibrate, zero-energy sensors and sensors that can be embedded in retail packaging, bridges or people.

Expected impacts include:

Short Term	Medium Term	Longer Term
Standardised and modular sensors will create cross- sector supply chains and reduce costs Sensors and sensor systems will become cheaper to manufacture with better data quality; designs will become more compact and integrated Improved text, image, video, sound and sensor processing	The ability to modularise and fuse information from distributed and multi-modal sensor systems will become more standardised Greater integration of sensing and processing in modular packages Secure and intrinsically safe sensing systems Advances expected in chemical and bio-based sensing triggered by medical applications Improved accuracy through advances in active perception technologies	New materials and processing techniques will yield new forms of sensing and data acquisition Low or zero energy systems based on ambient energy Self-configuring and adaptive sensors IoT supported by ubiquitous networks of AI-based sensors Newly emerging sensing principles

Figure 8. Sensing and perception impacts (from [3])

Knowledge and learning

The following high-level application-driven challenges/needs exist in this technology enabler [3]:

- The scaling and federation of AI systems ensure that simple AI models can seamlessly be composed and combined into large scale federated systems. This includes scenarios based on distributed data storage locations for data-in-motion and data-in-rest while satisfying the privacy, robustness and performance requirements from the user side.
- The development of data augmentation methods for transforming data assets into high-quality and augmented training data. This includes the automated generating of data labels, the generation of synthetic data, automatic methods for data verification, and methods to extract insights from small data.
- Methods for knowledge modelling and representation that enable the seamless integration of data and connection with the physical world. To support the reuse of integrated and continuous knowledge, its representation in a standardised format.
- Advanced learning methods to ensure scalability, reusability and explain-ability of the analytical outcome. This includes approaches for transfer learning, better online (e.g., continual lifelong) learning, explainable learning, meta-learning and knowledge representation learning.
- Methods that integrate data-driven and knowledge-based approaches to ensure that the AI system uses all the available sources of information and that models trained by data are legible for humans and compliant with given specifications.
- The development of methods for handling security and privacy concerns. This includes GDPR-compliancy in the processing and sharing of data sources, ensuring data privacy and data security standards along the data lifecycle, which also applies to distributed data and real-time data.

Short Term	Medium Term	Longer Term
Techniques for hybrid decision making Improve the human understandability of AI-produced decision Provide simple explanations detailing the rationale of a decision Ensure robust and reliable decision-making Increased transparency by estimating model uncertainty	Provide trustworthy and robust hybrid AI-based decision making Enable user dialogue to inform the user about the decision's rationale Efficient means for handling uncertainty in complex setting Reliable real-time decision making in dynamic and multi-actor environments Dependable decision making in safety and privacy critical environment Constraint-based planning and decision making in complex natural environments Planning and decision making under uncertainty	Explainable decision-making incorporating context information Intrinsically trustworthy decision making Human interrogation for decision making Adaptive decision-making by incorporation of environmental changes Human-centric and compatible decision-making by incorporation of social interaction and mental models

Figure 9. Knowledge and learning impacts (from [3])

<u>Reasoning and decision-making</u>

Different decision-making scenarios face combinations of the following challenges/needs [3]:

- Timeliness: ranging from decisions that must be taken immediately, in a matter of milliseconds, because the next steps/actions depend on every single decision (e.g. self-driving cars), to decisions that can be postponed with minimal risks of costs (e.g. predictive maintenance in production plants)
- Robustness ensures that decision making maintains its level of performance under any circumstance.
- Trustworthiness increases users' confidence in an AI and Robotics System by making it dependable and reliable. To increase trust in AI and Robotics systems, different aspects, such as transparency, explain-ability or controllability, might be needed to be addressed.

The following high-level challenges exist in this technology enabler [3]:

- Interpretation of context: Guiding machine or human to understand the proposed recommendation/decision better. This includes methods for providing explanations as well as methods ensuring the interpretability of models.
- Dealing with uncertainty: Decisions must be taken in the face of uncertainty in the models, perceptual data, and the effects of the system's actions. Resilient AI and Robotics systems must be able to cope with incomplete and contradictory information by combining quantitative and qualitative methods.
- Transparent anticipation: Decision making often involves the use of predictive models to forecast possible futures and take anticipatory actions. To ensure trustworthy decisions, it must be possible for both the designers and the users to inspect, understand, validate, and possibly challenge these models and the criteria used to make a choice based on their predictions.
- Reliability: The challenge is building decision-making systems that consistently prioritize the same option(s) for similar input.

- Human-centric planning and decision-making require the incorporation of background knowledge and mental models of human users when deciding the best sequence of action and information of related processes, activities, or tasks.
- Augmented decision making complements human cognitive capabilities in a supportive way that humans are free to focus on less repetitive and more advanced tasks.

Short Term	*Medium Term*	*Longer Term*
Techniques for hybrid decision making Improve the human understandability of AI-produced decision Provide simple explanations detailing the rationale of a decision Ensure robust and reliable decision-making Increased transparency by estimating model uncertainty	Provide trustworthy and robust hybrid AI-based decision making Enable user dialogue to inform the user about the decision's rationale Efficient means for handling uncertainty in complex setting Reliable real-time decision making in dynamic and multi-actor environments Dependable decision making in safety and privacy critical environment Constraint-based planning and decision making in complex natural environments Planning and decision making under uncertainty	Explainable decision-making incorporating context information Intrinsically trustworthy decision making Human interrogation for decision making Adaptive decision-making by incorporation of environmental changes Human-centric and compatible decision-making by incorporation of social interaction and mental models

Figure 10. Reasoning and decision-making impacts (from [3])

<u>Action and interaction</u>

There are a set of core challenges in the interaction technologies that relate to the processing of environmental cues to guide the decisional autonomy that drives the sequences of individual actions that form an interaction. This can involve multiple sources of data and the interpretation of perceptions within the context of an interaction sequence. [3]

Challenges [3]:

- The development of techniques and methods to achieve seamless and natural interaction in unstructured contexts, including multi-modal interaction and the development of generic interaction models.
- Improved natural language understanding, interaction and dialogue covering all European languages and age ranges
- Development of verbal and non-verbal interaction models for people and machines, including gesture and emotion-based interaction.
- The development of interaction technologies using Virtual Reality (VR) and Augmented Reality (AR) and their relation to digital and physical human interaction.
- The co-development of technology and regulation to assure safe interaction in safety-critical and unstructured environments. This includes the development of actuators, mechanisms and control strategies for safe operation.
- The development of confidence measures for interaction and the interpretation of actions leads to explanations of interaction decisions and improved decision making.

- The development of robust, interactive machine learning and decision support systems that interact with domain experts to obtain more accurate and realistic models.

Short Term	Medium Term	Longer Term
Improved application specific multi-modal multilingual interaction Improved interaction based on perception of non-verbal and emotion cues Extended use of VR and AR in interactions Agreed safety criteria for co-working in production Increased augmentation of human task Affordable implementation of digital companion	Longer continuous meaningful multilingual interactions over periods of 10 minutes or more Generic standards for multi-modal interaction Safe, human compatible, physical and social interaction and collaboration in a limited range of tasks Improved dexterous manipulation of unknown objects Increased automation supporting human work	Continued interaction over extended time periods of hours Ability to carry out complex dexterous tasks autonomously Complex collaborative interaction between multiple agents Complex social interaction in multi-actor environments Human environment reconfigured around interaction Safe interaction in dynamic and uncertain environments

Figure 11. Reasoning and decision-making impacts (from [3])

<u>Systems, methodologies, hardware and tools</u>

Challenges [3]:

- To develop tools that enable the design, development, and deployment of AI, Data and Robotics systems that achieve their requirements at a behavioural and technical level through the design and development process.
- To develop system integration processes and methodologies that are cross-domain and allow efficient system design that can deliver against Quality-of-Service criteria. In particular, these should integrate certification and validation criteria.
- To develop methodologies and processes that ensure that design and development consider the whole life cycle of a product or service, especially where the product learns to alter its behaviour over time and when it operates autonomously in unknowable environments. Existing exhaustive testing regimes are costly and act as a barrier to deployment; design-based autonomy assurance is a critical challenge.
- To develop system architectures and modular standards encompassing all aspects of data and physical systems. Critical to this is the co-development of data and physical modularity standards and the development of data standards for exchange and data asset generation that cover real-time, contextual, physical digital contexts and their associated meta-data. Data architectures will have to balance cloud functionalities and computing at the edge appropriately.
- To develop methods and metrics to evaluate the performance of AI, Data and Robotics systems, including the development of suitable benchmarks for complex, integrated and evolving systems.

Short Term	Medium Term	Longer Term
Data standards for exchange and meta data standards Platforms for data and algorithm sharing Testing and validation processes standardised Wide acceptance of definitions for dependability and trustworthiness Data quality standards Usability and human-machine interaction quality standards	Tools and processes that can more rapidly create AI, Data and Robotics systems with guaranteed performance Standardised trustworthiness AI architectures standardised and built into design tools System-level component modularity creating cross- sector supply chains Standardised knowledge models across domains	Stable design patterns across sectors Automated testing and soft validation of systems, including physical systems able to guarantee regulatory compliance Safety autonomous learning used in critical applications Assurance of autonomous systems in safety and privacy critical environments

Figure 12. Systems, methodologies, hardware and tools impacts (from [3])

Following sections present future trends/needs obtained from "deep dives". The more detailed needs and other observations in the following sections 2.3-2-2.3.4 have been cited and modified where feasible from AI, data and robotics SRDIA [3].

2.3.2 AI deep dive[8]

Discussion of AI has become siloed, and different approaches are seen as opposite of each other instead of searching for integrated approaches. Europe should obtain basic and fundamental knowledge in AI without prejudice toward the technology.

In sensing and perception, diverse activity recognition will be applied. Geometric deep learning becomes crucial. Robot learning of actions and controls based on the right amount of data and instructions improves robustness and flexibility. Machine learned robots are able to cope with changing environmental conditions.

The most well-known approaches in machine learning are based on deep neural networks. Although machine learning algorithms have gained recent success (such as deep neural networks), they often remain inefficient, unreliable, brittle or require manual tuning. Therefore, developing efficient and reliable learning systems with theoretical guarantees is in order. Machine learning also has to perform well in settings outside the training as autonomous vehicles and industrial control also need to address unseen situations.

Reasoning methods such as constraint solving, model checking, automated theorem proving, and SAT and SMT solving methods are widely used in areas such as robots and industrial automation. AI-based search methods include various techniques to solve tasks and find solutions to optimisation problems.

Instead of fully automated AI, better approaches are seen in designing systems which allow humans and AI tools to collaborate effectively. Collaboration relies on techniques such as natural language understanding,

[8] Original content from [3][2], cited and adopted where feasible.

gesture and activity recognition, understanding intention, creating and maintaining shared mental models, and interaction design.

Interactive learning techniques will become important for high-stake real-world applications. Human-centric machine learning needs to be transparent, accountable, interoperable and fair.

AI techniques and AI-based systems will evolve to techniques that can complement their decisions with machine- and human-understandable explanations as to why each decision was reached. Especially in domains where accountability of AI is important, such as autonomous driving.

Science for designing, analysing, operating, monitoring, maintaining and extending AI systems is needed. This area is closely related to robotics. Deep learning requires GPU clusters and publicly available software resources, and publicly available software suites. Latency makes edge solutions essential, which means limited computational resources and smaller sample sizes.

2.3.3 Data deep dive[9]

Data deep dive proposes actions on several topics that relate to European level data framework, namely ethical, privacy, policy, regulation and standardisation issues.

There are several issues that affect innovation ecosystems on data. Data science and skills strategy should be developed and promoted. Data sharing and data spaces should be trained, piloted and deployed with emphasis on interoperability across existing spaces. Relevant actors in the Europe and different stakeholders should be brought together.

Data protection is needed in machine learning, confidentiality and integrity of training data, models and test samples; in dynamic environments, and resource-constrained devices and data stores. Data processing needs to be compliant with legislation, and individuals must be anonymised.

Medium-term outcomes are expected in machine learning techniques and data protection techniques and tools. Also, user control, digital twinning with statistical but anonymous relevance and advances in automated compliance with regulations are likely to advance in the medium-term.

In sensing and perception, the following challenges have been identified in SRDIA:

- Trustworthiness: Transparency of algorithms, data processing and management, traceability, privacy, integrity, and accountability
- Data Heterogeneity: Formats, collection mechanisms, access methods, flow, and meta-data, as well as coping with diverse environmental conditions (physical, technical, human)
- Capacity: Connectivity coverage, quality, and capacity for carrying large volumes of data, edge capacity and security to cope with big, decentralized data and AI processing, energy consumption by physical sensors

In the short-term, expected outcomes in sensing and perception include hybrid data-driven models, multimodal data fusion models, and the deployment of decentralised and decoupled services over low latency and low energy systems and networks. Medium-term outcomes include the development of trusted

[9] Original content from [3][2], cited and adopted where feasible.

execution environments, large-scale pilots in data-based solutions, a coherent standardisation landscape covering formats, processes, APIs, services and microservices and deployment of energy-efficient solutions with self-configuring, low-power or energy harvesting capable sensor devices and low power transmission.

Challenges identified in SRDIA in knowledge and learning:

- Data Quality: Access and processing of data in a high-quality and efficient manner: addressing data pre-processing challenges for the various data types
- Extracting meaningful insights and improving knowledge representation from heterogeneous data improves the data assets by addressing data pre-processing challenges for the various data types, particularly unstructured data, such as language, images, video, text, sound, etc.
- Technical challenges directly linked to the deployment of sectorial and cross-sectorial European Data Spaces and data sharing
- The Scaling and Federation of Data and AI systems
- Ethical implications of the use of Data and Data-Driven AI
- Deriving value by combining data insights & domain knowledge

In the short-term, outcomes are expected in methods for annotating unstructured data sources, and methods for high velocity real-time big data. Medium-term outcomes include deployment of verification systems and services, methods for identification of risks and liability, large scale pilots for generation of enriched and high-quality data for analytic applications, deployment of frameworks for data governance, increased availability of interoperable datasets and general interoperability, AI-models seamless combination into federated systems, ethnical initiatives, and frameworks that provide combined insights from data-based solutions.

Challenges identified in SRDIA in reasoning and decision-making include:

- Heterogeneous Data: Decision-making with high-velocity data from different sources (edge-fog-cloud), high-variety of data types and formats. Lack of datasets to train decision-making models
- Trustworthiness: Transparency, explain-ability. Lack of testing and validation of AI-based solutions
- Reasoning: Decision-making with symbolic, sub-symbolic, non-symbolic and heterogeneous knowledge under uncertainty

Expected outcomes in reasoning and decision-making in the short term include IAs aimed at developing AI-based systems able to deal with different data types and formats supporting processing heterogenous data in the computing (edge/fog/cloud), RIAs to design new/ improve simulators to generate large enough datasets for specific decision-making tasks, quality standards for reference datasets to test and validate AI-based solutions, and RIAs focused on improving AI to work reliably with insufficient and missing data.

Medium-term outcomes include quality standards to validate datasets made by simulators, benchmarks for determining the performance, robustness, reliability, usability and other indicators for AI-based systems and the development of AI techniques that cope with background knowledge and high dimensional data.

Challenges identified in SRDIA in action and interaction include:

- Language understanding: Improved natural language understanding, interaction and dialogue covering all European languages and age ranges
- Collaborative intelligence: Human and AI symbiosis

- Natural interaction methods: Enhanced interaction for humans across the continuum of computing environments
- Data interaction technologies: combining data-driven methods with Virtual Reality (VR) and Augmented Reality (AR) and their relation to human interaction, both digital and physical
- Safety-critical Interactions: Ensure safe interaction in safety-critical and unstructured environments

Expected outcomes in action and interaction in medium-term include large scale pilots with multi-language/multi-modal solutions, language understanding frameworks, large scale pilots in improving the interaction between humans and AI, development of natural interaction techniques and methods, VR and AR user interactions with large scale datasets and the co-development of technology and regulation to assure safe interaction in safety-critical and unstructured environments.

Challenges identified in SRDIA in systems, methodologies, hardware, and tools include:

- Scalability: lack of an ecosystem to guarantee access to computing infrastructures across Europe
- Methodologies design, implementation, and operation of data-processing hardware-agnostic pipelines
- Reliability Ensuring robust, safe, reliable, and trustworthy operation of AI systems
- Deployment: Deploying modern AI applications in the computing continuum (embedded-edge—fog—cloud) and the transition from development to production environments

Expected outcomes in systems, methodologies, hardware, and tools in the short-term include resource managers to allocate computing resources to cope with AI heterogeneity dynamically, “by-design” approaches for implementing data-processing hardware-agnostic data and AI pipelines and advanced compiler technologies targeting both specialised hardware accelerators and programmable hardware. Medium-term outcomes cover effective exploitation of next-generation computing infrastructures and hybrid configurations, new models to efficiently distribute computation workloads, models and metrics to evaluate and software development process to manage and deploy AI systems, quality standards and methodologies to verify “by-design” approaches and frameworks and guidelines to ease the transition from development do deployment.

2.3.4 Robotics deep dive[10]

AI, data and robotics SRDIA identifies robotics needs related to framework level:

- Robotics need to consider autonomous operations and the possibility of direct effect to the environment.
- Robotics need also address the allocation of liability for physical actions as well as personal data related issues.
- Better citizen engagement and ecosystem development around application areas and core technologies.
- The legal framework for robotics is outdated.
- Regulation harmonization and updates are needed as well as standards and certification for upcoming market and cybersecurity.
- Interoperability through standardized system modularity and interfaces is needed.

[10] Original content from [3][2], cited and adopted where feasible.

- The mobile nature of robot platforms means that communications technologies are essential.
- Knowledge of the operating environment can be extended by drawing on external data sources.
- Cloud-based analytics could help in recognizing and dealing with unknown objects.

Some expectations relate to AI's impact on operations and performance:

- Simplification of the semantic interaction between people and robots and between robots and their operating environment by adding reasoning and knowledge to transparent decision making.
- AI that is naturally interpretable and decision making based on AI technologies is explainable.
- Actions, interactions and decision making become naturally intelligible to human operators in the context of the user's skills, background and working environment while taking into account privacy and data security issues.
- AI that enables the building of effective internal models that allow broader and deeper decisional autonomy. This allows for longer interactions in more complex operating environments.
- Prediction of human behaviour in order to offer tools that help an operator guide a vehicle or a robot.
- AI that does not negatively impact the safety (digital and physical) of people who are using robots or who are simply in the vicinity of them or of infrastructure installations while it provides an (economic) advantage through the improved operation.

Safety will no longer solely be accomplished by a dedicated layer but by the combination of various types of sensors for perception, high-level algorithms to interpret sensor data and trustworthy decision-making.

SRDIA identifies several challenges related to sensing and perception:

- Real-time interpretation of sensor data, particularly in complex environments or where multi-modal data (vision, touch, acoustic, chemical etc.) must be fused or correlated to increase self-awareness of robotic systems.
- Matching local points of view with world views, particularly in dynamic scenarios.
- Reliability of sensing in harsh environments (pressure, high or low temperature, radioactivity, corrosive atmospheres, explosive risk) and in diverse environments (ice, snow, rain, mist, fog, etc.), as well as in small scale environments (e.g. inside biological bodies).
- Micro scale detection of small objects such as nano particles and differentiation of chemical compounds, contaminants, and biological tissue (e.g. cancerous cells vs healthy cells).
- Full 3D perception systems and sensors able to decompose and interpret whole scenes in real-time to 4D.
- Fusion of machine learning and model-based approaches to ensure generality, robustness and accuracy.
- Identifying the optimal balance between different sensing methodologies in a given application and use cases.
- Social interpretation & understanding of human intention and robot interaction, particularly in everyday environments.
- Assurance of the safe operation of robots using data from safety-rated and standardized sensing devices.
- Monitoring of human bio-signals during robot interaction in order to prevent fatigue, stress, discomfort, etc.

Safe and efficient operations are assured using low power and high speed and using onboard processing. Integrating high-level information into low-level controllers will enable greater reactivity to dynamic environments. Embedding advanced sensing into mechanical structures can dramatically improve responsiveness and interaction quality.

In data, knowledge and learning robotics rely heavily on AI and data. Therefore, they are also subject to trustworthiness, privacy and other legal issues when using the data obtained. Data availability is related to data accuracy and data minimisation. Robots need to learn from experiences and from each other to improve and become more efficient. Therefore, highly efficient learning mechanisms are needed. Learning mechanism sets also need certifications to become less static.

SRDIA identifies several challenges related to data, knowledge and learning:

- Creation of an innovation ecosystem that allows robots to use external data systems to increase quality and coverage in large scale data-rich applications.
- Standardize information/knowledge/action sharing mechanisms among robots in applications where multiple robotic systems are required and standardized across Europe, including anonymization mechanisms where appropriate.
- Integrating robots into IoT and Smart City ecosystems, industrial asset management systems and digital twins, so that data and knowledge can be shared.
- Maintaining privacy and operation within relevant legal frameworks with respect to privacy and trust.
- Creation of hybrid AI systems, merging powerful deep learning techniques with reasoning / knowledge-driven approaches.
- Learning from sparse data in near real-time.
- Creating transparent interfaces such that AI results are explained and users are able to evaluate the validity and integrity of the results.
- Creation and refinement of models through learning that enhance decision making.
- Integrate safety assurance of self-learning components into safety-critical systems, both at design and opening them for the required verification activities and certification processes at run-time.

Enhancing robotics with data, knowledge, and learning does not only improve adaptation to operating conditions but also to complex environments such as factories, warehouses and hospitals. Safety requires not only design-time mechanisms but also run-time.

SRDIA identifies several challenges related to reasoning and decision-making:

- To deliver explanations of reasoning and decision-making processes that are human-understandable and which allow humans to validate decisions where necessary.
- Ensuring trustworthy decision making that includes human factors and human context, especially in safety-critical applications.
- Safety assurance of high-level decision making.
- Planning, replanning, and decision-making under uncertainty and incomplete knowledge in dynamic environments. Time, communication and computational constraints typically apply here as well. This challenge is amplified in multi-actor environments requiring collaborative action.
- The development of adaptive decision making that avoids over-tailored solutions and seeks to balance performance optimization with adaptability.
- Distributed decision making and coordinated decision making between robots and in combination with other external systems, including humans.

- Consistency and linkage both within and between the abstraction layers from robot components and skills to models used for reasoning, decision making, and explanation (upwards and downwards), including grounding in the real world.

When able to deal with uncertainty or incomplete knowledge, operating envelopes of robot systems are enlarged and autonomous operations are enhanced.

Constrained environment challenges are largely known, there are more challenges that relate to less constrained or unconstrained environments. Often - if not always - a successful physical interaction is achieved by a combination of intelligent mechatronics design together with computational intelligence at the task level. In human interaction, contextualised social and behavioural interpretation of both the environment and human co-workers is essential to long term interaction and co-working.

Action and interaction challenges:

- Safety in physical interaction is a high priority, especially in applications with close or continuous physical interaction or where the power of the robot actuators or its kinetic and potential energy could cause harm.
- Cybersecurity of robots in order to protect the safety of robot actions and user privacy.
- The speed and strength (Agility) of collaborative robots need to be increased while maintaining safety.
- Novel robot platform configurations or architectures (for example, exploiting novel materials, actuators, including bio-inspired actuators and design) or novel construction techniques including Additive Manufacturing or modular approaches.
- Building concepts of human-understandable socialized behaviour for robots and robot behaviour adapted to context and task, for example, socialized responses to a dangerous task or the need for closer interaction.
- Physical interactions with highly flexible or soft materials such as fabric or foodstuff, soft interaction with humans, animals or plants.
- Strategies and methods to control the action and interaction of a massive number of small robots to complete tasks collaboratively.
- Modelling the operator’s behaviour guiding telerobotics to design new paradigms of manipulation that effectively imitate human performance.

The main outcome is that robots will be able to interact with humans more collaboratively, in closer proximity and over longer periods of time. Also, robots will be able to handle a wider range of complex non-rigid objects, components and structures in a wide range of scales from meter scale to nano-meter scale and manipulate them. Interactions will need to reach beyond human speed with equivalent dexterity. Most importantly, robots will be able to mutually collaborate, including in large populations, for example, in producing advanced structures and materials, and to socialize their interactions with humans in context, for example, in handing a tool to a worker who is at the top of a ladder, or physically interacting on a collaborative maintenance task. The ability to certify uncaged robots with the power to harm humans as safe to work with will be a major step change that will open multiple applications. The goal is safe, dependable, predictable and secure robots that can interact usefully with people in natural and intuitive ways.

Systems, hardware, methods and tools challenges:

- Develop robotics specific components optimized for robotics use (e.g. sensing, batteries, actuators etc.).
- Developing "by Design" methodologies to address security, privacy, ethics, safety, trust, etc., resulting in certifiable or certified designs that meet specific regulatory criteria.
- Design methods and systems that create and ensure long term reliability and dependability and associated certification processes, particularly for trustworthiness.
- Increased robustness and reliability of robotic systems to endure real-life operating conditions and handling, particularly in harsh environments.
- Long term energy sustainable robotic systems, in diverse harsh environments from in vivo to underground and submerged environments, for robots of different scales.
- Greater modularity and clear/standardized interfaces in system construction and commoditized components.
- Both physical and digital, testing and development environments for specific application areas, e.g. nuclear, healthcare, transport, inspection and maintenance in risky environments, etc., where it is impossible to develop in real environments safely.
- End-to-end safety assurance, taking into account hardware, software and system aspects.
- Designing robotic systems for limited resource consumption (data, energy, communication bandwidth, materials) using low power designs (mechanical and electronic) and frugal algorithms.

Impact/outcomes:

- More efficient platforms and more efficient design processes lead to lower development, integration and deployment costs and higher quality products, especially in safety-critical applications. Improved dependability enables long-duration deployment in real-world applications.
- Greater modularity and interoperability create supply chain opportunities and improve configurability and integration.
- Intuitive configuration tools reduce the need to use robotics specialists in configuring and reconfiguring systems.
- Novel robot platform design and increased AI integration, for example, at the edge, open opportunities in new markets and applications.
- Tools and methods that provide end-to-end safety assurance lead to higher efficiency while maintaining a reasonable level of safety.

2.4 Made in Europe SRIA

The Made In Europe partnership made the strategic research and innovation agenda [4] in October 2021. Similarly to other SRIAs, it describes key technologies and enables as well as research and innovation activities.

2.4.1 Technologies and enablers

According to Made In Europe partnership, the following technologies and enablers are seen in key roles: [4]

Advanced smart material and product processing technologies and process chains (additive manufacturing, joining, shaping, structuring, surface tailoring, etc.)

- Smart mechatronic systems, devices and components
- Intelligent and autonomous handling, robotics, assembly and logistic technologies
- De-manufacturing, recycling technologies, and life-cycle analysis approaches
- Simulation and modelling (digital twins) covering the material processing level up to the manufacturing system, and factory and value network level from design until recycling.
- Robust and secure industrial real-time communication technologies, distributed control architectures and standardized equipment protocols such as OPC-UA
- Data analytics, artificial intelligence, machine learning and deployment of digital platforms for data management and sharing
- New business and new organisational approaches, including links with regulatory aspects such as safety, data ownership, and liability
- A skilled workforce
- Standards

Smart mechatronic systems, devices and components are seen to advance from vendor-locked solutions toward open-source solutions and standards. Product offerings transform towards data-driven value-added services. Cognitive approaches, data analytics and connectivity advances are evolving robotics and their synergies with humans. Product designs and engineering should take into account end of life strategies from an LCA and recycling perspective.

Physics understanding of the behaviour of materials and mechatronics systems are enhanced by real-time monitoring, data collection and AI. Communications will be improved by peer-to-peer communications, distributed ledger technologies, wireless communications incl. 5G and standardised protocols such as OPC-UA. Digital manufacturing platforms pave the way for data sharing and increasing innovations in ecosystems.

2.4.2 Research and innovation objectives

In addition to technologies and enablers Made in Europe SRIA defines a set of research and innovation objectives as follows [4]:

<u>Efficient, responsive and smart factories and supply chains</u>

Following mechatronics and robotics related needs can be identified from R&I objectives related to “Data ‘highways’ and data spaces in support of smart and real-time connected factories in dynamic and robust value networks” [4]:

- Data spaces with standardised data formats for the exchange of design, manufacturing, logistics and other (digital twin) product/component data to allow for in-bound, real-time deep-chain planning and control for logistic information and design modifications.
- The more data is available from manufacturing processes, the better the AI algorithms become. Data spaces provide a means to share data between more participants and improve AI algorithms.
- Distinguish the static digital twin describing the non-changing parameters and capabilities of a product/production vs the dynamic digital twin containing the current status, the gathered data etc.

- Interoperable, cyber-secure hybrid IoT architectures with big (small) data analytics capabilities and semantics support for data exchange and knowledge generation. The seamless fusion of data.

Following mechatronics and robotics related needs can be identified from R&I objectives related to "Scalable, reconfigurable and flexible first-time-right manufacturing" [4]:

- Upgradable and robust manufacturing systems are necessary for flexible, responsive and resilient manufacturing.
- Appropriate and reliable simulation tools are needed at hand to avoid trial and error.
- Model-Based Systems Engineering - Parametric and modular software for manufacturing equipment.
- Flexible control software for planning and operation of scalable, reconfigurable and flexible production systems.

Following mechatronics and robotics-related needs can be identified from R&I objectives related to "Zero-defect and zero-down-time manufacturing, including predictive quality and non-destructive inspection methods" [4]:

A holistic approach is needed in which the production process is simulated and monitored and the production equipment and peripheral equipment in a fully seamless digital integrated value chain.

- Innovative sensors, sensor materials and innovative inception methods (machine vision in combination with AI)
- Diagnostics and detection of anomalies in production lines and processes
- Digital twin concepts covering design/material/technology for predictive quality during the production process.
- Model-based systems engineering (MBSE)
- Machine learning (ML) solutions leveraging on previous experiences, including both supervised and unsupervised solutions.
- Flexible data acquisition platforms capable of ingesting data from a wide range of industrial sensors
- "Virtual sensors", camera-based systems, and state of the art Internet of Things devices.
- Interoperability is essential to interact with manufacturing equipment in both directions.

Following mechatronics and robotics related needs can be identified from R&I objectives related to "Artificial intelligence for productive, excellent, robust and agile manufacturing chains - Predictive manufacturing capabilities & logistics of the future" [4]:

- We need simplified AI tool sets for use in a manufacturing environment that can be configured without highly skilled personnel
- Training AI algorithm requires many datasets
- Configuration control methodologies that can cope with the complexity, dynamic nature, self-learning and local vs holistic application of AI solutions.
- Data fusion approaches and methodologies for multi-source heterogeneous data.
- Autonomous approaches to move from big data to relevant data.
- Standards and standardization for AI usage in a production environment.

Following mechatronics and robotics related needs can be identified from R&I objectives related to "Advanced manufacturing processes for smart and complex products [4]:

- Highly automated manufacturing and process control for complex parts and multi-material parts.
- Understand, model and optimise the full chain of process stages.

Following mechatronics and robotics related needs can be identified from R&I objectives related to "High precision manufacturing for miniaturisation and functional integration" [4]:

- Edge computing: smart devices with embedded AI, federated machine learning.
- A holistic approach linking simulation, online process control and quality assessment.

<u>Circular products & climate-neutral manufacturing</u>

The European manufacturing industry faces a twin transition, namely green and digital. The general objective for the manufacturing industry is to become more energy and resource-efficient, aiming at a zero-emission, zero-waste industry.

From a mechatronics and robotics point of view, the following needs can be seen as relevant in this section of SRIA [4]:

- Resource and energy efficiency
- Prediction and optimised planning of energy consumption
- Individual contribution to the overall product environmental impact
- More insights into the economic drivers of the implementation of new technologies
- Virtual end-to-end life-cycle engineering and manufacturing, such as:
    - Use of digital twins for real-time monitoring of the shop floor
    - Industry requires flexible and robust platforms for data acquisition, data analytics, and artificial intelligence based on standards and appropriate protocols.
- Extending the service lifetime of products
- Eco-design, design for dis-assembly, for de-manufacturing

<u>New integrated business, product-service and production approaches; new use models</u>

The role of services is seen increasing in business, especially in B2B. Made in Europe SRIA [4] identifies the need to couple flexible design, manufacturing and (re)-configuration of products with the associated services.

From a mechatronics and robotics point of view, the following needs can be seen as relevant in this section of SRIA [4]:

- Digital twins build on top of multi-site, multi-administrative B2B domains
- Reference architectures for Data Sharing Spaces
- Data governance, traceability and legal standards
- New distributed data security models

<u>Human-centered and human-driven manufacturing innovation</u>

From a mechatronics and robotics point of view, the following needs can be seen as relevant in this section of SRIA[4]:

- New manufacturing capabilities, materials and processes open up new possibilities for integrated functional designs.

- Advanced user interfaces (MR/AR/VR)
- AI-driven guidance and recommendations
- Incorporation of worker knowledge into digital twins
- Multi-scale multi-level safety control associated with powerful analytics, adapting the machine/robot behaviour for smart and safe interaction
- Detecting the present mode/state of the human before delivering information, advice or requirements/orders
- Mechanisms for instructions delivery to non-robot experts for failures recovery
- Different virtual interfaces for the same physical machine
- Simulation and modelling of the Human Machine Interaction in the digital twin factory environment; as part of the overall digital twin production process simulation
- Development of digital twins that can be interpreted, used and operated by domain experts instead of only by data scientists or ICT experts
- Integration of interactive simulation technology for digital twins into AR and VR user experiences.
- The need for increased overall productivity and flexibility of the European manufacturing industry is combined with the need for human-centred and human-driven manufacturing processes
- Human activity sensing
- Robot learning by demonstration/observation. Self-learning robots
- Faster and more flexible physical assistance systems
- Methodologies for fusing multimodal sensor data are important research and development tasks in order to be able to handle different materials, processes and environmental conditions.
- Future machine learning will play an important role in factories of the future, particularly for the detection, classification and determination of the position/pose of objects for handling and various process control tasks.
- Safety and protection for humans, safety concern, needs to be addressed
- Standards for affordable safety and security

2.5 Dutch national roadmap

As an example of national roadmaps, the Dutch national roadmap on large-scale scientific infrastructure [13] (NWO) has identified that fundamental scientific breakthroughs in fields such as artificial intelligence and systems engineering are required for advances in healthcare, energy, logistics, digitization, electronics and many other sectors.

Moreover, the Dutch national research agenda [14] describes the following needs:

1. An overhaul of service and maintenance in Industry 4.0. As opposed to reactive maintenance, predictive maintenance is required to decrease delays and save costs. Solutions such as Digital Twins are desired.
2. Flexibility in manufacturing. Modern consumers desire a large number of possible product modifications, and factories need to be able to adapt to this. Task flexibility is thus essential in control systems.

2.6 IMS 2020

IMS2020 (Intelligent Manufacturing Systems) is a European funded project which created roadmaps for international research. It involved many partners from Europe and outside Europe. The resulting (executive summary of the) roadmaps [15] can be found here. It is mainly focused on the manufacturing industry and focuses on the three points:

1. Rapid and adaptive user-centred manufacturing which leads to customized and eternal' life cycle solutions.
2. Highly flexible and self-organizing value chains which enable different ways of organizing production systems and related infrastructures while reducing the time between engaging with end-users and delivering a solution.
3. Sustainable manufacturing culture, from individual attitudes all the way up to corporate governance, supported by the enforcement of rules and a proper regulatory framework co-designed between governments, industries and societies and facilitated by adequate training, in line with EC's Strategic Framework for Education & Training, ET 2020.

The three focus points are described in five sections in the roadmap and are summarized as follows:

1. Sustainable manufacturing, products and services
    a. The sustainable industry is growing rapidly due to more eco-awareness and increasing price of resources and energy. The main research actions proposed are, therefore
        i. Scarce Resources Management
        ii. Technologies for Sustainability
        iii. Sustainable Lifecycle of products and production systems
        iv. Sustainable Product and Processes
        v. Sustainable Businesses
2. Energy-efficient manufacturing
    a. Due to the increasing greenhouse gases and energy consumption, manufacturing should try to decrease its energy consumption. The main research directions include
        i. Energy Sources for Factories
        ii. Efficient Production Processes
        iii. Energy Utilization in Collaborative Frameworks
        iv. Management and Control of Energy Consumption
3. Key technologies
    a. Previously, throughput and production costs were the driving factors for research. This will continue to play a role, in addition to the previously mentioned sustainability and efficiency. Four areas are proposed as new research directions:
        i. Flexible Manufacturing Systems
        ii. Cost-Saving Manufacturing Systems
        iii. Energy-Saving Manufacturing Systems
        iv. Key Technologies embedded in manufactured products
4. Standards
    a. Standards are very useful for sustainable and energy-efficient manufacturing. Furthermore, costs can be reduced due to standards. Standards which can support manufacturing are divided in IMS2020 as
        i. Interface standards,

    ii. Measurement standards,
    iii. Process standards,
    iv. Safety standards,
    v. Product and component standards and
    vi. Material standards.
5. Innovation, competence development and education
    a. Innovation and education can enhance the improvement of manufacturing. Therefore, several research topics are devised in IMS2020 which aid the development of this in manufacturing society and can be formulated as
        i. Teaching factories
        ii. Cross-sectoral education 7/27 Supporting Global Research for IMS2020 Vision
        iii. Communities of practice
        iv. From tacit to explicit knowledge
        v. Innovation agents
        vi. Benchmarking
        vii. Serious games
        viii. Personalized ubiquitous learning
        ix. Accelerated learning

2.7 Automotive industry roadmaps

This section identifies several needs and European roadmap topics related to the automotive industry and aligns with the ambitions set out in IMOCO4.E. These have been collected from sources [5], [6] and [7]. The automotive industry is central to the EU economy, as it accounts for more than 7% of EU GDP [7].

At the top level, [5] identifies sustainability and safety as priorities. In this context, sustainability relates to the reduction of emissions but also to increasing energy efficiency and enabling the use of renewable energy sources to secure mobility for future generations. It also identifies a need to be able to deal with disruptive events, such as COVID-19, that affect not only mobility in general but also supply chains and competitiveness. Cyber-security is also an important topic. More data gathering is enabled in vehicles while ensuring compliance with regulations such as the General Data Protection Regulation (GDPR).

The following topics align with IMOCO4.E ambitions [5]:

- Tools need to be developed (and integrated with existing toolchains) to assess the security and safety of electronics and firmware in connected systems;
- AI technology must enable safe driving yet comply with ethical standards, requiring the development of advanced verification methods;
- Realistic simulation models and simulation environments (a.k.a digital twins) will enable predictive and extensive assessment of safety risks and system effectiveness to ensure that market penetration can keep up with the rate of technology development;
- The energy efficiency of electric and hybrid vehicles will be enabled, among others, by miniaturized drive electronics suitable for rare-earth-free electric motors;

In addition, [6] lists the following topics:

- It identifies the need for a Computing Continuum, essentially the edge-to-cloud intelligence that is an IMOCO4.E ambition, to deal with many heterogeneous data sources and computing requirements that emerge at different layers;
- It advocates low-power, low-latency and reconfigurable AI platforms supporting AI implementations that can be understood and interacted with by humans. This understanding is fundamental in assessing the safety of such technologies;
- Standards, such as ISO26262 and SOTIF (ISO 21448) need to be addressed to develop fail-aware, fail-tolerant and fail-operational components for safe autonomous products and vehicles;
- Trustworthiness and cybersecurity are topics that are challenging due to extreme data bitrates and the need to sustain security throughout a vehicle lifecycle;

A remarkable trend noted in [7] is that future (electric) vehicles will have far fewer components than vehicles with combustion engines. There is a strong transition towards electronics and software, with four main trends: 1) centralised computer architectures with lower complexity, 2) standardised communication, 3) connectivity and cooperation, and 4) autonomous functions. A key opportunity for IMOCO4.E is the identified lack of access to the required software technologies to enable these trends within the EU [7], implying a clear need for such technology to secure competitiveness in the near future.

2.8 Electric drive technology trends

The development of electrical drives evolves in different directions as the specific needs of target applications highly influence it. Without a doubt, the fastest progress during the last couple of years has been realized in developing electrical drives for hybrid and fully electric vehicles [8]. Specificities of this development are the battery operation, attempts to use higher DC link voltage for the current and thus losses reduction, and wide speed operating range. Higher motor voltage leads to smaller, lighter and more environmentally friendly motors [11]. 800 V battery systems are becoming the de-facto standard. The development is realized in big companies like Toyota Motor Corporation, DENSO Corporation, Hitachi Automotive Systems, Tesla, etc. In Europe, we can talk about Siemens, Robert Bosch GmbH, BMW AG and others. In recent years, many projects have been conducted on the European level dealing with the design of new automotive powertrains. We can mention MotorBrain, 3Ccar, AutoDrive, 1000kmPlus, and AI4CSM.

There are many requirements which are in common with other electric drives, e.g. industrial ones or ones for consumer electronics. These are mainly increased efficiency but also mass and volume reduction, higher reliability and safety aspects, production simplification for cost reduction and fully automated production for guaranteed quality. Another common trend is integrating motor and inverter in one package, which brings savings in system packaging and easier integration of complete electrical drive as one component only. [9]

In the IMOCO4.E project, high performance, highly configurable current amplifier for servo control application for robotic applications will be developed as BB7. Its advantage will be its openness to novel algorithms like repetitive control, adaptive noise cancelling, the presence of fast interfaces for simple connection of sensors and the utilization of novel wide band-gap components.

2.9 Research projects

Several industry4.0 related ECSEL projects have been conducted over the years. The CSA-Industry4.E project made the list of industry4.E lighthouse projects and their focus. Figure 13 shows the matrix of Industry 4.E Lighthouse Projects and their relation to major challenges as well as emerging themes and innovation accelerators (green – main focus; yellow - tackled but no main focus of the project; white – not tackled):

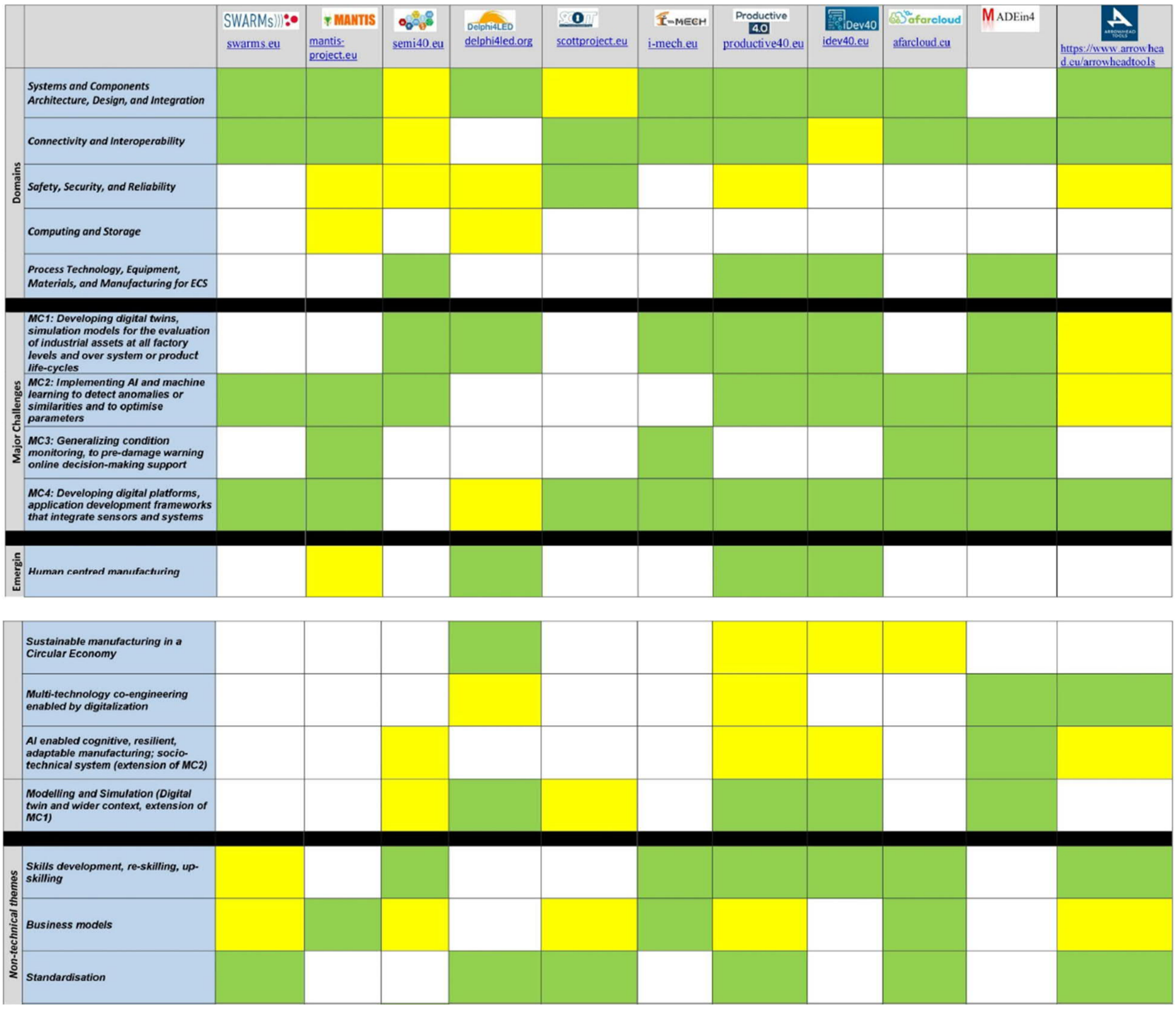

Figure 13. Matrix of Industry 4.E Lighthouse Projects (from [10])

The best way of incorporating knowledge – including needs and requirements – from the projects is if there are partners that have taken part in those projects. Although not all deliverables are public, some IMOCO4.E partners participated in the following pilot ECSEL initiatives. Hence the experience and knowledge gained there can be in parts utilised during the IMOCO4.E

Project name	*website*	*description*
I-MECH	www.i-mech.eu	IMOCO4.E predecessor, SotA analysis was used for certain building blocks as a baseline for updates for D2.2
Arrowhead	https://www.arrowhead.eu/	Focused on service-oriented architectures and communication between devices in industrial environments.
Arrowhead Tools	https://www.arrowhead.eu/	Continuation of Arrowhead project towards higher TRLs.
Productive 4.0	https://productive40.eu/	The largest project funded under ECSEL JU run in parallel to I-MECH.
AI4DI	https://ai4di.eu/	Source of inspiration for AI part of IMOCO4.E and edge computing architectures.
EMC2	https://www.artemis-emc2.eu/	The large project creates the baseline for HW topic in IMOCO4.E
MANTIS	https://industry4e.eu/project/mantis/	Focused on predictive maintenance and related data analysis, which is also part of IMOCO4.E Layers 3 and 4.

3. Industrial assessment on needs

3.1 Needs summary

This section summarises trends/needs collected from different roadmaps and projects described in the previous section. Chapter 2 discusses trends and needs in more detail. This section is a shorter summary of selected relevant needs from mechatronics and robotics points of view, focusing on identified key challenges.

Smart manufacturing	Trends/Needs
Responsive and smart manufacturing	
	Advances in self-healing and redundant automation systems
	Production that deploys both natural and artificial cognition
	Data spaces with standardised data formats for the exchange of manufacturing data to allow real-time planning and control.
	Sharing of data between different partners in order to improve AI algorithms
	Data fusion methodologies for multi-source heterogenous data
	Interoperable cyber-secure IoT architectures with data analytics and semantics support
	Dynamic digital twins that contain the current status of manufacturing
Dynamic and flexible manufacturing	
	Holistic and multidisciplinary approaches to improve the understanding of system behaviour, modelling and simulation
	Hybrid manufacturing simulation models (machine, cell, line, site)
	Structural reference architectures that take humans into account (holonic, multiagent)
	Novel approaches to combine different levels of information coming from humans, measurements, digital-twins/simulations; big data streams inline and in-site should be developed.
	Real-time digital twins emulating system and its dynamics “single source of truth”
	Decision support for autonomous control based on data-driven algorithms
	Neurocognitive manufacturing systems to make smart decisions
Agile manufacturing	
	New controlling methods for autonomous production units enabling reconfiguration of the shop floor
	Co-operating robots that can change tasks and position
	Autonomous mobile manipulators that allow repositioning and exchange of parts and grippers between robots
	Robotic systems with local autonomy relying on data from sensors and industrial internet

	Collective perception of robotic systems by sharing the data with production resources
	Integration of self-monitoring, self-assessment, self-learning and self-adjusting concepts with AI
Customer-driven manufacturing	
	Design platforms for customer requirements and co-design with customers
	Capturing customer opinion and feedback, social networks
	Design for additive manufacturing
	Solutions for efficient mass customisation and mass personalisation
	Zero-defect manufacturing in personalised production, industry4.0 for customised manufacturing systems (self-adjusting plug and play, self-adaptive etc.)
Sustainable and circular manufacturing	
	Resource and energy efficiency
	Monitoring energy, resource and waste and lifecycle assessment
	Virtual AI assistants helping on optimisation
	Design for remanufacturing, refurbishment and recycling
	Extending the lifetime of the products

Sensing	**Trends/Needs**
Sensing	
	Modularisation and standardisation of sensor interfaces, meta-information models
	Novel sensing and sensor systems in challenging environments and low cost, low energy, high accuracy sensors
	Methods to validate and certify sensor systems for privacy, safety, trustworthiness etc.
	Reliability of sensing in harsh environments and in diverse environments as well as in small scale environments
	Micro-scale detection of small objects
	Development of advanced sensors that can adapt and self-calibrate, zero-energy sensors and embedded sensors
	Greater integration of sensing and processing in modular packages
	Real-time interpretation of sensor data, particularly in complex environments or where multi-modal data must be fused or correlated to increase self-awareness of robotic systems
	Matching local point of view with worlds views
	Fusion of machine learning and model-based approaches to ensure generality, robustness and accuracy.
Perception	
	Faster and more accurate methods of perception that cover all data modalities and can operate in wide range of conditions (weather, objects, behaviour and human interactions)
	Active perception technologies that use cognition to guide the process
	Full 3D perception systems and sensors able to decompose and interpret whole scenes in real-time to 4D

Flexible production	
	Sensor-based reconfiguration of flexible robotic cells integrating multiple sensors (vision, RFID, presence…)

Motion control[11]	**Trends/Needs**
	Edge-to-cloud intelligence for motion control, i.e. a scalable and structured approach to intelligent motion control in which intelligence features are distributed across different layers.
	Motion control systems that can measure the performance of all instrumented components, like drives, sensors, actuators and use this data for predictive maintenance (for instance, via digital twins and AI techniques)
	Motion control systems that are continuously able to identify (changing) physical parameters to adapt and optimize feedback action
	Feedback control technologies that optimize their performance during repeated tasks
	Motion control system layers that can “perceive” the machine, “understand” the physics and “solve” the design and maintenance problems throughout the lifecycle
	New sensors that allow energy-optimal sensing and actuation
	Centralized motion control algorithms on scalable multi-core platforms that meet real-time execution requirements
	Detecting and rejecting residual vibrations by means of digital twins

Artificial intelligence	**Trends/Needs**
General	
	Trustworthiness of AI and robotics systems by making them dependable and reliable.
	Naturally interpretable AI and explainable AI
	Methods for handling security and privacy
Methods integration	
	Scaling and integration of AI systems ensuring that simple AI models may be combined into federated systems
	Methods for knowledge modelling and representation that enable seamless integration of data and connection to the physical world
	Methods that integrate data-driven and knowledge-based approaches
	Merging powerful deep learning techniques with reasoning/knowledge-based approaches.
Human interaction	
	Simplified AI tool sets are configurable without highly skilled personnel
	AI that is intelligible in the context of operator background and working environment and considering privacy and data security
	Transparency of operations in uncertain conditions
	Augmented decision-making that complements human capabilities
	Effective collaboration of humans and AI-tools

[11] As motion control is in direct scope of IMOCO4.E this part also covers needs addressed in GA.

	AI does not negatively impact the safety of people using robots or in the vicinity of them while providing advantages through improved operation
Decision-making	
	Simplification of the semantic interaction between people and robots and between robots and the operating environment by adding reasoning and knowledge to transparent decision-making.
	AI enabling the building of effective models that allow broader and deeper decisional autonomy
	Decision-making dealing with uncertainty and incomplete knowledge in dynamic environments
	Decision-making dealing with unseen situations
	Trustworthy and robust hybrid AI-based decision making
	Reliable real-time decision making in dynamic and multi-actor environments
	Adaptive decision-making by incorporating of environmental changes
	Distributed and coordinated decision making between robots and other systems, including humans
	Safety assurance of high-level decision-making
Learning	
	Large datasets for training AI algorithms
	Robot learning of actions and control
	Learning from sparse data in near real-time
	Geometric deep learning
	Deep neural networks
	Data augmentation methods for transforming data assets into high quality and augmented training data
	Advanced learning methods to ensure scalability, reusability and explain-ability
	Integrate safety assurance of self-learning components into safety-critical systems

Digital twins	**Trends/Needs**
General	
	Heterogeneity of systems, interoperability of digital twins, information sharing and standards
	Industrial robots' immersive telepresence from design toward production lines and other operational scopes
	Virtual commissioning to bring collaboration between different disciplines and models in the same environment and interoperability to use applications across platforms
	Tracking mode simulation: model adoption based on measurements
	Simulator-based design: continuous design improvement utilizing digital twins and virtual models
	Digital twins as a combination of physics and knowledge-based models
	Humans and knowledge integration, human in the loop simulations and networked simulations
	Autonomous capabilities development in the digital environment

	Digital twins for complex processes
	Digital twins applied to sustainability and circular economy
	Future digital twins could be the “single source of truth” at any moment in time
	Development of digital twins that can be interpreted, used and operated by domain experts instead of only by data scientists or ICT experts
	Integration of interactive simulation technology for digital twins into AR and VR user experiences

Systems, methods and tools	**Trends/Needs**
	Develop robotics specific components for robotics use
	Generative design approaches
	Early design phase simulators
	Develop “by design” methodologies to address security, privacy, ethics, safety, trust etc. that result in certifiable designs
	Design methods and systems that create and ensure long term reliability and dependability taking certification and trustworthiness into account
	Multidisciplinary approach for improving understanding of the system behaviour, modelling and simulation
	Increased robustness and reliability of systems, especially in harsh environments
	Long term energy sustainable robot systems in diverse harsh environments (underground, submerged) in different scale robots
	Greater modularity and clear/standard interfaces in construction and components
	Testing and development environments, both physical and digital, for specific application areas in risky environments
	End-to-end safety assurance
	Design of robot systems for limited resource consumption through the use of low power designs and frugal algorithms
	Intuitive configuration tools that reduce the need to use robot specialists

Human-machine interaction	**Trends/Needs**
General	
	Socially acceptable and transparent decisions
	Socially and legally acceptable technology
	Wearable and multimode interaction technologies
	Development of interaction technologies using VR and AR and their relation to human interaction
	Natural human interaction
Safety	
	Use of suitable spatial proximity sensors to avoid collisions
	Assurance of the safe operation of robots using data from safety-related and standardised sensing devices
	Safe trajectories generated by control software
	Machine perception and forecast of expected and unexpected activities

	Reaction to hazardous situations
	Perceived safety aspects are addressed (do users trust them)
	New materials and technologies for safety
Control & interaction	
	Sharing of the autonomy between human and robot
	Fusing human and artificial sensing and operating capabilities in order to make real-time smart decisions
	Prediction of human behaviour when helping operator to guide a robot
	Social interpretation & understanding of human intention and robot interaction
	Monitoring human bio-signals during robot interaction
	Remote operations and advanced perception
Human centred manufacturing	
	Advanced behavioural and cognitive models for humans in manufacturing
	Building concepts of human-understandable socialised behaviour for robots

Autonomous systems	**Trends/Need**
General robotics	
	Smart mechatronic systems, devices and components are seen to advance from vendor-locked solutions towards open source solutions and standards.
	Liability for physical actions, privacy and direct effect on the environment need to be addressed
	Regulation harmonisation, standards and certificates need updates
	Standardized information/knowledge/action sharing mechanisms among robots where multiple robotic systems are required
	Interoperability through modularity and interfaces is needed
	Communication technologies become essential due to robot platforms' mobility
	Operating environment knowledge enhanced by utilising external data sources
	Cloud-based analytics to support recognition and dealing with unknown objects
	Fully autonomous vehicles and autonomous robots in shopfloors
	Creation of an innovation ecosystem that allows robots to use external data sources
	Integrating robots into IoT and smart city ecosystems, industrial asset management systems and digital twins for data and knowledge sharing
	Cyber-security of robots to protect safety and user privacy
	The speed and agility of collaborative robots need to be increased while maintaining safety
Mobile robots (to replace conveyors)	

	Mobile manipulators with high speed and high precision localisation and navigation control
	The new generation of control algorithms enhances overall precision
	Safe and energy-efficient robots mounted on mobile platforms
Fleet control	
	Distributed algorithms that coordinate the behaviour of the swarm
	Centralised/decentralised control of the swarm, taking into consideration environmental constraints, multi-agent learning and self-repair.
Drones (logistics, assembly)	
	High positional accuracy with low tolerances in assembly
	Novel sensor systems working accurately over large spaces and position control algorithms
Advanced autonomous systems	
	Skill transfer from a human operator to the robot (i.e. learning and/or neural networks etc.) in straightforward (spray-painting) and more complicated tasks (deburring)
	Robots as machine tools would require active high stiffness through robot drive motors and direct endpoint position measurement
	Suitable sensors, grippers, smart programming and design for handling soft and limp materials.
	Strategies and methods to control massive numbers of small robots operating collaboratively

3.2 Industrial assessment on needs

In IMOCO4.E pilots, use cases and demonstrations verify the impact of IMOCO4.E results. For defining strategic directions, trends and needs in the context of IMOCO4.E were assessed with each pilot (P1-5), demonstration (D1-4) and use case (UC1-4) owner, collecting the following information with regards to the needs summary presented in chapter 3.1:

- Trend/need is relevant and will be addressed during IMOCO4.E (X)
- Trend/need is likely to become relevant in the future, after IMOCO4.E (F)
- Trend/need is not relevant (empty).

The following section describes each of the areas in more detail. For simplicity purposes, we call pilots, use cases and demonstrations with the joint name of “IMOCO4.E case” in the next section.

As European smart manufacturing needs form a basis for overall industrial needs for solutions, we have used that to link IMOCO4.E case needs into a more strategic perspective that European roadmaps contain. This also offers a unique perspective on how the strategic needs addressed in roadmaps are progressing within the industry.

In addition to the needs to be addressed within IMOCO4.E, future needs are assessed too, and these are taken into consideration when planning IMOCO4.E reference architecture to be future-proof and also to indicate the need for further support and research by European funding organisations so that the selected needs advance into concrete deployment within European industry.

3.2.1 Smart manufacturing

Table 1. Needs assessment on smart manufacturing

Smart manufacturing	Trends/Needs	P1	P2	P3	P4	P5	UC1	UC2	UC3	UC4	D1	D2	D3	D4
Responsive and smart manufacturing														
	Advances in self-healing and redundant automation systems		F	X				F		X			F	
	Production that deploys both natural and artificial cognition	F	F	X	F									F
	Data spaces with standardised data formats for exchange of manufacturing data to allow real-time planning and control.		X	F	F				F				F	F
	Sharing of data between different partners in order to improve AI algorithms		F						X				F	X
	Data fusion methodologies for multi-source heterogenous data	F		F				F	F					X
	Interoperable cyber-secure IoT architectures with data analytics and semantics support			F					F					F
	Dynamic digital twins on that contain current status of manufacturing	F	X	F	F			X	F					F
Dynamic and flexible manufacturing														
	Holistic and multidisciplinary approaches to improve the understanding of system behaviour, modelling and simulation	F	X	X				X			X		F	F
	Hybrid manufacturing simulation models (machine, cell, line, site)	F	X											F
	Structural reference architectures that take humans into account (holonic, multiagent)													F
	Novel approaches to combine different levels of information coming from humans, measurements, digital-twins/simulations; big data streams inline and in-site should be developed.		X	X				X	X				F	X
	Real-time digital twins emulating system and its dynamics “single source of truth”	F	X	F	F			X	F	F				F
	Decision support for autonomous control based on data-driven algorithms		X	X	F						X		F	X
	Neurocognitive manufacturing systems to make smart decisions			X					F					F
Agile manufacturing														
	New controlling methods for autonomous production units enabling reconfiguration of the shop floor		F	F						X	X		F	X
	Co-operating robots that can change tasks and position								F	X			F	F
	Autonomous mobile manipulators that allow repositioning and exchange of parts and grippers between robots								F					F
	Robotic systems with local autonomy relying on data from sensors and industrial internet								X				X	X
	Collective perception of robotic systems by sharing the data with production resources													F
	Integration of self-monitoring, self-assessment, self-learning and self-adjusting concepts with AI		X	X	F			F	F	X			X	X
Customer-driven manufacturing														
	Design platforms for customer requirements and co-design with customers													
	Capturing customer opinion and feedback, social networks			F										
	Design for additive manufacturing	F	X											
	Solutions for efficient mass customisation and mass personalisation											X		
	Zero-defect manufacturing in personalised production, industry4.0 for customised manufacturing systems (self-adjusting plug and play, self-adaptive etc.)			X	F			X			X	F		
Sustainable and circular manufacturing														F
	Resource and energy efficiency		F	F						X				F
	Monitoring energy, resource and waste and lifecycle assessment		X	F	F			X		F				F
	Virtual AI assistants helping on optimisation			X				F						
	Design for remanufacturing, refurbishment and recycling				F									
	Extending the lifetime of the products	F	X		X									

For further analysis, we ranked needs based on answers, for smart manufacturing they are as follows:

Table 2. Needs assessment ranked for smart manufacturing

Smart manufacturing	Trends/Needs	X	F
	Integration of self-monitoring, self-assessment, self-learning and self-adjusting concepts with AI	5	3
	Novel approaches to combine different levels of information coming from humans, measurements, digital-twins/simulations; big data streams inline and in-site should be developed.	5	1
	Holistic and multidisciplinary approaches to improve the understanding of system behaviour, modelling and simulation	4	3
	Decision support for autonomous control based on data-driven algorithms	4	2
	New controlling methods for autonomous production units enabling reconfiguration of the shop floor	3	3
	Zero-defect manufacturing in personalised production, industry4.0 for customised manufacturing systems (self-adjusting plug and play, self-adaptive etc.)	3	2
	Robotic systems with local autonomy relying on data from sensors and industrial internet	3	0
	Real-time digital twins emulating system and its dynamics “single source of truth”	2	6
	Dynamic digital twins on that contain current status of manufacturing	2	5
	Monitoring energy, resource and waste and lifecycle assessment	2	4
	Advances in self-healing and redundant automation systems	2	3
	Sharing of data between different partners in order to improve AI algorithms	2	2
	Extending the lifetime of the products	2	1
	Data spaces with standardised data formats for exchange of manufacturing data to allow real-time planning and control.	1	5
	Production that deploys both natural and artificial cognition	1	4
	Data fusion methodologies for multi-source heterogenous data	1	4
	Co-operating robots that can change tasks and position	1	3
	Resource and energy efficiency	1	3
	Hybrid manufacturing simulation models (machine, cell, line, site)	1	2
	Neurocognitive manufacturing systems to make smart decisions	1	2
	Design for additive manufacturing	1	1
	Virtual AI assistants helping on optimisation	1	1
	Solutions for efficient mass customisation and mass personalisation	1	0
	Interoperable cyber-secure IoT architectures with data analytics and semantics support	0	3
	Autonomous mobile manipulators that allow repositioning and exchange of parts and grippers between robots	0	2
	Design for remanufacturing, refurbishment and recycling	0	2
	Structural reference architectures that take humans into account (holonic, multiagent)	0	1
	Collective perception of robotic systems by sharing the data with production resources	0	1
	Capturing customer opinion and feedback, social networks	0	1
	Design platforms for customer requirements and co-design with customers	0	0

In many cases, AI integration with self-learning, self-adjusting, self-assessment, and self-monitoring concepts is addressed. Adopting novel approaches for combining information from different sources (digital twins, big data, humans) is also present in many cases. The holistic and multidisciplinary approaches to improving understanding of system and modelling are taking ground and addressed in several IMOCO4.E cases. Decision support for autonomous control and new controlling methods for reconfiguring the shop floor is also used in many cases. Zero-defect manufacturing in personalised production is also adopted or being adopted.

Needs for further research and deployment support is evident in several topics. From more future-oriented prospects, dynamic digital twins containing manufacturing statuses are advancing, with several partners either using or planning to take them into use in the future. The combination of natural and artificial cognition utilisation in production is maturing. Several partners see its potential to address it in the future.

Industrial data spaces (IDS) and GAIA-X initiatives are gaining lots of research (see, for example, https://internationaldataspaces.org/make/projects/). Results indicate that there is industry interest in data spaces, data sharing, and data fusion methodologies. Future research on this topic is relevant to move from research to deployment of data spaces in the manufacturing industry.

Sustainable and circular manufacturing needs are mostly seen as relevant after the IMOCO4.E, but there are already some activities, especially in monitoring energy/waste/resource and LCA and in extending the lifecycle of the products. One partner is also already addressing the use of virtual assistants. Energy/waste/resource efficiency and monitoring also seem to be relevant future research topics in this field.

3.2.2 Sensing

Table 3. Needs assessment on sensing

Sensing	Trends/Needs	P1	P2	P3	P4	P5	UC1	UC2	UC3	UC4	D1	D2	D3	D4
Sensing														X
	Modularisation and standardisation of sensor interfaces, meta-information models		X			F			F				F	X
	Novel sensing and sensor systems in challenging environments and low cost, low energy, high accuracy sensors	F	F		F/X	X				X	X	F	F	F
	Methods for validate and certify sensor systems for privacy, safety, trustworthiness etc.				F	F								
	Reliability of sensing in harsh environments and in diverse environments as well as in small scale environments				F	X			F					X
	Micro-scale detection of small objects					F					X			
	Development of advanced sensors that can adapt and self-calibrate, zero-energy sensors and embedded sensors		F			F								F
	Greater integration of sensing and processing in modular packages					F								X
	Real-time interpretation of sensor data, particularly in complex environments or where multi-modal data must be fused or correlated to increase self-awareness of robotic systems		X	X	F/X			F	X		X		X	X
	Matching local point of view with worlds views		F		F	F								F
	Fusion of machine learning and model-based approaches to ensure generality, robustness and accuracy.		F	X	F	F		F	X				X	X
Perception														X
	Faster and more accurate methods of perception that cover all data modalities and can operate in wide range of conditions (weather, objects, behaviour and human interactions)				F/X	F					X		X	F
	Active perception technologies that use cognition to guide the process			F	F/X				F					X
	Full 3D perception systems and sensors able to decompose and interpret whole scenes in real-time to 4D				F	F			F		X		F	F
Flexible production														X
	Sensor-based reconfiguration of flexible robotic cells integrating multiple sensors (vision, RFID, presence…)					F						F		F

For further analysis, we ranked needs based on answers for sensing they are as follows:

Table 4. Needs assessment ranked for sensing

Sensing	Trends/Needs	X	F
	Real-time interpretation of sensor data, particularly in complex environments or where multi-modal data must be fused or correlated to increase self-awareness of robotic systems	7	2
	Faster and more accurate methods of perception that cover all data modalities and can operate in wide range of conditions (weather, objects, behaviour and human interactions)	5	3
	Novel sensing and sensor systems in challenging environments and low cost, low energy, high accuracy sensors	4	6
	Fusion of machine learning and model-based approaches to ensure generality, robustness and accuracy.	4	4
	Modularisation and standardisation of sensor interfaces, meta-information models	2	3
	Active perception technologies that use cognition to guide the process	2	3
	Reliability of sensing in harsh environments and in diverse environments as well as in small scale environments	2	2
	Methods for validate and certify sensor systems for privacy, safety, trustworthiness etc.	2	0
	Full 3D perception systems and sensors able to decompose and interpret whole scenes in real-time to 4D	1	5
	Micro-scale detection of small objects	1	1
	Greater integration of sensing and processing in modular packages	1	1
	Matching local point of view with worlds views	0	4
	Development of advanced sensors that can adapt and self-calibrate, zero-energy sensors and embedded sensors	0	3
	Sensor-based reconfiguration of flexible robotic cells integrating multiple sensors (vision, RFID, presence…)	0	3

Identified sensing related needs are well addressed in the IMOCO4.E cases, and most have the potential to be followed up as IMOCO4.E cases advance. Most active work is carried out in real-time interpretations of data related to complex environments and/or self-awareness of robotic systems. Fusion of machine learning with model-based approaches, faster and more accurate methods of perception and cognition use is also advancing.

There are also several trends/needs that will be more relevant after the IMOCO4.E especially full 3D perception systems, matching local views with world views, more advanced sensors (self-calibration, zero energy, embedded) and sensor-based reconfiguration of robotic cells. These needs may also need more research support to be deployable in the near future after the IMOCO4.E.

3.2.3 Motion control

Table 5. Needs assessment on motion control

Motion control	Trends/Needs	P1	P2	P3	P4	P5	UC1	UC2	UC3	UC4	D1	D2	D3	D4
	Edge-to-cloud intelligence for motion control, i.e. a scalable and structured approach to intelligent motion control in which intelligence features are distributed across different layers.	F	F				X	X		X	X			F
	Motion control systems that can measure the performance of all instrumented components, like drives, sensors, actuators and using this data for predictive maintenance (for instance via digital twins and AI techniques)		X		X	F	X	X		X	X			F
	Motion control systems that are continuously able to identify (changing) physical parameters to adapt and optimize feedback action	X	X		F/X	F	X	F		X	X			X
	Feedback control technologies that optimize their performance during repeated tasks	X	X				X	X		X				X
	Motion control system layers that can “perceive” the machine, “understand” the physics and “solve” the design and maintenance problems throughout the lifecycle		F		F/X	F	X			X				F
	New sensors that allow energy-optimal sensing and actuation		F			F	F		F	F				F
	Centralized motion control algorithms on scalable multi-core platforms that meet realtime execution requirements	X	F		F	X	F	X		X				X
	Detecting and rejecting residual vibrations by means of digital twins	F			F/X		X	X		X				

For further analysis, we ranked needs based on answers. For motion control, they are as follows:

Table 6. Needs assessment ranked for motion control

Motion control	Trends/Needs	X	F
	Motion control systems that are continuously able to identify (changing) physical parameters to adapt and optimize feedback action	7	2
	Motion control systems that can measure the performance of all instrumented components, like drives, sensors, actuators and using this data for predictive maintenance (for instance via digital twins and AI techniques)	6	2
	Feedback control technologies that optimize their performance during repeated tasks	6	0
	Centralized motion control algorithms on scalable multi-core platforms that meet realtime execution requirements	5	3
	Edge-to-cloud intelligence for motion control, i.e. a scalable and structured approach to intelligent motion control in which intelligence features are distributed across different layers.	4	3
	Detecting and rejecting residual vibrations by means of digital twins	4	2
	Motion control system layers that can “perceive” the machine, “understand” the physics and “solve” the design and maintenance problems throughout the lifecycle	3	4
	New sensors that allow energy-optimal sensing and actuation	0	6

As motion control is the main focus of IMOCO4.E project, it is not surprising that most of the needs here are also relevant to the IMOCO4.E case owners. In addition to those needs addressed during the IMOCO4.E, especially new sensors with energy-optimal sensing and actuation and also partially motion control systems that solve design and maintenance problems through the lifecycle are most likely to be realised better after the IMOCO4.E project.

3.2.4 Artificial intelligence

Table 7. Needs assessment on artificial intelligence

Artificial intelligence	Trends/Needs	P1	P2	P3	P4	P5	UC1	UC2	UC3	UC4	D1	D2	D3	D4
General														
	Trustworthiness of AI and robotics system by making it dependable and reliable.	X	F	X	F/X	F			X\F					
	Naturally interpretable AI and explainable AI		F	X	F/X	F			F					
	Methods for handling security and privacy			F		F			F				F	
Methods integration														X
	Scaling and integration of AI systems ensuring that simple AI models may be combined into federated systems			F				F						X
	Methods for knowledge modelling and representation that enable seamless integration of data and connection to physical world			F				X	X					F
	Methods that integrate data-driven and knowledge-based approaches	X	X	X	F/X		F	X	X\F				X	F
	Merging powerful deep learning techniques with reasoning/knowledge based approaches.		F	X	F/X	F		F	X		X		X	F
Human interaction														X
	Simplified AI tool sets configurable without highly skilled personnel		X	X		F		F			X			X
	AI that is intelligible in context of operator background and working environment and considering privacy and data security		X	F					X\F					F
	Transparency of operations in uncertain conditions			X	F	F							F/X	F
	Augmented decision-making that complements human capabilities			X	F	F			X\F					
	Effective collaboration of humans and AI-tools			X	F	F			X				X	X
	AI does not negatively impact on the safety of people using robots or in vicinity of them while providing advantages through improved operation			X	F/X	X			X					X
Decision-making														X
	Simplification of the semantic interaction between people and robots and between robots and operating environment by adding reasoning and knowledge to transparent decision-making.				F	F			F				X	F
	AI enabling building of effective models that allow broader and deeper decisional autonomy			X		F			F				X	X
	Decision-making dealing with uncertainty and incomplete knowledge in dynamic environments			X	F	F			X				F	X
	Decision-making dealing with unseen situations		F	X	F	F			X					X
	Trustworthy and robust hybrid AI-based decision making			X	F	F			X					F
	Reliable real-time decision making in dynamic and multi-actor environments		F	X	F	F			F		X		X	F
	Adaptive decision-making by incorporating of environmental changes		F	X	F	F			F					X
	Distributed and coordinated decision making between robots and other systems including humans			X	F	F			X	F				F
	Safety assurance of high level decision-making			X	F	F			F					F
Learning														X
	Large datasets for training AI algorithms	X	F	F	F/X	F		F	F	F	X		X	
	Robot learning of actions and control				F/X			X	F	F				X
	Learning from sparse data in near real-time	F		X	F/X				F					F
	Geometric deep learning			X					F					
	Deep neural networks		X		F	F		F	X\F					X
	Data augmentation methods for transforming data assets into high quality and augmented training data			X	F/X			F	F				F/X	X
	Advanced learning methods to ensure scalability, reusability and explain-ability		X	X				F	F				X	X
	Integrate safety-assurance of self-learning components into safety critical systems			F	F/X				F					F

For further analysis, we ranked needs based on answers. For artificial intelligence, they are as follows:

Table 8. Needs assessment ranked for artificial intelligence

Artificial intelligence	**Trends/Needs**	**X**	**F**
	Methods that integrate data-driven and knowledge-based approaches	7	4
	Merging powerful deep learning techniques with reasoning/knowledge based approaches.	5	5
	AI does not negatively impact on the safety of people using robots or in vicinity of them while providing advantages through improved operation	5	1
	Large datasets for training AI algorithms	4	7
	Trustworthiness of AI and robotics system by making it dependable and reliable.	4	4
	Data augmentation methods for transforming data assets into high quality and augmented training data	4	4
	Simplified AI tool sets configurable without highly skilled personnel	4	2
	Effective collaboration of humans and AI-tools	4	2
	Advanced learning methods to ensure scalability, reusability and explain-ability	4	2
	Reliable real-time decision making in dynamic and multi-actor environments	3	5
	Deep neural networks	3	4
	Decision-making dealing with uncertainty and incomplete knowledge in dynamic environments	3	3
	Decision-making dealing with unseen situations	3	3
	Robot learning of actions and control	3	3
	AI enabling building of effective models that allow broader and deeper decisional autonomy	3	2
	Naturally interpretable AI and explainable AI	2	4
	Transparency of operations in uncertain conditions	2	4
	Adaptive decision-making by incorporating of environmental changes	2	4
	Distributed and coordinated decision making between robots and other systems including humans	2	4
	Learning from sparse data in near real-time	2	4
	AI that is intelligible in context of operator background and working environment and considering privacy and data security	2	3
	Augmented decision-making that complements human capabilities	2	3
	Methods for knowledge modelling and representation that enable seamless integration of data and connection to physical world	2	2
	Trustworthy and robust hybrid AI-based decision making	2	2
	Simplification of the semantic interaction between people and robots and between robots and operating environment by adding reasoning and knowledge to transparent decision-making.	1	4
	Safety assurance of high level decision-making	1	4
	Integrate safety-assurance of self-learning components into safety critical systems	1	4
	Scaling and integration of AI systems ensuring that simple AI models may be combined into federated systems	1	2
	Geometric deep learning	1	1
	Methods for handling security and privacy	0	4

Utilising AI "everywhere" is a key role in Industry4.0. From IMOCO4.E cases, we can see that AI adaptation and use are actively related to several trends/needs identified in European roadmaps. Many cases address the integration of data and knowledge-driven approaches, AI's positive impact on safety, deep learning techniques, the trustworthiness of AI and providing large datasets for the training of AI.

There are several needs that are relevant and addressed already now but mostly after the IMOCO4.E, namely reliable decision making in the dynamic multi-actor environment, deep neural networks, naturally interpretable and explainable AI, transparency of operations in uncertain conditions, adaptive AI in changing environment, distributed and coordinated decision making between robots and other systems such as humans. As AI advances, methods that specifically address security and privacy become more relevant.

3.2.5 Digital twins

Table 9. Needs assessment on digital twins

Digital twins	Trends/Needs	P1	P2	P3	P4	P5	UC1	UC2	UC3	UC4	D1	D2	D3	D4
General														X
	Heterogeneity of systems, interoperability of digital twins, information sharing and standards		X			F			F				F	
	Industrial robots immersive telepresence from design towards production lines and other operational scope									X				
	Virtual commissioning to bring collaboration between different disciplines and models in the same environment and interoperability to use applications across platforms					F	X	X		X				
	Tracking mode simulation: model adoption based on measurements	F			F/X									
	Simulator-based design: continuous design improvement utilizing digital twins and virtual models	X	X		X	X	X	X					F/X	X
	Digital twins as a combination of physics and knowledge-based models				X	F		X	F	X				
	Humans and knowledge integration, human in the loop simulations and networked simulations										X			
	Autonomous capabilities development in digital environment			F	F/X	X					X			X
	Digital twins for complex processes	F	X			F		X	X\F	X	X			F
	Digital twins applied to sustainability and circular economy													F
	Future digital twins could be the “single source of truth” at any moment in time		F		F			F	F					F
	Development of digital twins that can be interpreted, used and operated by domain experts instead of only by data scientists or ICT experts		X		X	X		F	F					F
	Integration of interactive simulation technology for digital twins into AR and VR user experiences				F/X	X			X\F				X	

For further analysis, we ranked needs based on answers. For digital twins, they are as follows:

Table 10. Needs assessment ranked for digital twins

Digital twins	**Trends/Needs**	**X**	**F**
	Simulator-based design: continuous design improvement utilizing digital twins and virtual models	8	1
	Digital twins for complex processes	5	4
	Autonomous capabilities development in digital environment	4	2
	Integration of interactive simulation technology for digital twins into AR and VR user experiences	4	2
	Development of digital twins that can be interpreted, used and operated by domain experts instead of only by data scientists or ICT experts	3	3
	Digital twins as a combination of physics and knowledge-based models	3	2
	Virtual commissioning to bring collaboration between different disciplines and models in the same environment and interoperability to use applications across platforms	3	1
	Heterogeneity of systems, interoperability of digital twins, information sharing and standards	1	3
	Tracking mode simulation: model adoption based on measurements	1	2
	Industrial robots immersive telepresence from design towards production lines and other operational scope	1	0
	Humans and knowledge integration, human in the loop simulations and networked simulations	1	0
	Future digital twins could be the "single source of truth" at any moment in time	0	5
	Digital twins applied to sustainability and circular economy	0	1

Digital twins trends and needs in European roadmaps focus on moving from single product digital twins towards more complex process simulations, combining physics and knowledge. In IMOCO4.E, the most common needs addressed continuous design improvement utilising digital twins and virtual models, complex process digital twins, autonomous capabilities development utilising digital twins and integration of interactive simulation technology.

Digital twins as a "single source of truth" also raised questions about whether it is really a realistic goal. In IMOCO4.E cases, this was seen mostly as something that could be approached in the future.

3.2.6 Systems, methods and tools

Table 11. Needs assessment on systems, methods and tools

Systems, methods and tools	Trends/Needs	P1	P2	P3	P4	P5	UC1	UC2	UC3	UC4	D1	D2	D3	D4
	Develop robotics specific components for robotics use				X	F				X				
	Generative design approaches													X
	Early design phase simulators	X	X		X	X							X	
	Develop "by design" methodologies to address security, privacy, ethics, safety, trust etc. that result in certifiable designs													
	Design methods and systems that create and ensure long term reliability and dependability taking certification and trustworthiness into account					F								
	Multidisciplinary approach for improving understanding of the system behaviour, modelling and simulation	X	F	F	X					X				
	Increased robustness and reliability of systems, especially in harsh environments					X			F		X		F	
	Long term energy sustainable robot systems in diverse harsh environment (underground, submerged) in different scale robots					F				F				
	Greater modularity and clear/standard interfaces in construction and components		F			F			F		X			
	Testing and development environments both physical and digital, for specific application areas in risky environments		X			X								
	End-to-end safety assurance													
	Design of robot systems for limited resource consumption through the use of low power designs and frugal algorithms								F				F	
	Intuitive configuration tools that reduce the need of using robot specialists					F			F					X

For further analysis, we ranked needs based on answers. For systems, methods and tools, they are as follows:

Table 12. Needs assessment ranked for systems, methods and tools

Systems, methods and tools	Trends/Needs	X	F
	Early design phase simulators	5	0
	Multidisciplinary approach for improving understanding of the system behaviour, modelling and simulation	3	2
	Increased robustness and reliability of systems, especially in harsh environments	2	2
	Develop robotics specific components for robotics use	2	1
	Testing and development environments both physical and digital, for specific application areas in risky environments	2	0
	Greater modularity and clear/standard interfaces in construction and components	1	3
	Intuitive configuration tools that reduce the need of using robot specialists	1	2
	Generative design approaches	1	0
	Long term energy sustainable robot systems in diverse harsh environment (underground, submerged) in different scale robots	0	2
	Design of robot systems for limited resource consumption through the use of low power designs and frugal algorithms	0	2
	Design methods and systems that create and ensure long term reliability and dependability taking certification and trustworthiness into account	0	1
	Develop "by design" methodologies to address security, privacy, ethics, safety, trust etc. that result in certifiable designs	0	0
	End-to-end safety assurance	0	0

There is more diversion in the results in systems, methods, and tools based on needs. Early design phase simulators, as well as multidisciplinary approaches, are well addressed in several IMOCO4.E cases.

Greater modularity is seen as one of the main future needs. Although security aspects are relevant in IMOCO4.E with specific BB9 for security-related issues, the need for “by design “methods that would result in certifiable designs is not seen as relevant. Also, end-to-end safety assurance is not seen as relevant in tools and methods.

3.2.7 Human-machine interaction

Table 13. Needs assessment on human-machine interaction

Human-machine interaction	Trends/Needs	P1	P2	P3	P4	P5	UC1	UC2	UC3	UC4	D1	D2	D3	D4
General														
	Socially acceptable and transparent decisions		X	X	F/X	X							X	
	Socially and legally acceptable technology				F/X	X			F					
	Wearable and multimode interaction technologies					F			X\F					
	Development of interaction technologies using VR and AR and their relation to human interaction					F			X\F				F	
	Natural human interaction			X	F/X	X			X				X	
Safety														
	Use of suitable spatial proximity sensors to avoid collisions				F/X	X								X
	Assurance of the safe operation of robots using data from safety- related and standardised sensing devices				F/X	X		X	F					
	Safe trajectories generated by control software		X		F/X	X		X					X	X
	Machine perception and forecast of expected and unexpected activities				F/X	F			X					F
	Reaction to hazardous situations				F	X			F					
	Perceived safety aspects are addressed (do users trust them)					X			F					
	New materials and technologies for safety								F					
Control & interaction														F
	Sharing of the autonomy between human and robot				F/X	F			F					
	Fusing human and artificial sensing and operating capabilities in order to make real-time smart decisions			X	F	F			X		X			
	Prediction of human behaviour when helping operator to guide a robot				F/X	F			X\F				X	
	Social interpretation & understanding of human intention and robot interaction				F/X	F			X\F					
	Monitoring human bio-signals during robot interaction				F	F			F					
	Remote operations and advanced perception			X		F			X					
Human centred manufacturing														
	Advanced behavioural and cognitive models for humans in manufacturing								F					
	Building concepts of human understandable socialised behaviour for robots								F					

For further analysis, we ranked needs based on answers. For human-machine interaction, they are as follows:

Table 14. Needs assessment ranked for systems, methods and tools

Human-machine interaction	Trends/Needs	X	F
	Safe trajectories generated by control software	6	1
	Socially acceptable and transparent decisions	5	1
	Natural human interaction	5	1
	Prediction of human behaviour when helping operator to guide a robot	3	3
	Assurance of the safe operation of robots using data from safety- related and standardised sensing devices	3	2
	Fusing human and artificial sensing and operating capabilities in order to make real-time smart decisions	3	2
	Use of suitable spatial proximity sensors to avoid collisions	3	1
	Machine perception and forecast of expected and unexpected activities	2	3
	Social interpretation & understanding of human intention and robot interaction	2	3
	Socially and legally acceptable technology	2	2
	Remote operations and advanced perception	2	1
	Development of interaction technologies using VR and AR and their relation to human interaction	1	3
	Sharing of the autonomy between human and robot	1	3
	Wearable and multimode interaction technologies	1	2
	Reaction to hazardous situations	1	2
	Perceived safety aspects are addressed (do users trust them)	1	1
	Monitoring human bio-signals during robot interaction	0	3
	New materials and technologies for safety	0	1
	Advanced behavioural and cognitive models for humans in manufacturing	0	1
	Building concepts of human understandable socialised behaviour for robots	0	1

Control systems safety trajectories, socially acceptable and transparent decisions, natural human interaction, assurance of safe operations and fusing human and artificial sensing are all relevant needs to be addressed in several use cases.

Many are also either addressed during the IMOCO4.E or in the near future, namely machine perception and forecast also for unexpected activities, prediction of human behaviour, interpretation & understanding of human intention.

Trending needs that become relevant mostly in the future include VR/AR interaction to human interaction, sharing of autonomy between robot and human and monitoring human bio signals during robot interaction.

3.2.8 Autonomous systems

Table 15. Needs assessment on autonomous systems

Autonomous systems	Trends/Need	P1	P2	P3	P4	P5	UC1	UC2	UC3	UC4	D1	D2	D3	D4
General robotics														
	Smart mechatronic systems, devices and components are seen to advance from vendor-locked solutions towards open source solutions and standards.		X			F		F						
	Liability for physical actions, privacy and direct affect to environment need to be addressed					F								
	Regulation harmonisation, standards and certificates need updates			F		F								
	Standardized information/knowledge/action sharing mechanisms among robots where multiple robotic systems are required				F	F							F	
	Interoperability through modularity and interfaces is needed		X		F	F			F					
	Communication technologies become essential due to robot platforms mobility					F			X				X	
	Operating environment knowledge enhanced by utilising external data sources					F								
	Cloud based analytics to support recognition and dealing with unknown objects								F					
	Fully autonomous vehicles and autonomous robots in shopfloors								F					
	Creation of innovation ecosystem that allows robots to use external data sources					F			F					
	Integrating robots into IoT and smartcity ecosystems, industrial asset management sytems and digital twins for data and knowledge sharing								F					F
	Cyber-security of robots to protect safety and user privacy			X		F			F					F
	Speed and agility of collaborative robots need to be increased while maintaining safety				F	F			X/F				F	F
Mobile robots (to replace conveyors)														
	Mobile manipulators with high speed and high precision localisation and navigation control													
	New generation of control algorithms to enhance overall precision								F					
	Safe and energy-efficient robots mounted on mobile platforms								F					
Fleet control														
	Distributed algorithms that coordinate behaviour of the swarm												F	
	Centralised/decentralised control of the swarm taking into consideration environmental constrains, multi-agent learning and self-repair.													
Drones (logistics, assembly)														
	High positional accuracy with low tolerances in assembly													
	Novel sensor systems working accurately over large spaces and position control algorithms								F					
Advanced autonomous systems														
	Skill transfer from human operator to robot (i.e. learning and/or neural networks etc.) in straightforward (spray-painting) and more complicated tasks (deburring)				F/X	F			F					F
	Robots as machine tools would require active high stiffness through robot drive motors and direct endpoint position measurement					F			F					
	Suitable sensors, grippers, smart programming and design for handling soft and limp materials.					F			X/F					
	Strategies and methods to control massive numbers of small robots operating collaboratively													

For further analysis, we ranked needs based on answers. For autonomous systems, they are as follows:

Table 16. Needs assessment ranked for autonomous systems

Autonomous systems	Trends/Need	X	F
	Communication technologies become essential due to robot platforms mobility	2	1
	Speed and agility of collaborative robots need to be increased while maintaining safety	1	5
	Skill transfer from human operator to robot (i.e. learning and/or neural networks etc.) in straightforward (spray-painting) and more complicated tasks (deburring)	1	4
	Interoperability through modularity and interfaces is needed	1	3
	Cyber-security of robots to protect safety and user privacy	1	3
	Smart mechatronic systems, devices and components are seen to advance from vendor-locked solutions towards open source solutions and standards.	1	2
	Suitable sensors, grippers, smart programming and design for handling soft and limp materials.	1	2
	Standardized information/knowledge/action sharing mechanisms among robots where multiple robotic systems are required	0	3
	Regulation harmonisation, standards and certificates need updates	0	2
	Creation of innovation ecosystem that allows robots to use external data sources	0	2
	Integrating robots into IoT and smartcity ecosystems, industrial asset management sytems and digital twins for data and knowledge sharing	0	2
	Robots as machine tools would require active high stiffness through robot drive motors and direct endpoint position measurement	0	2
	Liability for physical actions, privacy and direct affect to environment need to be addressed	0	1
	Operating environment knowledge enhanced by utilising external data sources	0	1
	Cloud based analytics to support recognition and dealing with unknown objects	0	1
	Fully autonomous vehicles and autonomous robots in shopfloors	0	1
	New generation of control algorithms to enhance overall precision	0	1
	Safe and energy-efficient robots mounted on mobile platforms	0	1
	Distributed algorithms that coordinate behaviour of the swarm	0	1
	Novel sensor systems working accurately over large spaces and position control algorithms	0	1
	Mobile manipulators with high speed and high precision localisation and navigation control	0	0
	Centralised/decentralised control of the swarm taking into consideration environmental constrains, multi-agent learning and self-repair.	0	0
	High positional accuracy with low tolerances in assembly	0	0
	Strategies and methods to control massive numbers of small robots operating collaboratively	0	0

European roadmaps identified needs for autonomous systems are visible but mostly approaching in IMOCO4.E cases only after IMOCO4.E. Especially increases in agility and speed of collaborative robots and skills transfer from human operators to robots are of interest. The need for interoperability and cyber-security of the robots is recognised to protect safety and user privacy and standardized information-sharing mechanisms among robots in case multiple robot systems are involved.

3.2.9 Future technological needs

We also collected information from IMOCO4.E case owners with regards to the most critical technologies they see becoming relevant in the next few years:

Table 17. Future technological needs

Case	Most critical technologies
P2	High-speed vision-in-the-loop control. Scalable AI processing for vision
P3	Microservices in industrial environment. Explainable AI. Human-centered paradigms.
P4	Digital (Twin) models driving and being re-used throughout the entire product cycle from initial concept exploration to development, manufacturing and service/maintenance processes.
P5	Advanced neural network / AI based algorithms and detection methods for object recognition in changing environments Data and information models (ecosystems) for seamless interoperability with other (robotized) work cycles/processes Remote control (and diagnostics) of mobile machines in harsh and limited bandwidth environments Reliable methods to sense and model dynamic environments (for motion control purposes) in harsh locations Adaptive and error-prone collision free path planning and execution of robot movements in dynamic environments
UC2	AI-based control algorithms using hybrid models
UC3	Advances in wireless technologies and uptake of TSN in an industrial setting. Future development of AI enabled computer vision system with both generalized and customized Industry 4.0 applications. Increased human robot interactions and collaborations incorporating both physical and cognitive tasks and processes. Real-time advances in CoBot dexterity and artificial cognitive understanding of humans, thus ever increasing the domains where robots can be deployed in the real world. Advancement in fields such as neuromorphic computing are also likely to compliment the above future developments.
D1	Fast and high precision 3D measurements.
D3	In the domain addressed in Demonstrator 3, visualization components, as well as powerful (often GPU based) integrable system components, will play an essential role in forming the basis for new AI approaches. If the performance cannot be integrated on the machine, a powerful communication technology plays an essential role. Due to the expected increasing number of autonomous Systems, a focus on energy saving aspects in the control and on energy optimized components necessary. Different kinds of cloud systems (web or edge) will be the enabler for enhanced AI developments.
D4	Faster video processing hardware to increase the computation-intensive perception speed of the full pick and place cycle. Easier to adapt AI perception models.

Although IMOCO4.E cases differ in domain and focus, a strong need for AI technologies and more complex models that take into account either other robots or humans can be seen.

3.2.10 Needs assessment conclusion

As seen in European Union's latest research programs, Industry 4.0 and European smart manufacturing are simultaneously going through two main transitions, green and digital. As different roadmaps summarised here indicate, there are many technological issues to be solved in order to keep European smart manufacturing companies and their technology operators competitive. The industrial needs are diverse and cover many different technology areas and domains in the context of mechatronics and robotics.

The needs assessment by end-users of IMOCO4.E shows that there is a difference in that which needs are seen as more relevant across the IMOCO4.E cases and which needs are seen as most relevant in the timeline of IMOCO4.E (until 2024), and which needs are becoming relevant only after IMOCO4.E (beyond 2024).

The needs assessment will be utilised during the IMOCO4.E in several ways. In order to be future-proof, reference architecture (final version in forthcoming D2.4) should address such requirements that are relevant now and take into account such needs that are likely to become relevant after the IMOCO4.E. IMOCO4.E tasks in technical WPs focus on solving specific technology challenges. The needs assessment should support the most relevant needs across the use cases and set goals for the given technology challenge. IMOCO4.E cases will verify the results of IMOCO4.E, and results will be measured as defined in the grant agreement. Needs assessment offers positioning of the results into the European smart manufacturing industry context.

Finally, IMOCO4.E solutions, i.e. building blocks, address specific solutions for the industry in intelligent motion control. The next section discusses building blocks and specific supporting technologies in each technology focus area relevant to the building block.

4. Identified solutions in IMOCO4.E

IMOCO4.E has identified several solutions (namely building blocks) that help European smart production in achieving the concept of industry 4.E and beyond in mechatronics and robotic systems.

For the purpose of positioning building blocks with regard to the European smart manufacturing needs, the following mapping was made for the building blocks based on the joint workshop with building block owners and partners.

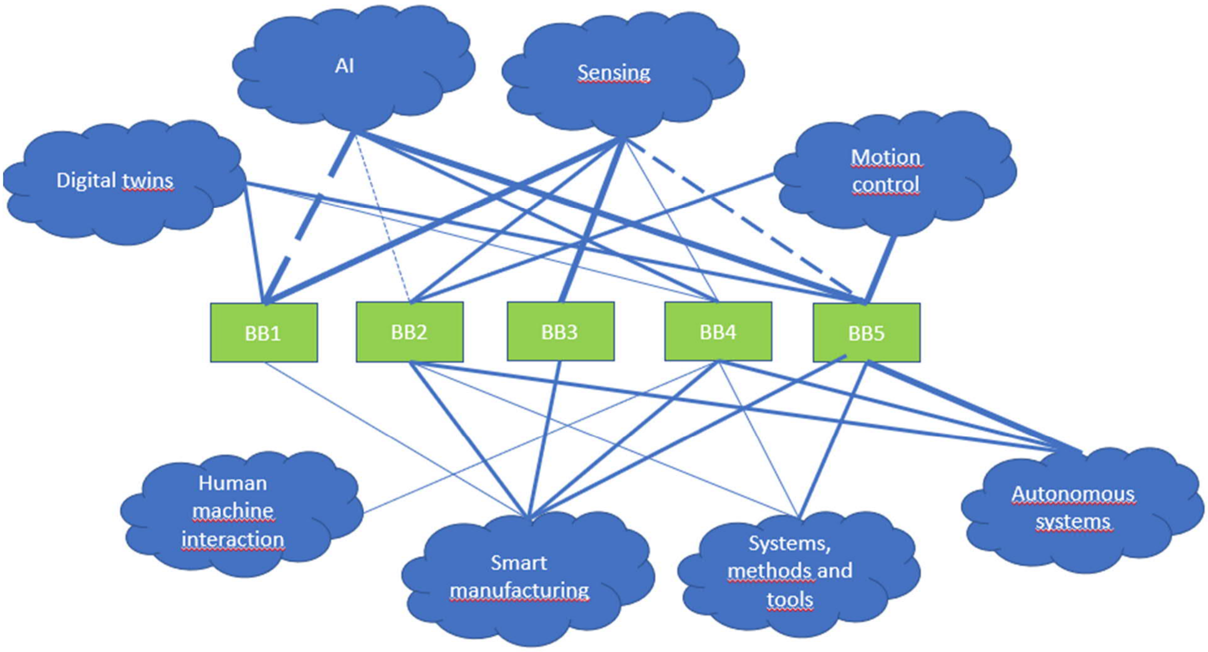

Figure 14. Mapping of building blocks BB1-BB5 to trends and needs

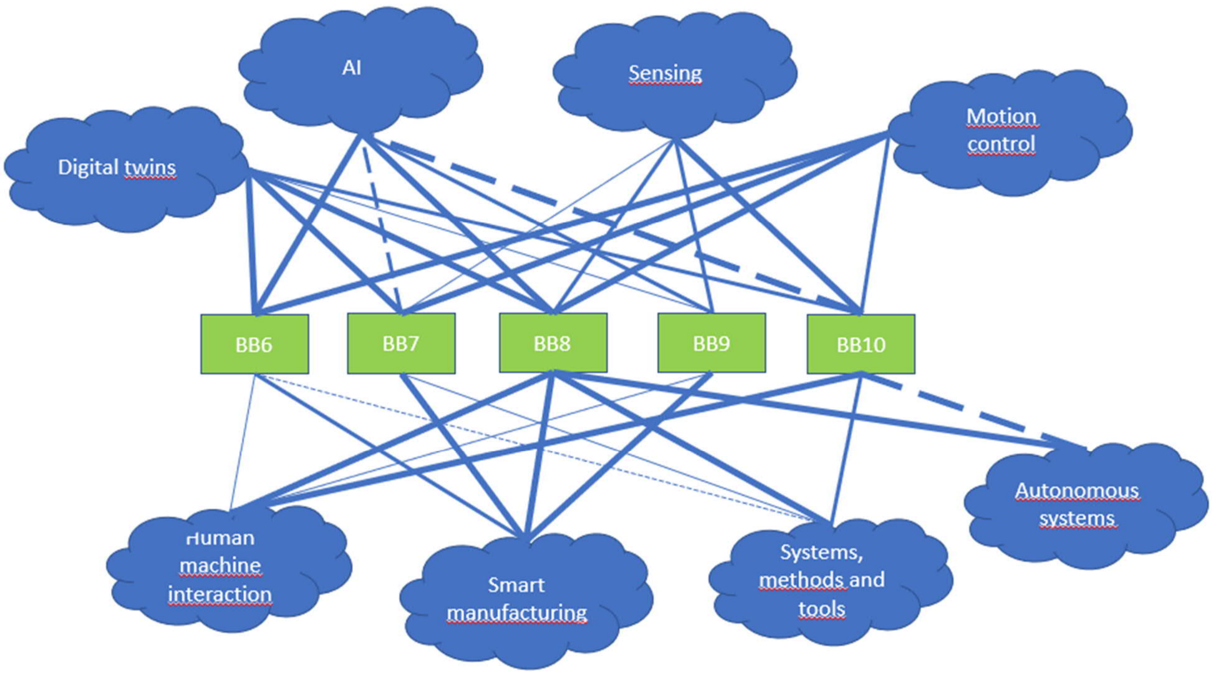

Figure 15. Mapping of building blocks BB6-BB10 to trends and needs

Each building block was mapped to trends/needs using the following system:

- No line: no identified trends/needs in this category
- Thin line: One trend/need identified in this category
- Thicker line: 2-3 trends identified in this category
- Thickest line: More than 3 trends/needs identified in this category
- Dotted thin line: One future trend/need identified in this category
- Dotted thicker line: 2-3 future trends/needs identified in this category
- Dotted thickest line: More than 3 future trends/needs identified in this category
- In case both current and future trends/needs were in the same category, the current was used as dominant when making the selection on line thickness.

The following section describes each building block and identifies bottlenecks (from D2.1) and smart manufacturing key technologies most relevant to building blocks. Smart manufacturing technology topics have been collected from the trends/needs list.

Technologies in the next section are divided into two parts, Within IMOCO4.E, i.e. technologies that will be addressed during the IMOCO4.E project in the selected building block. And After IMOCO4.E, i.e. technologies that link to needs that are not likely to be addressed during the IMOCO4.E building block development but instead are likely to become relevant in the near future after the IMOCO4.E and thus should be taken into account in the planning of future proof reference architecture.

4.1 Building block 1: SoC/FPGA platforms

This building block will rely on heterogeneous FPGA and microprocessors-based industrial AI-edge embedded computing platforms – as opposed to standard computer platforms – to incorporate high-performance computing close to the deep edge of the system. In line with the Industry 4.0 vision, standard and open methodologies will be applied at different layers to orchestrate the different elements while preserving the determinism and reliability of the control system. The direct interface with the physical signals will yield latency and performance to power ratio improvements. [12]

4.1.1 Identified shortcomings

The main shortcomings are the operationalization and deployment (inference) of AI-powered technologies on embedded devices. Mainly because embedded devices have different requirements, and their generally limited available computational resources and diversified architectures require tailored solutions, which usually lack an integrated toolchain. The integration of the already deployed sensors and fieldbuses into the Time Sensitive Network (TSN) will be another topic to be covered [12] if the technology development of TSN meets the project timeline. The TSN as an IEEE standard for real-time deterministic networking is under development and has not been completed yet.

4.1.2 Key technologies focus

Table 18 summarises technology topic (as identified from needs/trends analysis) and links it to supporting technologies. Table is divided into two sections: topics that are seen relevant within the IMOCO4.E project and those that are likely to become relevant in the future.

Table 18. Technology topics in BB1 with supporting technologies

<u>Within IMOCO4.E</u>

Technology topic	Specific feature (if identified	Supporting technologies
Advances in self-healing and redundant automation systems	Zero-time recovery	IEEE 802.1cb (seamless-redundancy)
	Network adaptation	Runtime monitoring and configuration compliant with IEEE 802.1Qcc/Qdj
Modularisation and standardisation of sensor interfaces, meta-information models	Standard interfaces	1GbE: 1000-Base-X Nw. timing: PTP, gPTP
Redundancy and industrial environment reliability	Zero-time recovery	IEEE 802.1cb (seamless-redundancy)
Processing nodes and sensors on the same network	Network convergence	Mixed-critical and deterministic QoS support based on IEEE 802.1Q time scheduled traffic.
	SoC FPGA platforms	Xilinx and Altera SoCs TSN stations present in the Edge. PolarFire SoC-FPGA with 5 RISC-V microprocessors, one E51 monitor core,

		four U54 application cores, and a 250,000 LE FPGA fabric.
Determinism in the real-time interpretation of sensor data	Low latency & jitter	IEEE 802.1Q time-based scheduling time-critical data stream QoS support.
	Time synchronization	Sub-µs time synchronization (gPTP/PTP)
Convergent infrastructure	Network convergence	Mixed-critical and deterministic QoS support based on IEEE 802.1Q time scheduled traffic.
Continuous design improvement utilising digital twins and virtual models	Network monitoring	IEEE 802.1Qcc compliant TSN traffic telemetry
	SoC FPGA platforms	Digital twin execution supported in the Edge

<u>After IMOCO4.E</u>

Technology topic	Supporting technologies
Trustworthiness of AI and robotics systems Naturally interpretable AI and explainable AI	Enhanced time synchronization and frequency distribution
	IEEE 802.1cb supporting redundant processing nodes.
Security and privacy technologies	IEEE 802.1Qci per-stream filtering and policing
	PTP securitization (RFC 7384).
Transparency of operations in uncertain conditions	Self network adaptation and IEEE 802.1cb seamless-redundancy
Reliable real-time decision-making in a dynamic environment	Advanced network adaptation based on IEEE 802.1Qcc/Qdj

4.2 BB2 High speed Vision in the Loop

Building Block 2 will fuse requirements from High-Performance Computing (HPC) and high-speed camera data acquisition on a Real-Time deterministic computing platform. Applications will include co-located closed-loop feedback control and will implement algorithms from classic control as well as various machine learning algorithms. [12]

4.2.1 Identified shortcomings

Although learning control has increased a lot in the last few years, by, for instance, adding (rational) basis functions, learning control for complex (linear parameter varying, multi-rate, etc.) systems can still be improved. This can be explained since, typically, black-box methods are used for these complex systems, where the known structure of the system is lost. [12]

Complex programming interface excluding utilisation of tested mainstream software libraries. Although AI and machine vision algorithms have developed greatly during the last decennium, alas, the emphasis on time-critical and time deterministic requirements has lagged. [12]

State of the art machine learning algorithms for object detection and image classification are usually compute-intensive and thus may have higher inferencing latencies, whereas closed-loop control systems are more likely to have low latency requirements for a control cycle. [12]

4.2.2 Key technologies focus

Table 19 summarises the technology topic (as identified from needs/trends analysis) and links it to supporting technologies. The table is divided into two sections, namely those topics that are seen as relevant within the IMOCO4.E project and those topics that are likely to become relevant in the future.

Table 19. Technology topics in BB2 with supporting technologies

Within IMOCO4.E

Technology topic	Specific feature (if identified	Supporting technologies
Dynamic digital twins that contain current statuses of manufacturing	Real-time model-based control updated by high-speed camera inputs	Industrial interfaces such as CoaXPress, CameraLink and PCIe
Integration of self-monitoring, self-assessment, self-learning and self-adjusting concepts with AI	Iterative learning control or reinforcement learning	Application-specific
Novel sensing and sensor systems in challenging environments and low cost, low energy, high accuracy sensors	New metrological concepts that reduce complexity	Application-specific
Matching local point of view with worlds views		Classic image processing augmented with Deep Learning
Motion control systems that are continuously able to identify (changing) physical parameters to adapt and optimize feedback action	Vision in the loop	Application-specific
Centralized motion control algorithms on scalable multi-core platforms that meet real-time execution requirements	HPC merging real-time requirements	GPGPU and multi-many cores. Maybe POSIX
Open-source solutions and standards instead of vendor-locked systems	GPGPU	OpenCL, Linux
Interoperability through modularity and interfaces		OpenCL, Linux
Robots as machine tools – active high stiffness through robot motors and direct endpoint position measurement	Motion control tuning over high bandwidth control	Application-specific

After IMOCO4.E

Technology topic	Supporting technologies
Feedback control technologies that optimize their performance during repeated tasks	High-speed vision-in-the-loop
Detecting and rejecting residual errors by means of digital twins	High-speed vision-in-the-loop

4.3 BB3 Novel sensors

BB3 deals with the development of sensing ecosystems that are typically applied in motion control systems. Since this is still a very broad definition, the scope of BB3 in the IMOCO4.E project is deliberately narrowed down to the following exemplary sensor types [12]:

- Radar
- Overmolded sensor
- Event camera
- Vibration sensor
- 3D Depth Sensor

4.3.1 Identified shortcomings

Radar

Radar antennas and frontend are not suitable for Demo 3 (forklift application). A new radar frontend with a re-designed antenna is required. Data interface(s) to be adapted to Demo 3, data formats to be defined with partners, data interfaces and formats capable of obstacle detection, path planning and autonomous navigation in industrial environment. Processor capabilities not usable for AI and neural network algorithms implementation, a new radar backend with AI processing capabilities. [12]

Overmolded sensor

The main challenges regarding overmolding sensors are the thermal expansion coefficients mismatch between the sensor die material (mostly silicon) and the injected polymer, which can cause destructive stress on the sensor structure. [12]

Event camera

In terms of technology, DVS sensors only respond to moving objects in a visual scene if the sensor is placed still and cannot capture static images; The advantage of output sparsity is lost if the sensor moves; High pixel bandwidth makes it sensitive to frequency components that're not visible to human eyes, like light flickering etc.; power advantage over conventional CMOS image sensor at the expense of coarse signal quantization. [12]

Vibration sensor

The main challenge is to provide a solution that will convince demo owners or end-users that the implementation of additional sensors for machine condition monitoring using vibration sensing is beneficial and would help avoid unexpected downtimes or serious damages. On a technical level, there could be limitations in the operational time of the device and the need for periodic service/replacement/charging of the sensor node. Also, integrating a designed sensor network node into a specific application can be an implementation challenge, including the dimension and weight of the sensor. [12]

3D Depth Sensing

3D depth-sensing technologies can provide some advantages over traditional 2D laser scanners or alternative 3D vision-based technologies such as stereo vision. There are some specific challenges related to the robotics domain, specifically around reliable movement detection (as in UC3 demonstrator). Providing high enough resolution (<5mm) at a reasonable frame rate (>30fps), in different ambient light conditions over temperature, and in a wide reflectivity range is challenging to achieve in a cost-effective manner with state of the art solutions.

4.3.2 Key technologies focus

Table 20 summarises technology topic (as identified from needs/trends analysis) and links it to supporting technologies. The table is divided into two sections: topics that are seen relevant within the IMOCO4.E project and those that are likely to become relevant in the future.

Table 20. Technology topics in BB3 with supporting technologies

Within IMOCO4.E

Technology topic	Specific feature (if identified	Supporting technologies
Advances in self-healing and redundant automation systems		
Modularisation and standardisation of sensor interfaces, meta-information models		External data interfaces: Ethernet, USB, wireless (WiFi/BLE) Internal data interfaces: CSI-2, SPI, I2C, RS232 Low power wireless communication interface (BLE, IEEE 802.15.4)
Novel sensing and sensor systems in challenging environments and low cost, low energy, high accuracy sensors	Low cost, low energy, high accuracy vibration sensors	Miniaturization and integration, low power consuming devices, low power sensing elements, power-optimized wireless communication
Development of advanced sensors that can adapt and self-calibrate, zero-energy sensors and embedded sensors	Self-powered sensors Overmolded sensors	NFC technology
Real-time interpretation of sensor data, particularly in complex environments or where multi-modal data must be fused or correlated to increase self-awareness of robotic systems		
Matching local point of view with worlds views	Low motion distortion 3D depth sensor	

Fusion of machine learning and model-based approaches to ensure generality, robustness and accuracy.	Integrated signal processing in the vibration sensor	
Faster and more accurate methods of perception that cover all data modalities and can operate in a wide range of conditions (weather, objects, behaviour and human interactions)	Radar sensor	
Full 3D perception systems and sensors able to decompose and interpret whole scenes in real-time to 4D	3D depth sensing	3D Time of Flight (ToF) Depth Sensor based on CMOS sensor technology

After IMOCO4.E

Technology topic	Supporting technologies
Data fusion methodologies for multi-source heterogeneous data	
Interoperable cyber-secure IoT architectures with data analytics and semantics support	
Modularisation and standardisation of sensor interfaces, meta-information models	
Suitable sensors, grippers, smart programming and design for handling soft and limp materials.	
Methods to validate and certify sensor systems for privacy, safety, trustworthiness etc.	
Reliability of sensing in harsh environments and in diverse environments as well as in small scale environments	CMOS 3D depth-sensing technology
Sensor-based reconfiguration of flexible robotic cells integrating multiple sensors (vision, RFID, presence…)	CMOS 3D depth-sensing technology

4.4 BB4 Real-Time Smart-Control Platform

The goal of BB4 is to enable multiple different workloads at the edge on a single board while ensuring safety and performance. The use of hypervisors will allow partitioning of the available computing resources to separate the AI models from the smart control algorithms or the vision-in-the-loop and enhance the performance guarantee required for the system. In addition to the computation, communication between edge devices and the digital twin will be performed by latency-aware mechanisms, such as TSN or EtherCAT, in order to improve the reliability while guaranteeing the required performance. [12]

In this way, it is necessary to focus on different aspects of a platform suitable for that purpose:

- Data processing capacity
- Communication capabilities
- Partitioning
- Flexibility and programmability

4.4.1 Identified shortcomings

Shortcomings are identified in many places. At the Digital Twin layer, BB4 will enhance quality checks, alarm detection, and recovery to further increase automation and efficiency. BB4 will enable modular and efficient application development of onboard machines at the edge layer. In between, BB4 will facilitate reliable multi-machine communication (M2M). BB4 will also facilitate the necessary intra- and interprocess communication and the ability to take advantage of multithreading or parallel computing on multiple cores. This includes a framework that allows the integration of generated and/or legacy code from external origins (such as Simulink models). BB4 also provides a flexible Hardware Abstraction Layer to accommodate projects with different hardware connections (like EtherCAT). [12]

There is a clear lack in the identified platform solutions landscape (current market, coming trends, and partners solutions); it is related to a single platform which seamlessly integrates all the requirements for the BB4: real-time processing and communications, vast data processing capabilities, advanced features to speed-up ML/AI applications required operations, multi-core approach, heterogeneous L2-L3 communication plane, modularity, reconfigurability, etc. It is a need to create such a platform, and it will be done by task 3.3. [12]

4.4.2 Key technologies focus

Table 21 summarises the technology topic (as identified from needs/trends analysis) and links it to supporting technologies. The table is divided into two sections: topics that are seen relevant within the IMOCO4.E project and those that are likely to become relevant in the future.

Table 21. Technology topics in BB4 with supporting technologies

<u>Within IMOCO4.E</u>

Technology topic	Specific feature (if identified	Supporting technologies
Processing nodes and sensors on the same network	Network convergence	Mixed-critical and deterministic QoS support based on IEEE 802.1Q time scheduled traffic.
	SoC FPGA platforms	Xilinx and Altera SoCs TSN stations present in the Edge.
Determinism in real-time interpretation of sensor data	Low latency & jitter	IEEE 802.1Q time-based scheduling time-critical data stream QoS support.
	Time synchronization	Sub-µs time synchronization (gPTP/PTP)
Convergent infrastructure	Network convergence	Mixed-critical and deterministic QoS support based on IEEE 802.1Q time scheduled traffic.
Continuous design improvement utilizing digital twins and virtual models	Network monitoring	IEEE 802.1Qcc compliant TSN traffic telemetry

	HeSoC platforms	Digital twin execution supported in the Edge
Support for both natural and artificial cognition in production	HeSoC platforms with AI acceleration	SoCs present at the Edge, including FPGA, GP-GPU, Neural network engines
Computing Hardware Virtualisation	Operating system heterogeneity	Partitioning hypervisors to isolate applications Arm v8 virtualization extensions
Enabling technologies: real-time networking	Network convergence	SoC FPGA with TSN capable switch
Isolation from virtualisation, security extensions in TSN	Isolation enforcement	Arm v8 virtualization extensions
Flexible TSN configurations	SoC FPGA platforms	External global configuration of the switches
Mixed-criticality for safety-, security- and privacy- relevant environments	Isolation enforcement	Hypervisor and RTOS with strong isolation properties
Methods for handling security and privacy	Isolation enforcement	Isolation from virtualization, security extensions in TSN for handling security and privacy
Safety assurance of high-level decision-making	Isolation by design	Latency safety, functional safety is offered by the couple TSN and virtualization that we offer to not only the decision-making algorithms but any client application
	OS support	RTOS support with, e.g. Erika, FreeRTOS, Zephyr, NuttX
Deep neural networks	HeSoC platforms with AI acceleration	AI-enabled platforms, i.e. Nvidia Jetson Xavier, Huawei Atlas 200DK

After IMOCO4.E

Technology topic	Supporting technologies
Holistic and multidisciplinary approaches to improve the understanding of system behaviour, modelling and simulation	The inherent determinism of TSN is a means to improve and help system design.
Regulation harmonisation, standards and certificates need updates	

4.5 BB5 Smart control algorithms library

Building block 5 constitutes a framework for smart control algorithms. The framework covers key solutions for mechatronic systems, ranging from feedback algorithms, including vibration damping, force control, predictive control, and robust control, to data-driven learning algorithms, covering repetitive control, iterative learning control, and machine learning algorithms. Both centralized or SISO (Task 4.3) and decentralized or MIMO (Task 4.4) controllers are included in BB5. [12]

4.5.1 Identified shortcomings

COTS controllers for motion control applications (PLC/CNC) offer very limited advanced control functionalities. Some of them do not present the means to implement ad-hoc functionalities properly. For example, impedance control application in robot manipulators is limited as most manufacturers do not even allow controlling joint drives at a proper rate. In addition, COTS solutions and required licenses are usually very expensive. On the other hand, open-source and free tools are not very useful sometimes. [12]

Although learning control has increased a lot in the last few years, by, for instance, adding (rational) basis functions, learning control for complex (linear parameter varying, multi-rate, etc.) systems can still be improved. This can be explained since, typically, black-box methods are used for these complex systems, where the known structure of the system is lost. Although AI and machine vision algorithms have developed greatly during the last decennium, alas, the emphasis on time-critical and time deterministic requirements has lagged. [12]

4.5.2 Key technologies focus

Table 22 summarises the technology topic (as identified from needs/trends analysis) and links it to supporting technologies. The table is divided into two sections: topics that are seen relevant within the IMOCO4.E project and those that are likely to become relevant in the future.

Table 22. Technology topics in BB5 with supporting technologies

Within IMOCO4.E

Technology topic	Specific feature (if identified	Supporting technologies
Holistic and multidisciplinary approaches to improve the understanding of system behaviour, modelling and simulation	xIL approach for model-based design (Task 4.2, not directly BB5)	Simulink+Simscape SIEMENS Amesim Co-Simulation approaches Model reduction techniques
Real-time digital twins emulating system and its dynamics	xIL approach for model-based design (Task 4.2, not directly BB5)	Simulink+Simscape Code Generation
Co-operating robots that can change tasks and position – collaborative robotics	Compliant control	Compliant-impedance control Compliant joint/actuators Cobots available in the market

Sensor-based reconfiguration of flexible robotic cells integrating multiple sensors (vision, RFID, presence…)	BB10	
Edge-to-cloud intelligence for motion control, i.e. a scalable and structured approach to intelligent motion control in which intelligence features are distributed	Inverse model identification of LPV/position-dependent systems. Data-driven learning for robot dynamic modelling	System identification applied in feedforward control Off-line machine learning
Motion control systems that are continuously able to identify (changing) physical parameters to adapt and optimize feedback action	Friction compensation Impedance Control	State Observers/Estimators Feedback control
Feedback control technologies that optimize their performance during repeated tasks	Multivariable Iterative Learning Control	Iterative Learning Control
Motion control system layers that can “perceive” the machine, “understand” the physics and “solve” the design and maintenance problems throughout the lifecycle		Feedforward control based on model identification?
Centralized motion control algorithms that meet real-time execution requirements	Centralized control functionalities: - Multivariable ILC - MIMO control - Machine Learning-based robot compliant control	MIMO control. Matlab/Simulink Hardware: BB4
Detecting and rejecting residual vibrations by means of digital twins	Active and passive vibration damping Vibration damping in time-varying elastic systems	Model-based feedforward control and feedback loop tuning
Effective collaboration of humans and AI-tools	Machine Learning-based robot compliant control Impedance Control	Force sensors Kinematic calculations Robot dynamic models Gazebo (simulation)
AI does not negatively impact the safety of people using robots or in vicinity of them while providing advantages through improved operation	Machine Learning-based robot compliant control Impedance Control	Force sensors Kinematic calculations Robot dynamic models Gazebo (simulation)

AI enabling the building of effective models that allow broader and deeper decisional autonomy	Machine Learning-based robot compliant control	Machine Learning
Robot learning of actions and control	Machine Learning-based robot compliant control	Machine Learning Iterative Learning Control
Deep neural networks	Machine Learning-based robot compliant control	Machine Learning
Advanced learning methods to ensure scalability, reusability and explain-ability	Machine Learning-based robot compliant control Multivariable Iterative Learning Control	Machine Learning Iterative Learning Control
Simulator-based design: continuous design improvement utilizing digital twins and virtual models	xIL approach for model-based design (Task 4.2, not directly BB5)	Simulink+Simscape SIEMENS Amesim Co-Simulation approaches Model reduction techniques
Digital twins as a combination of physics and knowledge-based models	xIL approach for model-based design (Task 4.2, not directly BB5)	Simulink+Simscape SIEMENS Amesim Co-Simulation approaches Model reduction techniques
Design methods and systems that create and ensure long term reliability and dependability taking certification and trustworthiness into account	xIL approach for model-based design (Task 4.2, not directly BB5)	FMU Matlab/Simulink: code generation
Multidisciplinary approach for improving understanding of the system behaviour, modelling and simulation	xIL approach for model-based design (Task 4.2, not directly BB5)	FMU Simulink+Simscape SIEMENS Amesim Co-Simulation approaches Model reduction techniques System identification
Intuitive configuration tools that reduce the need to use robot specialists	Machine Learning-based robot compliant control Impedance Control	Assuming robot specialists in a broad sense, e.g. automatic control algorithms that remove the need for an engineer to model a system
High positional accuracy with low tolerances in assembly	Friction compensation Impedance Control Active and passive vibration damping Vibration damping in time-varying elastic systems Multivariable Iterative Learning Control	
Robots as machine tools would require active high stiffness through robot drive motors and direct endpoint position measurement	Accuracy improvement of industrial robots	Secondary encoders Compensation using external measurement systems

After IMOCO4.E

Technology topic	Supporting technologies
Advances in self-healing and redundant automation systems	Self-diagnostics
Fusion of machine learning and model-based approaches to ensure generality, robustness and accuracy.	Hybrid models for feedback and feedforward control strategies with continuous learning of system characteristics

4.6 BB6 Algorithms for condition monitoring, predictive maintenance and self-commissioning of industrial motion control systems

4.6.1 Identified shortcomings

Multiphase drives require special hardware, i.e. motor, inverter and controller. They also require special software for the control of multiphase drives, for the diagnostics and for the control during functional fault. The redundancy concept leads to the utilization of more components and thus to higher complexity. [12]

4.6.2 Key technologies focus

Table 23 summarises technology topic (as identified from needs/trends analysis) and links it to supporting technologies. Table is divided into two sections, namely those topics that are seen relevant within the IMOCO4.E project and those topics that are likely to become relevant in the future.

Table 23. Technology topics in BB6 with supporting technologies

Within IMOCO4.E

Technology topic	Specific feature (if identified	Supporting technologies
Sharing of data between different partners in order to improve AI algorithms		MQTT, MATLAB
Holistic and multidisciplinary approaches to improve the understanding of system behaviour, modelling and simulation		MATLAB, Simulink/Simscape, Amesim
Hybrid manufacturing simulation models (machine, cell, line, site)		MATLAB, Simulink/Simscape, Amesim
Edge-to-cloud intelligence for motion control, i.e. a scalable and structured approach to intelligent motion control in which intelligence features are distributed across different layers.	Cloud storage of synthetic indexes on performance and monitoring	Fieldbuses, MQTT
Motion control systems that can measure the performance of all	Control performance assessment	Control performance assessment

instrumented components, like drives, sensors, actuators and using this data for predictive maintenance (for instance, via digital twins and AI techniques)	Scheduled maintenance based on condition monitoring.	Sensing and data acquisition, data management, data processing and interpretation.
	Diagnostics of inverter components.	MATLAB, Simulink/Simscape, ANN, sensors.
Motion control systems that are continuously able to identify (changing) physical parameters to adapt and optimize feedback action	Online model identification	Model identification
Motion control system layers that can “perceive” the machine, “understand” the physics and “solve” the design and maintenance problems throughout the lifecycle		Model and disturbance estimation, self-tuning, self-diagnostic
Detecting and rejecting residual vibrations by means of digital twins	Vibration model and estimation	MATLAB, Simulink/Simscape, Amesim
Scaling and integration of AI systems ensuring that simple AI models may be combined into federated systems		elastic weight consolidation, knowledge distillation and federated learning
Methods for knowledge modelling and representation that enable seamless integration of data and connection to the physical world		KKR techniques for modelling and verification
Methods that integrate data-driven and knowledge-based approaches	Digital-twin continuous update during the lifecycle	Learning toolbox (Pytorch, Tensorflow, MATLAB) MATLAB, Simulink/Simscape, Amesim
Merging powerful deep learning techniques with reasoning/knowledge-based approaches.		Learning toolbox (Pytorch, Tensorflow, Matlab)
Simplified AI toolsets configurable without highly skilled personnel		User-friendly tools for data-driven learning
Augmented decision-making that complements human capabilities		Self-diagnostic and self-tuning
Decision-making dealing with unseen situations		AI-Based and Model. Based anomaly detection
Trustworthy and robust hybrid AI-based decision making		
Reliable real-time decision making in dynamic and multi-actor environments		
Tracking mode simulation: model adoption based on measurements		Digital-twin continuous update during the lifecycle Self-tuning
Simulator-based design: continuous design improvement utilizing digital twins and virtual models		Digital-twin continuous update during the lifecycle
Digital twins as a combination of physics and knowledge-based models		Digital-twin continuous update during the lifecycle

Humans and knowledge integration, human in the loop simulations and networked simulations		Digital/VR simulator XIL design and prototyping
Digital twins for complex processes		Modular approach, model-based data-driven and knowledge-driven approach
Development of digital twins that can be interpreted, used and operated by domain experts instead of only by data scientists or ICT experts		Knowledge, Representation and Reasoning (KRR) techniques
Integration of interactive simulation technology for digital twins into AR and VR user experiences		VR telepresence
Development of interaction technologies using VR and AR and their relation to human interaction		Digital/VR simulator

After IMOCO4.E

Technology topic	Supporting technologies
Naturally interpretable AI and explainable AI	
Virtual commissioning to bring collaboration between different disciplines and models in the same environment and interoperability to use applications across platforms	
Autonomous capabilities development in the digital environment	
Digital twins applied to sustainability and circular economy	
Multidisciplinary approach for improving understanding of the system behaviour, modelling and simulation	

4.7 BB7 Algorithms for condition monitoring, predictive maintenance and self-commissioning of industrial motion control systems

Miniature DC servo drive with advanced motion control features and EtherCAT communication, with the possibility to add a custom control algorithm into the drive firmware. [12]

4.7.1 Identified shortcomings

There are still only a few out of the box and open solutions to build a motion control system connected to a Windows/Linux master. EtherCAT is relatively open (e.g. SOEM, SOES), but building a real-time EtherCAT master within an RTOS and to configure it to run alongside Windows/Linux requires a lot of experience and knowledge. [12]

Commercial servo drives have limited or inflexible options to stream internal signals for diagnosis, especially signals at a faster rate than the servo loop (for instance, the current control signals). These signals are essential for high-quality current control tuning. Only a few available solutions allow user-defined algorithms to be directly incorporated into the drive firmware. [12]

4.7.2 Key technologies focus

Table 24 summarises the technology topic (as identified from needs/trends analysis) and links it to supporting technologies. The table is divided into two sections: topics that are seen relevant within the IMOCO4.E project and those that are likely to become relevant in the future.

Table 24. Technology topics in BB7 with supporting technologies

Technology topic	Specific feature (if identified	Supporting technologies
Advances in self-healing and redundant automation systems	Detection of changes in system dynamics based on repetitive control algorithm data analysis	Data analysis tools
Co-operating robots that can change tasks and position	Contribution to impedance control for cooperative robotics security	Control system toolbox
Integration of self-monitoring, self-assessment, self-learning and self-adjusting concepts with AI	Low-level monitoring of drive parameters and alarms	Data analysis tools
Resource and energy efficiency	Repetitive control contributes to energy efficiency for periodic tasks	N/A
Novel sensing and sensor systems in challenging environments and low cost, low energy, high accuracy sensors	Inertial sensor integrated on servo drive electronics, allowing identification of drive position	N/A

Edge-to-cloud intelligence for motion control, i.e., a scalable and structured approach to intelligent motion control in which intelligence features are distributed across different layers.	BB7 is suitable for vertically distributed repetitive control, and it will cooperate with trajectory generators at higher layers	N/A
Motion control systems that can measure the performance of all instrumented components, like drives, sensors, actuators and using this data for predictive maintenance (for instance, via digital twins and AI techniques)	BB7 will contribute to drives' monitoring and diagnostics	N/A
Motion control systems that are continuously able to identify (changing) physical parameters to adapt and optimize feedback action	Repetitive control which is able to detect changing parameters or disturbances	EtherCAT, MATLAB, Rexygen, control system toolbox, identification toolbox
Feedback control technologies that optimize their performance during repeated tasks	Repetitive control	EtherCAT, MATLAB, Rexygen, control system toolbox, identification toolbox
Detecting and rejecting residual vibrations by means of digital twins	For periodic vibrations, repetitive control can be used to reject vibrations	
Digital twins as a combination of physics and knowledge-based models	Realtime internal drive signals access	EtherCAT, MATLAB
Develop robotics specific components for robotics use	BB7 can be customized for various use cases	N/A
Multidisciplinary approach for improving understanding of the system behaviour, modelling and simulation	BB7 includes knowledge in hardware, software, sensors, interfaces	MATLAB, Rexygen

<u>After IMOCO4.E</u>

Technology topic	Supporting technologies
Monitoring energy, resources and waste and lifecycle assessment	Advanced drive monitoring
Large datasets for training AI algorithms	Machine learning platforms
Robot learning of actions and control	Smart repetitive control
Long term energy sustainable robot systems in diverse harsh environments (underground, submerged) in different scale robots	Electronic packaging techniques for harsh environments

4.8 BB8 AI, Machine learning, deep learning algorithms (real-time part)

4.8.1 Identified shortcomings

Current partner solutions (EDI pick & place robot) and market-ready SotA approaches can be fine-tuned to a specific task, but in a use-case defined by partner MADARA, where the robot has to manipulate many different objects, pick them from differently packed boxes, and has to be able to easily learn new objects, the current approaches require a lot of manual labelling and machine learning expertise. EDI's synthetic data approach still requires some data acquisition because of the gap between real and generated data. Also, the current approach allows robots to learn perception but not action. [12]

4.8.2 Key technologies focus

Table 25 summarises the technology topic (as identified from needs/trends analysis) and links it to supporting technologies. The table is divided into two sections: topics that are seen relevant within the IMOCO4.E project and those that are likely to become relevant in the future. As BB8 is an AI building block, the technology topics it covers are broad and thus presented at a more upper level than in the case of other BBs.

Table 25. Technology topics in BB8 with supporting technologies

<u>Within IMOCO4.E</u>

Technology topic	Specific feature (if identified)	Supporting technologies
Responsive and smart manufacturing	High-accuracy and high-speed perception	Dynamic Vision Sensor (DVS) based perception system AI-supported human movement in 3D using ToF camera technologies. AI-supported human hand movement using HMI technologies.
	Long-term analytics (clustering) and anomaly detection for control algorithm performance evaluation and optimisation	ElasticSearch, Python, Kafka Streams, KSQL
	New approaches for automated quality checks.	

Dynamic and flexible manufacturing	New approaches for dynamic parameter changes.	
Agile manufacturing	Partial self-learning, retraining of robots to work with new objects and in limited changes of the task.	Reinforcement Learning, Sim2Real transfer, robot simulation software.
	Autonomous working of industrial robots.	DNN-based perception, RL-based motion planning. Use of AI/ML algorithms to improve latency in teleoperated industrial robots.
Customer-driven manufacturing		
Sustainable and circular manufacturing	Perception computation on edge devices	FPGA, SoCs, tools for converting DNN models to FPGA implementation.
Sensing	High-speed inference	MobileNet or EfficientNet and position identification of a semiconductor die based on those models
	Perception functionalities to enable automatic adjustment of machine behaviour	
	Data acquisition from heterogeneous sources	AI-supported sensing approaches using ToF cameras and HMI devices.
Sensing - perception	Robust perception working in changing environment.	Deep Neural Network-based object detectors, image segmentators. OCR for text detection + recognition. Advanced AI/ML algorithms used to support sensing of the human arm and hand movement applied to teleoperated robotics.
Sensing - Flexible production	Reconfigurable distributed perception network	Distributed data acquisition topology and sensor fusion algorithm to work on a CAN bus heterogeneous sensor network
Motion control	Visual servoing	Moveable camera by using motor-controlled axis, zoom or kinematics of a robot

	Scheduled maintenance based on condition monitoring	Sensing and data acquisition, data management, data processing and interpretation
AI - general	Improved inference speed and scalability	Deep Neural Networks, Supervised, Unsupervised, and Reinforcement Learning, Synthetic data generation. Use of CNNs deployed at local and remote SoC – FPGA devices for tele-operated robotics use cases. Research and development into the use of AI/ML techniques in the management and support of sensor errors/noise.
	Perception functionalities to enable automatic adjustment of machine behaviour	
	Data acquisition in distributed architectures	
	Data acquisition from heterogeneous sources	
	AI algorithms working on synthetic data or those generated via other BB solutions (e.g., BB2/BB4)	
	Coping with possibly missing info in available machine logs (no info on the real sensor used)	
AI – methods integration	Neural networks on embedded systems	TensorRT, TensorFlow Lite, Quantization, CNNs on SoC – FPGAs.
	New modelling approaches to highlight interdependences among independently designed machine parts	
AI – human interaction	Easy control and teaching of robots by humans.	Preference-based Reinforcement Learning, Imitation Learning
AI – decision making	Alert generation, Report Generation, Data analytics interactive visualizations	Kafka message broker, Grafana, Laravel, React

	Real-time decision-making functionalities	Reinforcement Learning, DNN-based planning
AI - learning	AI optimization, Knowledge Distillation	
	High-performance access to historical data	ElasticSearch
	New approaches for data correlation extraction in the presence of unbalanced data sets	Data augmentation, data generation through virtual worlds (Unity, Unreal, Blender, Isaac Sim, Ignition Gazebo) Taking AI cloud-based solutions and re-engineering and scaling for edge-based deployments.
	Ability to learn from a very small amount of real, labelled data	
	Continuous learning systems	
Digital twins	Synthetic data for training	Isaac Sim, Ignition Gazebo, Unity engine, Blender, Unreal
Systems, methods and tools	Open Source	TensorFlow, Keras, PyTorch, OpenCV, ROS, Linux, RTOS, partitioning hypervisor
	New architecture reference for app development	
	New approaches for multi-machine communications	
	Security by design and by default	
Development of interaction technologies using VR and AR and their relation to human interaction	Low power, low latency, multiple heterogeneous sensor data acquisition and processing capability.	End-point neural network processor or module of high computing efficiency and small form-factor. Light-weight fusion algorithm for high-speed vision sensor (e.g., DVS), microphone, vibration and inertial sensor, etc. Capture and processing of ToF camera data and HMI - IMU data for VR and AR interaction technologies.

Human-machine interaction - safety		Preference-based Reinforcement Learning, Virtual Reality / Augmented Reality
Human-machine interaction – control & interaction		Imitation learning, gesture recognition, DNN-based perception. Use of ToF camera and HMI for human interaction and control.
Human-machine interaction – Human-centred manufacturing		Use of AI to support humans in the loop for teleoperated robotics.
Autonomous systems – general robotics	Robots are capable of adapting to changes in the environment using external camera data	Linux, 3D cameras, DNN-based object detection.
Advanced autonomous systems	Autonomous or semi-autonomous operations for quality check and alarm detection and classification (i.e., the suggestion of recovery actions)	Linux, visual scene understanding using deep learning-based methods, object recognition, imitation learning

After IMOCO4.E

Technology topic	Supporting technologies
Interoperable cyber-secure IoT architectures with data analytics and semantics support	Anomaly (cyber-security threat) detection
Solutions for efficient mass customization and mass personalization	Generative models (GAN, VAE, diffusion models). AI tools and methods to provide increased robot dexterity for humans-in-the-loop interacting with teleoperated robotic platforms.
Zero-defect manufacturing in personalized production, industry4.0 for customized manufacturing systems (self-adjusting plug and play, self-adaptive etc.)	Reinforcement Learning, Online learning, Isaac Sim, Ignition Gazebo
Resource and energy efficiency	TinyML, FPGA, SoC, ASIC implementation. Increased performance, range of ML algorithms, and energy efficiencies for AI processing on edge-based devices. The emergence of dedicated AI edge devices with optimization for specific applications such as ToF operations.
Monitoring energy, resources and waste and lifecycle assessment	
Virtual AI assistants helping with optimization	Chatbots
Design for remanufacturing, refurbishment and recycling	

Tracking mode simulation: model adoption based on measurements	
Digital twins applied to sustainability and circular economy	
Future digital twins could be the "single source of truth" at any moment in time	Digital twins as the standard interface for interaction with teleoperated robotic platforms.
Long term energy sustainable robot systems in diverse harsh environments (underground, submerged) in different scale robots	Ultra-low-power (sub-mWatt) end-point machine learning and neural network inference processing platform for always-on environment perception, positioning, path planning and motion control.
Natural human interaction	Imitation learning, DNN-based human pose, gesture, and voice command recognition. Increased precision and haptic feedback for humans-in-the-loop in teleoperated robotic solutions.
Sharing of the autonomy between human and robot	
Prediction of human behaviour when helping operator to guide a robot	
Social interpretation & understanding of human intention and robot interaction	DNN-based action recognition, gesture recognition, speech recognition. Increasing support and advancement of AI and Affective Computing (AC) tools and techniques for human intention and robot interaction.
Remote operations and advanced perception	End-point/distributed smart sensors with machine learning and decision-making capability to enable low data-rate and short message remote communication.
Advanced behavioural and cognitive models for humans in manufacturing	
Building concepts of human-understandable socialized behaviour for robots	Use and integration of AI-powered AC advancements to increase both the understanding and processing of human social behaviour/interaction by machines and robots.
Cyber-security of robots to protect safety and user privacy	Edge processing.
The speed and agility of collaborative robots need to be increased while maintaining safety	Soft robotics, real-time vision in the loop. Increased research into robotic systems' style and physical casing to increase the uptake and safety in industrial and other interactive user environments.
Strategies and methods to control massive numbers of small robots operating collaboratively	Swarm robotics, federated learning.

4.9 BB9 Communication protocols and cyber-security tools

BB9 aims to offer a thorough cybersecurity framework for Industrial IoT systems, focusing on secure communications and data exchange and especially feedback systems deployed in IMOCO4.E. The work within this BB will facilitate interoperability between IMOCO4.E modules in terms of secure data communications: It will provide secure and trustworthy data management aggregated from novel sensors (BB3) and exploited by FPGAs (BB1) by the IMOCO4.E real-time smart control platform (BB4), and the high-performance servo-drives (BB7). Moreover, it will facilitate fast and secure accessibility to data for the IMOCO4.E AI components (BB8) and algorithms (BB5, BB6). [12]

BB9's position in complex Digital twins will ensure the deployment of all the necessary cyber security mechanisms (i) with respect to real-time synchronization and communication with digital twins and (ii) in the operation of the IMOCO complex digital twins' systems. As for BB9's relation to AI edge-to-cloud vertical deployment, it will provide cyber security technologies facilitated by AI-based anomaly detection mechanisms and will exploit federated learning approaches (AI edge-to-cloud deployments) to ensure multi-level cyber security assurance. [12]

4.9.1 Identified shortcomings

GNT's data fusion mechanism has been tested with heterogeneous data sources (e.g., various text-based content and image/video/sound metadata), and within the project, we will further increase the efficiency of the aggregation and pre-processing of the different types of data derived from multiple data sources increasing the fusion **speed by at least 20%.** [12]

Together with ITML, we will increase the **accuracy (>95%)** of existing AI/ML algorithms for real-time data clustering and classification at the edge aiming toward more accurate anomaly detection in data flows from IoT devices. [12]

Currently, the suggested solutions are developed for application in various domains (e.g., financial, transportation); within the scope of IMOCO we are planning to tailor the tools in the manufacturing sector to be exploited for predictive maintenance of complicated mechatronic systems. [12]

SIOUX:

Partly due to the wide variety of use-cases, these projects' architectures, tools, and technologies currently differ substantially. When setting up a new project, it is relatively hard to re-use previous architectures, knowledge, tools, etc. Many of these projects clearly solve a similar set of problems but appear to lack mutual compatibility and interoperability. In the end, there are so many new tools and technologies, standards, regulations, etc., that it is hard to see the forest for the trees. [12]

4.9.2 Key technologies focus

Table 26 summarises the technology topic (as identified from needs/trends analysis) and links it to supporting technologies. The table is divided into two sections: topics that are seen as relevant within the IMOCO4.E project and those that are likely to become relevant in the future.

Table 26. Technology topics in BB9 with supporting technologies

Technology topic	Specific feature (if identified	Supporting technologies
Data spaces with standardised data formats for the exchange of manufacturing data to allow real-time planning and control.	Pub/Sub message system, deterministic capability, and seamless redundancy for the safety-critical communication.	Distributed Kafka broker with configurable topics, TSN Switch/Data plane/Platform
Sharing of data between different partners in order to improve AI algorithms	Pub/Sub message system, Persistent storage	Distributed Kafka broker with configurable topics, accessible ElasticSearch database for persistent storage
Data fusion methodologies for multi-source heterogeneous data	Data cleaning/sanitisation, Data normalisation, Data imputation, Data transformation, Data consolidation	Distributed Kafka broker with configurable topics
Interoperable cyber-secure IoT architectures with data analytics and semantics support	Anomaly detection in data streams	
Novel approaches to combine different levels of information coming from humans, measurements, digital-twins/simulations; big data streams inline, and in-site should be developed.	Data cleaning/sanitisation, Data normalisation, Data imputation, Data transformation, Data consolidation	Distributed Kafka broker with configurable topics
Real-time interpretation of sensor data, particularly in complex environments or where multi-modal data must be fused or correlated to increase self-awareness of robotic systems	Data transportation, fusion, storage, access, network infrastructure for mixed critical communication and time synchronization.	Distributed Kafka broker with configurable topics, TSN Switch/Data plane/Platform
Fusion of machine learning and model-based approaches to ensure generality, robustness, and accuracy.	Data transportation, fusion, storage, access	Distributed Kafka broker with configurable topics, accessible ElasticSearch database for persistent storage
Trustworthiness of AI and robotics systems by making them dependable and reliable.	Authentication, Data redundancy/replication, data security at rest and in flight	Distributed Kafka broker, Keycloak, X509 certificate-based asset provisioning
Methods for handling security and privacy	Authentication, cyber-threat (anomaly) detection, data access control (authorisation),	Keycloak, X509 certificate-based asset provisioning

	data security at rest and in flight	
Large datasets for training AI algorithms	ML-compliant persistent storage	ElasticSearch
Heterogeneity of systems, interoperability of digital twins, information sharing, and standards	Data exchange among multiple endpoints, Standard, vendor-neutral and interoperable interfaces for the data plane and the control plane (standard API for configuration and monitoring)	Distributed Kafka broker, TSN Switch/Data plane/Platform
Interoperability through modularity and interfaces is needed	Modularity, scalability, Pub/Sub message system	Kubernetes, Docker, Distributed Kafka broker

4.10 BB10 Motion / path planning, collision avoidance and navigation algorithms

In today's world of intralogistics, there is a massive shift from previously predominantly manually oriented processes to automated and autonomous processes. High workloads, an expected increase in performance and output needs in factory processes, the demand on less accidents and process breakdowns are requesting a change towards new technologies to support this journey. This will require a variety of sensory and algorithmic developments up to the extended use of simulation and AI.

In mining applications, the trend is to increase the level of automation to reduce the workload of the operator and to increase productivity and safety. In pilot 5 the focus is on mining applications. In this context, trajectory and path planning are considered as planning motions for the boom of the mining machine. The goal is to avoid collisions of the boom structures to the obstacles like walls of the tunnel or the machine itself. Information from the sensor, e.g., LIDAR, is used for modeling the working environment of the mining machine and AI-based methods are utilized for detecting features like drilling holes.

BB10 is therefore dedicated to the question of how modern mobile systems (e.g. AGVs and mining machines) can be supported technologically in their work in real environments. BB10 is directly linked to demonstrator 3 and pilot 5 witch outcome will show how a realization can look like. So, BB 10 could be understood as a toolkit with various features optimized for supporting real world approaches

4.10.1 Identified shortcomings

All in all, this is a very complex overall system in which shortcomings cannot be ruled out. The shortcomings, especially in the logical part, are depending on open shifts of available technologies and toolkits into a more matching form to fulfil the requested functions are needed. Selected and necessary interfaces, software modules and chosen hardware will be adapted during the project. Below some of them are listed, where a team of partners will work on during this project

- Radar antennas and frontend not suitable for Demo 3 (forklift application) -> new radar frontend with re-designed antenna
- Data interface(s) to be adapted to Demo 3, data formats to be defined with partners -> data interfaces and formats capable for obstacle detection, path planning and autonomous navigation in industrial environment
- Processor capabilities not useable for AI and neural network algorithms implementation -> new radar backend with AI processing capabilities
- Simulation and Deep Reinforcement Learning has to be used to optimise Human-Machine cooperation
- Camera systems and other sensors has to be checked for satisfying functionality
- Robustness against changing conditions / environments / uncertainties

4.10.2 Key technologies focus

Table 27 summarises technology topic (as identified from needs/trends analysis) and links it to supporting technologies. Table is divided into two sections, namely those topics that are seen relevant within the IMOCO4.E project and those topics that are likely to become relevant in the future.

Table 27. Technology topics in BB10 with supporting technologies

Within IMOCO4.E

Technology topic	Specific feature (if identified	Supporting technologies
Modularisation and standardisation of sensor interfaces, meta-information models	Alignment to a basic robotics platform	BB10 uses standardized platforms such as ROS and RACK as well as ISAAC to link systems together informatively
Novel sensing and sensor systems in challenging environments and low cost, low energy, high accuracy sensors		Solid-State-Lidar, Radar, different Types of camera systems (TOF, RGB, RGB-D)
Reliability of sensing in harsh environments and in diverse environments as well as in small scale environments		System selection of suitable system and protection techniques
Real-time interpretation of sensor data, particularly in complex environments or where multi-modal data must be fused or correlated to increase self-awareness of robotic systems	Preference on GPU over CPU technology due to a high image load	Use of Nvidea GPU powered bords like for example Nvidia Jetson
Transparency of operations in uncertain conditions	Transparent status of mobile systems	In Imoco, it will be checked to which extent this can be represented by a higher-level control system. In any case, the

		information is provided on the AGV.
AI does not negatively impact on the safety of people using robots or in vicinity of them while providing advantages through improved operation		This is checked in detail in the reinforcement learning activities.
Simulator-based design: continuous design improvement utilizing digital twins and virtual models		Since the algorithms have to be suitable for large fleets, the use of simulation models is unavoidable. Nvidia Omniverse is used as a basis for this.
Integration of interactive simulation technology for digital twins into AR and VR user experiences	User experience with VR glasses	Test whether the use of VR glasses is helpful in designing the demonstrator
Increased robustness and reliability of systems, especially in harsh environments	Key request in industrial use cases	
Development of interaction technologies using VR and AR and their relation to human interaction		Technologies not yet defined, possibility of implementation under review
Natural human interaction	RGB LED Installation on AGVs	Use of different visual methods of the AGV
Use of suitable spatial proximity sensors to avoid collisions	Person protection system	Use of Radar and 2D Laser Scanner
Assurance of the safe operation of robots using data from safety- related and standardised sensing devices	Person protection system	In mining application lidar is used for detecting humans coming to the work space of the machine
Safe trajectories generated by control software		Use of a supervisory fleet management system in action with safety functions on AGVs. In mining application control algorithms are developed for avoiding collisions and limit/prevent boom movements near human opearator.
Machine perception and forecast of expected and unexpected activities		Estimation of possible motion vectors of persons via installed standard sensors
Reaction to hazardous situations		Situation based AGV control based on on-board sensors. In mining application safe way to stop movements or the boom.
Communication technologies become essential due to robot platforms mobility	5G Campus Network	
Standardization of communication between fleet management system and AGVs		Implementation and potential expansion of VDA5050 standard

Sharing autonomy between humans and robots		In mining applications, e.g., charging process consists of automatic boom movements and operations made by human operator.

After IMOCO4.E

Technology topic	Supporting technologies
Fusion of machine learning and model-based approaches to ensure generality, robustness and accuracy.	Aspect required for successful industrial implementation. Technology approaches expected from Imoco
Motion control systems that are continuously able to identify (changing) physical parameters to adapt and optimize feedback action	Vision based approach needed
Feedback control technologies that optimize their performance during repeated tasks	Helpful to reduced needed compute capacities
Trustworthiness of AI and robotics system by making it dependable and reliable.	Evidence based NN
Simplified AI tool sets configurable without highly skilled personnel	Aspect required for successful industrial implementation. Technology approaches expected from Imoco
Simplification of the semantic interaction between people and robots and between robots and operating environment by adding reasoning and knowledge to transparent decision-making.	Aspect required for successful industrial implementation. Technology approaches expected from Imoco
Large datasets for training AI algorithms	Using Cloud technologies
Digital twins for complex processes	Using AAS
Intuitive configuration tools that reduce the need of using robot specialists	Aspect required for successful industrial implementation. Technology approaches expected from Imoco
Prediction of human behaviour when helping operator to guide a robot	Using of dynamic pose estimation
Regulation harmonisation, standards and certificates need updates	
Standardized information/knowledge/action sharing mechanisms among robots where multiple robotic systems are required	
Fully autonomous vehicles and autonomous robots in shopfloors	Enhancement of existing AGV technology
Integrating robots into IoT and smartcity ecosystems, industrial asset management sytems and digital twins for data and knowledge sharing	Smart factory approach

Cyber-security of robots to protect safety and user privacy	Aspect required for successful industrial implementation. Technology approaches expected from Imoco
Speed and agility of collaborative robots need to be increased while maintaining safety	Aspect required for successful industrial implementation. Technology approaches expected from Imoco
Novel sensor systems working accurately over large spaces and position control algorithms	Aspect required for successful industrial implementation. Technology approaches expected from Imoco

4.11 Summary on building blocks

IMOCO4.E building blocks form a core of IMOCO4.E solutions. As this chapter demonstrates, many technologies are available for solving a particular challenge. Furthermore, technologies evolve at a very rapid pace.

The European smart manufacturing ecosystem has identified several needs and challenges in order to be competitive and reach levels that make industry4.0 a reality and adaptable to the smart manufacturing market. The needs and challenges have been identified in several roadmaps, as presented in chapter 2.

This chapter further positions IMOCO4.E building blocks into overall European smart manufacturing ecosystem needs. Due to a large number of needs and different technologies available, we have focused on selected main topics relevant to mechatronics and robotics. Their mapping to BBs has been presented at the beginning of chapter 4. In building block-specific sections, we have shown which technology topics are relevant and which technologies support specific technology topics.

Conclusion

In this deliverable, we have identified and summarised future needs and requirements for European (smart) manufacturing and Industry 4.0 from many projects and initiatives that the European Commission has supported to this end in recent years from a mechatronics and robotics perspective. The identified needs were further assessed by the industrial end-users of the consortium for defining the strategic directions within the IMOCO4.E project.

Future needs were collected from several European roadmaps. The main focus was on two recent roadmaps that cover the scope of IMOCO4.E-related needs in more detail, namely Manufuture 2030 and AI, Robotics and Data SRDIA. The main needs from European roadmaps were categorised in several main topics and presented in this deliverable based on the identified needs. The assessment serves as a link to how IMOCO4.E cases are positioned compared to the strategic needs set up in European roadmaps, addressing currently relevant needs and needs that are likely to become relevant after the IMOCO4.E.

Based on the inputs from IMOCO4.E deliverable D2.1 “State-of-the-art methods in Digital Twinning for motion-driven high-tech applications” and partner inputs for each IMOCO4.E solution, i.e., building block, this deliverable provides set of key technologies that IMOCO4.E should focus on to benefit competitive European manufacturing ecosystem. The work carried out in this deliverable will be utilised in forthcoming IMOCO reference architecture and further building block planning during the IMOCO4.E project.

References

[1] Electronic components and systems strategic research and innovation agenda 2022. January 2022. https://aeneas-office.org/pdf/strategic-research-and-innovation-agenda-2022/ (available 4/2022)
[2] Manufuture 2030 SRIA. February 2019. http://www.manufuture.org/wp-content/uploads/ManuFUTURE_SRIA_2030_Vfinal.pdf (available 4/2022)
[3] AI, data and robotics SRDIA. September 2020. https://ai-data-robotics-partnership.eu/wp-content/uploads/2020/09/AI-Data-Robotics-Partnership-SRIDA-V3.0.pdf (available 4/2022)
[4] MADE IN EUROPE The manufacturing partnership in Horizon Europe - Strategic Research and Innovation Agenda (SRIA) version October 2021. https://www.effra.eu/sites/default/files/made_in_europe-sria.pdf (available 4/2022)
[5] European Automotive Research Partners Association (EARPA), High-level Position Paper, 2020
[6] European Automotive Research Partners Association (EARPA), Position Paper: Connectivity, Automation, Safety – Using new tools and technologies supporting road safety and greening, and their interaction, 2021
[7] European Parliament - Policy Department for Economic, Scientific and Quality of Life Policies, The Future of the EU Automotive Sector, 2021
[8] Husain, I. & Ozpineci, Burak & Islam, Md Sariful & Gurpinar, Emre & Su, Gui-Jia & Yu, Wensong & Chowdhury, Shajjad & Xue, Lincoln & Rahman, Dhrubo & Sahu, Raj. (2021). Electric Drive Technology Trends, Challenges, and Opportunities for Future Electric Vehicles. Proceedings of the IEEE. PP. 10.1109/JPROC.2020.3046112.
[9] ELECTRIC MOTORS FOR ELECTRIC VEHICLE MARKET - GROWTH, TRENDS, COVID-19 IMPACT, AND FORECASTS (2022 - 2027) [available online 4/2022: https://www.mordorintelligence.com/industry-reports/electric-motors-for-electric-vehicle-market]
[10] Industry 4.E-CSA project. Report on Industrial digitalisation roadmap gaps identification. 2019. https://industry4e.eu/wp-content/uploads/2020/02/D1.2-final.pdf (available 4/2022)
[11] Jolley, D.: Shifting to 800-volt systems: Why boosting motor power could be the key to better electric cars. DRIVEMODE, Feb. 2021 [available 4/2022 online: http://drivemode-h2020.eu/shifting-to-800-volt-systems-why-boosting-motor-power-could-be-the-key-to-better-electric-cars/]
[12] D2.1 "State-of-the-art methods in Digital Twinning for motion-driven high-tech applications". To be available from IMOCO4.E as a public deliverable.
[13] Dutch national roadmap on strategic infrastructure 2021: Nationale Roadmap Grootschalige Wetenschappelijke Infrastructuur 2021. (Available 4/2022) https://www.nwo.nl/sites/nwo/files/media-files/WEB%20roadmap.pdf
[14] Dutch national portfolio for research and innovation https://www.nwo.nl/sites/nwo/files/media-files/WEB%20roadmap.pdf (available 4/2022)
[15] IMS2020 Roadmaps executive summary. https://data.fir.de/projektseiten/ims2020/files/IMS2020_Action-Roadmap_Executive-Summary.pdf (Available 4/2022)