Contents

1 EXECUTIVE SUMMARY p.7

2 STRUCTURE OF THIS PAPER p.10

3 TRENDS IN MANUFACTURING p.18

3.1 Green transformation p.19

3.2 Higher digitalization, automation or autonomy levels p.19

3.3 Smarter objects & industrial assets p.20

3.4 Emerging behaviour p.20

3.5 Knowledge transformation & acceleration p.21

3.6 Engineering complexity of generative industrial systems p.22

3.7 Extended one-of-a-kind, designed by end-user, omni channel delivery as ordered to home p.22

3.8 Dynamics in manufacturing p.22

3.9 Reimagining global value networks p.22

3.10 Resilient manufacturing & repurposing p.23

3.11 Brownfield transformation (legacy challenges) p.24

3.12 Tactile digital workplaces p.24
4

FLAGSHIP CONCEPTS p.25

A. Virtual commissioning p.25
B. Industrial service business, remote operations p.28
C. Modular factories p.29
D. 100% autonomous production lines p.30
E. Autonomous worksite p.32
F. 5G factory p.32
G. Human-machine collaboration p.33
H. Manufacturing as a Service (MaaS) p.34
I. Industrie4.0 p.35
J. Industry5.0, Cognitive production p.36
K. Carbon-free production p.36
L. Solid foundations in the past, also relevant and necessary in the future p.38

5

ENABLING TECHNOLOGIES PORTFOLIO p.42

5.1 Artificial Intelligence p.42
5.2 Digital twins, mixed or augmented reality, telepresence p.43
5.3 Design and Architecture p.45
5.4 Software Engineering p.47
5.5 Quality, Reliability, Safety, Cybersecurity and Trust p.49
5.6 Digital platforms p.51
5.7 Edge and cloud computing, 5G p.53
5.8 Responsive and smart production p.55
5.9 Sustainable production p.56
5.10 Autonomous systems, robotics p.58
5.11 Industrial service business, lifecycles, remote operations and teleoperation p.59

6

Groundwork for Success p.62

7

Conclusion p.65
| Figure.1 | Industry4.E Lighthouse LIASE Members | p.7 |
| Figure.8 | Automation in Industry | p.31 |
| Figure.15 | Rembering Industry's Past | p.38 |
| Figure.21 | Emerging computing architecture of embedded computing, near computing and central computing. | p.54 |
| Figure.2 | Modelling and simulation in process industry | p.25 |
| Figure.9 | Autonomous Vehicles | p.32 |
| Figure.16 | ISA 95 Levels | p.40 |
| Figure.22 | The visionary manufacturing system for adding value over the life cycle with decentralised technical intelligence | p.57 |
| Figure.3 | Real and digital/ simulated plant running in parallel | p.26 |
| Figure.10 | Nokia Bell Labs | p.33 |
| Figure.17 | Virtual commissioning in process industry | p.44 |
| Figure.23 | I4.E CSA Project Partners | p.60 |
| Figure.4 | Giving on-line assistance from a remote service center | p.26 |
| Figure.11 | Human - Machine Collaboration | p.34 |
| Figure.18 | Continuous development processes | p.46 |
| Figure.24 | ECSEL Lighthouse Projects | p.62 |
| Figure.5 | Giving on-line assistance from a remote service center | p.27 |
| Figure.12 | Dimensions of Industrie4.0 | p.35 |
| Figure.19 | FIWARE digital platform for manufacturing | p.51 |
| Figure.25 | I4.E Lighthouse Porject Portal (Screenshot) | p.63 |
| Figure.6 | From service partner to networked partner | p.29 |
| Figure.13 | Topics and enabling technologies of Industrie4.0 | p.36 |
| Figure.20 | Evolution of digital frameworks in EU funded projects | p.52 |
| Figure.7 | A generalised overview of autonomous system technologies and functionalities. | p.30 |
| Figure.14 | Moving from Industrie4.0 to Industry5.0 | p.37 |
Acknowledgements:

Founding and developing the Industry4.E Lighthouse over the past three years has been a challenging and enjoyable experience for us all. We would like to acknowledge the support we have received from the ECSEL Governing Board and indeed the ECSEL Administration Office, led by Bert De Colvenaer. The Lighthouse initiative continues to build on its impact metrics in terms of connectivity, relationship management, dissemination and policy directive inputs and we are very grateful for the continuing support we have received across the entire ECS research ecosystem.

We would also like to acknowledge the work of the I4.E CSA partners (Irish Manufacturing Research IMR, VTT, Steinbeis 2i, Aquatt, and Mondragon Unibertsitatea) for their excellent support to the Industry4.E LIASE group. The work undertaken in dissemination activities, workshops, conferences, website development and in deploying the Lighthouse projects portal, is exceptional and something we are all rightly proud of. We would also like to thank the many Lighthouse4.E project participants, portal developers, researchers and practitioners who helped develop the thoughts and ideas expressed in this whitepaper.

Dr Andrew Lynch
Chief Innovation Officer IMR
LIASE I4.E Chair
Executive Summary
1. Executive Summary

One of the biggest challenges currently facing Europe is the execution of an effective strategy for twin transition (green and digital). Today, the digital landscape remains fractured, with significant challenges in areas such as standardisation, interoperability, and translating research to real commercial impact. These challenges must be met effectively if we are to achieve a strong, resilient, responsive European economy, where sustainable, human-centric solutions help Europe achieve strategic autonomy into the future.

In supporting the overall European digitisation strategy, the ECSEL JU has set up three Lighthouse Initiatives in the areas of mobility, connected health and Industry4.E (manufacturing, process and machine industries). Each Lighthouse is guided by a LIASE (Lighthouse Initiative Advisory Service) which acts as a strategic guide to the initiative and supports its engagements in a practical manner. The members of the I4.E LIASE (pictured) present this whitepaper as part of our initial work in setting up the I4.E Lighthouse structures.

This paper outlines the future trends in manufacturing, building on an environmental scan of the digital research landscape (supported by the I4.0 CSA). We develop the key flagship concepts which will need to be the focus for policy and advanced ECS research into the future. We also evaluate the critical enabling technologies underpinning these endeavours and provide a roadmap to execute on same. Success on this paradigm is critical to the digital sovereignty of the European Union and will ultimately require closer connectivity between I4.E related policy, strategies, funding initiatives, projects, end-users, and general stakeholders.

Figure 1  Industry4.E Lighthouse LIASE Members
Our Mission:

To provide strategic support to the broad ECS/KDT research agenda, through cross-sectoral collaboration and nurturing an EU-wide vision for evolving Industry 4.0.

To accelerate the real-world impact of EU invested RD&I projects by realising digital technologies and innovations to help Europe master its digital future.
Introduction
2. Introduction

This whitepaper is presented by the LIASE of the ECSEL Lighthouse4.E and outlines our vision for the future of manufacturing and the resultant critical focus areas for the ECS research community. The work presented here is the result of extensive work carried out by the I4.E LIASE, with the support of the Lighthouse CSA (I4.E Lighthouse CSA), and is outlined in the next five sections of this document: Section 2. An environmental scan of the ESC research community (including a determination of the main challenges and gap analysis) Section 3. Future Trends in Manufacturing Section 4. Key Flagship Concepts Section 5. Underlying Enabling Technologies Section 6. Groundwork for future impact and success

Our initial environmental scan of the ECS community is presented in this section of the white paper (ref: section 2), where we undertook an evaluation of the ten programs outlined below. Each roadmap / vision document was assessed to determine the main challenges addressed therein and a review undertaken on the resultant gaps and overlaps between each (see table 1.0 overleaf).

1. EFFRA’s ‘The manufacturing partnership in Horizon Europe Strategic Research and Innovation Agenda’ (Made in Europe SRIA).
4. Manufuture Vision 2030 & Strategic and Innovation Agenda 2030 (SRIA)
5. CPS Roadmaps (Platforms4CPS, Road2CPS and CPSoS)
7. HiPEAC Vision
8. The Industrie 4.0 (national/German) Roadmap/Guidelines and the associated Working Group Documents
10. AI PPP SRIDA (Strategic Research, Innovation and Deployment Agenda) (aipp)

In section 3 of this document, we explore future trends in manufacturing, which outline the major driving principles set to govern manufacturing processes for the coming decade. Guiding principles here like global warming, circularity, increased deployment of technology etc., will have a significant impact on production facilities and how we prioritise our focus over the shorter to medium term.
The development of flagship concepts arising from the main trends’ analysis, gives voice and structure to the main initiatives either founding or in development, in the manufacturing world. These initiatives, which are detailed in section 4, are gaining momentum and are reaching an impact critical phase in Europe right now. These concepts will transform manufacturing processes throughout the lifecycle of the product and beyond. This in turn gives rise to a more focused look at the enabling technologies, the digital framework and supports that are required to make this vision a reality (section 5).

We end the paper (section 6) we review the work done by the Industry 4.E Lighthouse Initiative to date to ensure better connectivity and collaboration between the ECS research and industrial communities. Clearly there is a need to better connect the research world with real world problem statements and to develop synergies between these rich and diverse communities. There needs to be an identification and acknowledgement of the key focus points for digital RD&I initiatives and policy, specifically where industrial impact can be best supported.
## An environmental scan of the ESC research community (main challenges and gap analysis)

<table>
<thead>
<tr>
<th>Main Challenges</th>
<th>ECSEL SRA 2020</th>
<th>EFFRA</th>
<th>SMART EUREKA</th>
<th>Process.IT</th>
<th>Manu-FUTURE</th>
<th>Industrie 4.0</th>
<th>2018 WMF trends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart, resilient, adaptable factories</td>
<td>MC2: AI-enabled cognitive, resilient, adaptable manufacturing</td>
<td>MiE (Made in Europe) Specific Objective ‘Excellent, responsive and smart factories’</td>
<td>Intelligent and adaptive mfg systems</td>
<td>Resilient and adaptive manufacturing</td>
<td>Cognitive mf &amp; Rapidly Responsive Manufacturing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Life Cycle engineering</td>
<td></td>
<td>MiE (Made in Europe) Specific Objectives ‘Circular economy (symbiotic manufacturing networks)’ and ‘Parallel product and manufacturing engineering’</td>
<td>Advanced Mfg Processes</td>
<td>Mastering complexity of products, processes &amp; systems</td>
<td>End-to-end nature, engineering over life cycle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Human-centred manufacturing</td>
<td>MC4: Human-centred manufacturing</td>
<td>MiE (Made in Europe) Specific Objective ‘Human-driven innovation’</td>
<td>Person-Machine collaborati on</td>
<td>Competence management</td>
<td>Innovation ecosystem</td>
<td>Inclusive Manufacturing</td>
<td></td>
</tr>
<tr>
<td>Main Challenges</td>
<td>ECSEL SRA 2020</td>
<td>EFFRA</td>
<td>SMART EUREKA</td>
<td>Process.IT</td>
<td>Manu-FUTURE</td>
<td>Industrie 4.0</td>
<td>2018 WMF trends</td>
</tr>
<tr>
<td>----------------</td>
<td>----------------</td>
<td>-------</td>
<td>---------------</td>
<td>-------------</td>
<td>-------------</td>
<td>---------------</td>
<td>----------------</td>
</tr>
</tbody>
</table>
| **Customer-based mfg** | | MiE (Made in Europe) Specific Objective New integrated business, product-service and production approaches; new use models’:
Collaborative product-service engineering for costumer driven manufacturing value networks
Manufacturing processes and approaches near to customers or consumers
Transparency, trust and data & IP integrity, open systems and cyber security along the product and manufacturing life-cycle | Customer-based mfg | | | | Hyper-Per-sonalised Manufacturing |
<p>| <strong>Digital transformation</strong> | | Was and is a pillar in Factories of the Future and Made in Europe Partnership. | Digital, virtual and efficient companies | | Digital transformation and new business models | | |
| | | | | | | | |</p>
<table>
<thead>
<tr>
<th>Main Challenges</th>
<th>ECSEL SRA 2020</th>
<th>EFFRA</th>
<th>SMART EUREKA</th>
<th>Process.IT</th>
<th>Manu-FUTURE</th>
<th>Industrie4.0</th>
<th>2018 WMF trends</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Security</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Ref Factories of the Future Partnershop (see the ICT-08-2019projects COLLABS and SeColAs)</em></td>
<td>Trust, security, safety and privacy</td>
<td>Cybersecurity</td>
<td>Global Risks-Resilient Manufacturing</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MiE (Made in Europe) Specific Objective New integrated business, product-service and production approaches; new use models*: Transparency, trust and data &amp; IP integrity, open systems and cyber security along the product and manufacturing lifecycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Digital Platforms</strong></td>
<td>MC3: Developing digital platforms, application development frameworks that integrate sensors/actuators &amp; systems</td>
<td></td>
<td>Key enabler across the programme. Covered in Factories of the Future Partnershop (see <a href="https://www.connectedfactories.eu/origin-project-and-outreach">https://www.connectedfactories.eu/origin-project-and-outreach</a>)</td>
<td></td>
<td>Integration of IT, OT and ET</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MiE (Made in Europe) Specific Objective ‘Excellent, responsive and smart factories’</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Data highways and data spaces in support of smart factories in dynamic value networks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Scalable, reconfigurable and flexible first-time right manufacturing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Zero-defect and zero-downtime high precision manufacturing, including predictive quality and</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital Twins</td>
<td>MC1: Developing digital twins, simulation models for the evaluation of industrial assets at all factory levels, and over system or product life cycles</td>
<td>Key enabler across the programme</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>----------------------------------</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
|               | MiE (Made in Europe) Specific Objective **New integrated business, product-service and production approaches; new use models**
|               | Collaborative product-service engineering for costumer driven manufacturing value networks
|               | MiE (Made in Europe) Specific Objective’
|               | Human-driven innovation’
<p>|               | Digital platforms and engineering tools supporting creativity and productivity of manufacturing development |</p>
<table>
<thead>
<tr>
<th>Main Challenges</th>
<th>ECSEL SRA 2020</th>
<th>EFFRA</th>
<th>SMART EUREKA</th>
<th>Process.IT</th>
<th>Manu-FUTURE</th>
<th>Industrie4.0</th>
<th>2018 WMF trends</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart, resilient, adaptable factories</td>
<td>MC2: AI-enabled cognitive, resilient, adaptable manufacturing</td>
<td>Made in Europe – specific objective - excellent, responsive &amp; smart factories</td>
<td>Intelligent and adaptive mfg systems</td>
<td>Resilient and adaptive manufacturing</td>
<td>Cognitive mfg. And Rapidly Responsive Manufacturing</td>
<td>Made in Europe – specific objective - excellent, responsive &amp; smart factories</td>
<td>Made in Europe – specific objective - excellent, responsive &amp; smart factories</td>
</tr>
</tbody>
</table>
3. Trends in Manufacturing

Building on the work carried out in the ECS environmental scan, this section outlines the future trends we see as important to the manufacturing community in the next ten-year cycle.

“Whilst technology is evolving at an even faster pace, there are overarching trends, such as the push to a greener economy, which provide a broader vision and context for research and applications going forward”.

Trends are something that we see as happening now or soon. Trends show directly or indirectly how business conditions, technology or engineering scenarios look like in the hazy but credibly foreseen future, typically 5-10 years forward. Whereas, the future canvas is populated with a number of flagship concepts, describing in a visionary manner how do the postulated future building blocks look like. Flagship concepts should be described in a language of a customer, an end user, or as coarse requirements or market needs. The flagship concepts should serve here as concrete targets or lighthouses for the decisions and actions to be undertaken. The third category here is the enabling technologies listing and describing what are the technology building block to enable or reach flagship concepts.

Our format here is meant to be modular, easy to update and expand. Such white papers or roadmaps are often written once and they are updated regularly. With the adopted modular structure, such reiterations are easy to do. In the course of time, typically trends will appear and vanish (but not very dynamically) and new flagship will be discovered and some may turn obsolete or just uninteresting. We have described the enabling technologies in the same modular way as trends and flagship concepts.

To enlarge the white paper into a development program, it is advised to first describe the enabling technology building block more accurately as long-term technology targets (not just AI but what kind of AI, etc.), then make a survey of the respective state-of-arts, and finally to design the actions or projects that will take us from the present stage to the envisioned stage, for each flagship concept.
3.1 Green transformation

The world has become strikingly environmental aware. Although the progress may not be the same in all countries or sectors, the alerting observations and predictions of atmosphere, oceans, soil, rivers and lakes, ice smelting, etc., have been waking up ordinary citizens and customers to saving the planet. Europe as a whole and many member countries have adopted very ambitious targets for the green transformation. What is even more significant now is that industrial companies are taking care of the environment more than expected only few years ago. They are obviously more environment aware themselves, and they foresee that customers or B2B stakeholders downstream in value networks will not buy anything or something which have been harmful for environment. The stock prices of questionable companies are falling. There exists also clear evidence from the recent industrial history that by putting truly greener technologies in place, the local air quality, water quality, biodiversity, etc., have been improved. Or even when more accurate and careful technologies and operating procedures are adopted, all performance indicators – technical, profitability, and yes ecological indicators – are optimized. In many ways, industries are thus encouraged to take the environmental directions, although many substantial obstacles remain.

There are many ways to fight for ecological efficiency:

- **Zero carbon**: Replace carbon-based fuels and raw materials from industrial processes. If carbon is inevitable, close the material loops to refrain from CO2 discharges, or filter or wash the carbon away from streams, or develop specific carbon capture technologies. The aim is to avoid CO2 discharges to stop the global warming. There are also some other harmful gases, e.g., methane that should be avoided similarly.
- **Sustainable production**: Companies should be striving towards optimised materials economy. There are some so-called rare earth metals to save, and any kind of careless materials usage can be proven uneconomical and risk to the environment. Recycling and reuse are becoming increasingly popular and important means of saving the planet.
- **Knowledgeable, accurate, and well managed engineering and operation are often the most effective means of being efficient.** The biggest discharges occur often in technological and operational failures or unpredicted stoppages, with poorly tuned algorithms and controllers, in off-quality production and by using poorly fabricated parts, components, and systems.
- **Green transformation will advance in economically and politically stable and growing conditions.** When there are resources, time, and will to act, the priorities are favourable for nature. Recession, pandemics, turmoil, or war reduce the engagement with the ideals of green transformation.

3.2 Higher digitalization, automation or autonomy levels

Wider use of digitalization and automation brings along more efficient, faster, safer, more stable, more economical, better managed and trusted production. Aiming for 100% autonomy and digitalization may not always be the optimum
strategy. Products may change over time quicker than automation efforts allow and some tasks may be next to impossible to automate or digitize. In the foreseen future, automation and digitalization degrees clearly increase, case by case, and the automation degrees of European factories have been high already, but often the well-educated and skilled human operators compensating the gaps of technology may offer immediate or realistic solutions. Semi-autonomy continues to be the main goal for the foreseeable future. Indeed, the role of human centred and factory automation have proved crucial in effectively addressing global outbreaks such as COVID-19. There is a trend in accelerating digitisation and modernisation of manufacturing and supply chains.

3.3 Smarter objects and industrial assets

The impact of the internet and globalization are ubiquitous but, there is a clear industrial trend where intelligence is migrating closer to machinery, processes, or becoming more local instead of global or centralized.

“Smart systems are composed of smart objects and assets rather than monolithic software”.

Smart objects allow modular structures that are easier to manage. Component, machine, or system vendors often want to take larger shares of their customers’ businesses and a natural choice for extensions is to make one’s product more capable by software. Encapsulating technologies into smart objects is also an effective means of protecting IPR. On the other hand, end customers may find it advantageous to buy technology in larger and more capable quantities. Even though the capacity of global communication is becoming every larger, engineers and companies are becoming more reluctant to spread their critical data around the globe and will often find good engineering reasons not to do such. The current trend of edge-cloud system or platform architectures inherently suggest distributed solutions of smart objects. It is also more than anecdotal to remind the reader that communication technologies are bandwidth limited but, moreover, energy limited, i.e., high-performance communication is about to consume more energy than is absolutely feasible or is against the urgent need for substantial energy savings.

3.4 Emerging behaviour

The evolution of rigid manufacturing sites into increasingly flexible manufacturing networks interconnecting highly transparent and modular asset-light manufacturing ecosystems is an emerging trend that is gaining momentum as CPS also gain increased connectivity and intelligence. In this context, IoT and SoS already generates value in many ways. Emerging functionality and behaviours
constitute future possibilities. Here emerging and automated business models is one way of unleashing the real potential. While intelligence will grow at asset level, the ability of individual CPS to interact and cooperate with their environment, augmented workforce and peers under increasingly dynamic contexts derives in industrial System of System emergence. This trend in manufacturing networks will have an impact in terms of how industry articulates business models, industrial system capabilities, e.g. resilience and operations, e.g. optimisation.

An automated business model in the IoT domain must firstly identify where it can capture and deliver value and subsequently define how to leverage the unique characteristic of IoT solutions that connects, monitors and controls 24/7/365 the customer’s environment to produce innovative and differentiated value. The “subscription model”, for example, adopts a software as a service (SaaS) approach to monetise the product, with a monthly subscription, but also with periodic paid upgrades or a “freemium” model, if possible. The “asset sharing model” tries to maximise the usage of the IoT product across multiple customers, reducing the single partner price and ensuring faster market penetration, if compared to the traditional approach where a single customer pays entirely for the IoT product. The “data monetisation” model proposes to provide value to the customers with the IoT solution and to collect from the customers valuable data that can be sold to third parties. The “service offering” model distinguishes from the “as a service” model because it uses an IoT solution to offer a new service, intended more in the traditional way (e.g. an IoT solution to monitor machinery for preventive maintenance, allows the selling of a maintenance contract). The “pay per usage” model consists of charging the customers for the exact amount of time they have used the IoT product/solution: monitoring the customers’ environment allows indirectly also to know how much the IoT product/solution is used. With the “razor blade” model the IoT product/solution is an excuse to sell other products: the IoT product/solution can be sold at cost or even at a loss but, in turn, the customers will buy other products that generate more revenues (e.g. this is the typical example of a device manufacturer that converts to an IoT solution provider, without leaving its core business). And, eventually, the “outcome model” is based on the idea that the customer pays for the outcome or benefit that the IoT product/solution delivers: e.g. when the customer wants to buy a car, probably he/she is not interested in the car but only in moving from point A to point B, and IoT generates a benefit not in the car but in the travel.

The business possibilities from emerging functionality of SoS is interesting. By new orchestrations of the available IoT services emerging functionalities can be realised in a short time frame. Combining this with automated business models opens interesting business perspectives.

### 3.5 Knowledge transformation acceleration

To benefit of extensive digitalization, ever more complex systems, multi-technology, etc., easily drift companies into turmoil: how to operationalize this, or how to build competitive edges about it?
“If personnel don’t understand the technology related *know-how*, then it will significantly delay the respective technology uptake in a practical sense”.

Technologies may not be mature enough yet after piloting or proofs of concepts, or perhaps the building of applications lacks useful engineering tools, interlinks with the existing or legacy systems have not been worked out. Building a good engineering practice may be far more demanding task than developing a technology itself onto a certain TRL, and it may take years for end customers, engineering offices, software vendors, standards, etc., to understand, adopt or accept the new technology item. The trend is an acceleration in the knowledge transformation with the aim of reducing the time to market of highly innovative digital products and greener more circular digital production solutions and ecosystems.

### 3.6 Engineering complexity of generative industrial systems

There is a trend in both product and production system complexity that scales exponentially associated with the trend of increased (block-box or explainable) intelligence and machine learning capabilities at the product, asset and system levels that one would associate with adoption of generative industrial systems. Even though factories may be made more flexible and resilient, capable of manufacturing higher variety of products, the need for designing and building new factories or renewing or upgrading the existing ones, remains important. The engineering projects are getting more complex, e.g., since the products and production systems are getting more complex. The products will be profoundly multi-technological and, in general, consist of software and algorithms to a growing extent beyond electro-mechanical physical components. On the other hand, time is becoming more critical meaning the more complex design and engineering projects need to be performed in less and less time, without sacrificing quality.

### 3.7 Extended one-of-a-kind, designed by end-user, omni channel delivery /home orders.

The proportion of one-of-a-kind products will expand. Or, to put it another way, the variability of product families will broaden and therefore a reduction of production batches. The focus of engineering moves more downstream in the value chains, and in the end, single customers may want to define what kind of particular product, service, or experience he/she would have. Products will be manufactured to orders more commonly. So-called omni-channel deliveries
become general meaning products are ordered from home with high degree of tailoring, they need to be manufactured fast, and delivered at home, at desired time. Pressures of the design and manufacturing, logistics, user interfaces for web-based transactions are multiplied and more complex (in line with a simplification of the overall user/consumer experience).

3.8 Dynamics in manufacturing

There will be a longer involvement in manufacturing cycle, evolving further into the lifecycle of the product. Accelerated by the AI infrastructure that we are already beginning to see evolving into products, (e.g., Tesla software updates). Products, systems, machines, production lines or factories are initially designed and built as version 1.0 and, as conditions and needs change, they will undergo perhaps considerable extensions, upgrades, face lifts. The trend is therefore that the manufacturers are extending their influence and enriching their active participation into new components of the value chain. Their role and contribution to product-service system (PSS) and business models is increasing.

3.9 Reimagining global networks

Networking remains a major trend in business. Manufacturing will be global, although enterprises must become reader to move their businesses between locations. Closeness to customers over lifetimes, closeness to materials and supply networks, availability of skilled people, and logistics conditions – matter. On the other hand, increased communications, remote operations, distributed tools and working conventions make businesses location agnostic. The trend is that supply chain and manufacturing operations will suffer from a significant transformation to increase resilience and response.

3.10 Resilient manufacturing and repurposing

The sudden expansion of the current COVID-19 pandemic is a wake up call and has induced many kinds of analyses, preparedness planning and quick actions, also in manufacturing [cf. e.g. the WMF Manufacturing beyond Covid-19 report]. But especially high-volume industries have always been careful about not becoming dependent on a single component, company, or person, to help then stay resistant to unexpected occurrences. Often, being resilient means good engineering practices applied extensively. More and more industries, products or processes are becoming more safety or cyber critical, meaning that safety analysis methods, etc., must be more rigorously practiced. Develop resilience” is easy to say but hard to define, and yet harder to do. Industries for long have remained persistently focused on near- and medium-term earnings, typically assuming ongoing smooth business conditions. To drive manufacturing anticipation and response, the resilience trend will progress beyond the financial realm towards (1) operational resilience ensuring continuity and flexibility, (2) technological resilience against cyber threats and lock ins, (3) organisational resilience for workforce up and re-skilling, and business-model resilience to customer demand.
shifts. Production repurposing will be an emerging trend that will be central to the implementation of this new forms of resilience that will respond to a more uncertain operational environment characterised by more frequent and more severe disruptions (techno-economic, cyber breach, geo-political, climate, pandemic, etc....)

3.11 Brownfield transformation (legacy challenges)

The trend of manufacturing industry is to engage in a continuous excellence cycle in Zero-X manufacturing (zero waste, zero-defect, zero unplanned breakdowns, etc...). An equal trend is to realise such Zero-X excellence extending and even providing a second (circular) life to major capital investments, products and components/materials therein. Industrial systems tend to have long operational lifetimes. The trend is in a development of a more continuous digital investment flow to complement more capital investments. The time ranges have been shortening (particularly for digital investments) but compared to, e.g., software or electronic systems for citizens, the lifetimes still remain relatively long. On the other side, many valuable inventions and solutions remain most relevant into the future. New technologies and concepts do not overshadow the old, whereas new systems must be seamlessly consistent and compatible with the existing one. In all longer life factories and along with respective products, tedious multigeneration situations prevail.

3.12 Tactile digital workplaces

There is a trend towards implementation of safer, more secure and resilient human-machine-machine collaboration, coordination and cooperation in the manufacturing workplace to boost manufacturing competitiveness. There is a need to go beyond individual asset contexts and exploit advanced smart network and services to optimise the real-time operation of more complex and smarter industrial CPSoS, particularly for manufacturing SMEs. The need for increased user centricity, production agility, supply chain transparency and remote manufacturing network and asset operation is calling manufacturing as well for increased ubiquity, intelligence and connectivity. The trend is for industry to operate such intelligence from anywhere, anytime and by anyone. 5G Public Network (PN) and Non-Public Networks (NPN) infrastructures are supporting the first use of wireless and mobile technologies in shopfloor automation and information management to support more flexible, modular and remote operation of manufacturing assets (CPS). The integration of 6G wireless tactile networking capabilities (deep, holographic, ubiquitous, intelligent) coupled with advanced embedded computing intelligence platforms will play a central role in the realisation of such next generation digital manufacturing workplaces.
4. Flagship concepts

This section looks at the more visionary concepts and approaches that are currently evolving and developing. These concepts are critical to realising the future potential of industrialisation and digitisation plays a crucial and underpinning role in each. The resultant technologies provides the focus of the following section.

a. Virtual commissioning

![Diagram](image)

Figure 2. Modelling and simulation in process industry [VTT archives]

Modelling and simulation (M&S) offer proven advantages for decision making. In industry, simulation has been widely used in virtual prototyping, simulation-aided design and testing, as well as, in training and R&D. At early days of digitalization, M&S was mainly regarded as a scientific exercise, and the coverage, accuracy, or reliability with regard to real industrial components, processes or systems was far from adequate. Gradually, the performances have improved. Simulation skills have remained a challenge, and the time and effort required to achieve realistic models have continued to be frustratingly large. Fortunately, automatic model generation based of design drawings have progressed a lot.

When replacing a working machine, a production line, or a process device, the plant should be out of operation, of as little time as possible. The same is true for commissioning new automation or operational software. Equally, when a new factory is being built, the full operational capacity should be obtained as fast as possible. These can be achieved by a careful and thorough design, extensive testing and good planning for the critical change-over period. Virtual commissioning can be of great help here.
Virtual commissioning means using simulation technology to design, install or test control or other software off-line, with a virtual model before installing the real system. Ideally, in virtual commissioning the entire factory acceptance test (FAT) performed by the main contractor or vendor can be based on models, instead of physical mock-ups or leaving parts of the final testing to the operative plant.

To achieve virtual commissioning, the necessary models must evolve in parallel with design, at all stages for all components, systems, processes, etc. M&S must be an integral part of any design and engineering activity. Design faults, alternatives and optimizations are dealt with early enough and the engineering processes become more manageable. The engineering platform with the necessary design tools must deal effectively with models and simulators, and it must enable simulator-based design. It must be easy to operate or test designs against simulators and to manage the massive amounts of input and output data. Automation and information systems are software based, or have their emulated software counterparts, and therefore, the simulation environment should be capable of running these as if in the real plant – without the need to re-engineer them into the simulation stage.
Advantages of virtual commissioning are:

- M&S needs a thorough understanding of the design item at hand which brings along a better managed engineering. The component wise or partial simulator tests help a lot in later design stages, or the entire FAT testing can be built up gradually.

- Simulators allow better optimization than physical mock-ups. With the help of simulators, engineers can test much more extensively than with mock-ups. Failure situations and the systems’ or operators’ readiness to respond can also be tested off-line. Simulation tests can also be part of the safety, quality, reliability, etc., procedures and documentation.

- Operators, maintenance and other personnel can be trained in advance for the new installation.

- The actions, procedures, logistics, etc., of the plant building or changeovers can be tested and trained beforehand.

- The M&S environment can be used in the running plant in many ways. On one hand, the data of the actual plant can be used for simulator tuning and other improvements, and the simulators can be used at any issues the production system encounters: to analyse failures, to test suggested repairs beforehand and to give forecasts of the future behaviours and performances of the plant.

- Virtual commissioning or simulator-based design and operations is seldom complete or up-to-date. But it may turn out useful even when implemented partially. Since adopting virtual commissioning is a long-range engineering effort, industries may successfully live with many kinds of mixed virtual and physical environments for years.

*Figure 5. Giving on-line assistance from a remote service center.*
b. Industrial service business, remote operations

We are witnessing a strong transition from product, software or system business towards value-added services related to a particular product, software, or system. Most typically, such services include condition monitoring, operations support, spare parts and maintenance services, help desks, troubleshooting, operator guidance, performance reporting, as well as an increasing demand, advanced big data analytics and prognostics-based decision support. The market for this service is still in its infancy. Many end-customers are still hesitant to outsource their condition monitoring but, at the same time, significant joint benefits have been demonstrated by organizing such business processes as commercial services and allowing the end-users to pay more attention to furthering their core businesses. Nevertheless, today there are machine vendor companies for whom the industrial services represent a more valuable part of their total offering than the original machine, part, system, or software business.

A modern industrial service business is based on 1) B2B contracts, and 2) efficient platforms or communication technologies on top of which the automated and remote or human assisted service functions are implemented. Earlier, service businesses were heavily dependent experienced maintenance personnel travelling globally in a short notice. But today, a lot of services are being automated or implemented remotely.

A well progressing industrial service business has many of the following characteristics:

▪ The company intending to enter service business must prepare itself for doing after-sales business. The products have become extended products, and the company have adopted design-for-lifecycle type activities in its R&D.

▪ The company has obtained good knowledge and experience on how its products are being used, how do they fail, are the customers capable of using the product in best possible manner, etc.

▪ The company has effective data gathering, communications, and advanced data processing technologies in place, from the customer sites to home office, understand the many kinds of issues that endangers or worries the customer. The digitalization infra leans on proper and tailored digital platform or smart-IoT, edge, and cloud architectures.

▪ The company has a dedicated service operations center in the back-office. The experienced maintenance professionals do not travel around the globe so much but solve the customer issues either by themselves or tutoring the others. The back-office is equipped richly by efficient communication facilities to the customers’ premises, powerful computers run extensive analyses about the sensor readings, extensive and accurate simulators are double-checking the behaviour of machines, knowledge gathered from design time are organized and adapted to be easily at hand in operational contexts, and the extensive and continuous big data from customer factories constantly update the back-office systems.
The subcontractors participate in the service operational and actions, taking the full lifetime responsibility of their respective products, components, software, etc.

At customer sites, there is an effective and knowledgeable local service ecosystem of companies close to the customer site, with due access to operational service data.

Depending on agreements, partner capabilities, business policy instances, etc., it is flexible to arrange ownership of data or processed data, store data and install computational elements or algorithms either focused on customer premises, or on back-office, or mixed.

The service providers benefit effectively of the extended installed base gathering information, knowledge and experience from diverse locations, up to thousands of measurements about the same component. This is called fleet management.

The service provider can take care of the lifetimes of their own installed base and, in addition, of the similar machines, devices, etc., of lifetime services of other, even competitors’ machines or devices. Customer companies may also want to outsource the maintenance, etc., of an entire department, production line, etc., which the service provider must be capable of including in their service base.

c. Modular factories

Instead of building ever bigger factories to respond to a bigger demand, many enterprises have found it useful to take modularization one or two steps further, make reasonable production entities more independent and perhaps geographically distributed, and obtain the necessary product variability and flexibility due to market conditions by reorganizing production through varying module constellations. Even the next generation nuclear power plants are expected to be flexible modular constellations of mini plants, and there will be no more 1000 MW plants.

Today’s dynamic business conditions may vary due to many reasons: Make-to-order buying schemes are getting widespread. Customer as a designer is becoming a demand. Product tailoring has not stopped as a trend. Production lines tend to have a shorter lifetime, meaning factories are in more or less
constant brown field construction. Therefore, it has become worthwhile to organize an enterprise in smaller and better managed factory units. They can be switched on or off, from full operation to outage, etc., easier according to market and other conditions. The factory modules may be at the same site, or distributed geographically according to closeness to customers, access to raw materials, or availability of staff.

A former version of this modern concept is making orders to other companies when the own capacity is not enough to satisfy a peaking demand. This is sure a valid business routine still.

d. 100% autonomous production lines

It may be tricky to define a fully autonomous system. When designing the automation of a factory, the automation task is dissected into process or manufacturing tasks and then, the designer decides how he/she would implement each task: manual, automatic, or mixed. The proportion of automatic tasks is called degree of automation. Therefore, a fully autonomous factory or production line has the degree of automation of 100%. The control of an autonomous vehicle is described in somewhat different manner, cf. Fig. x above.
“In general, industries are evolving towards 100% autonomy. But there are many examples where true 100% autonomy is still some years away, e.g., autonomous driving in open traffic”.

It is essential to emphasize here that in practice, the degree of automation or autonomy is mostly an engineering decision. A higher degree of automation is usually well justified and brings along several advantages or competitive viewpoints, but usually not at any cost, if the attainable solution is uncertain or brittle, etc. Especially in dynamic manufacturing conditions where products vary, production volumes vary, product lifetimes are short, etc., good compromises below 100% autonomy are often recommended.
e. Autonomous worksite

Autonomous driving has been one of the most studied challenges in car industry, i.e., having cars that can drive without human intervention in road, street, and parking conditions. Autopiloting is or will be common in aviation, marine, and space. Free terrain driving remains still a very far target.

Driving or moving in certain worksites can be conveniently standardized to make navigation, collision avoidance, etc., realistic. Such realizations exist already for harbors, warehouses and factory floors and mining corridors where moving carriages or working machines operate without drivers. It is also commonplace to exclude humans from such areas to avoid injuries, or having humans and autonomous vehicles in the same floor area is an R&D topic. In industrial settings, it is also not any problem to place machine readable tags, wireless lighthouses, embedded wiring, etc., to considerably ease the AI based navigation.

Perhaps the most significant point of development is the logistics chain, where ill-formed, (etc.,) items need to be handled effectively and in fast growing volumes between transportation points like warehouse nodes, logistic hubs, etc. Due to the increase of web-based business, the demand of global logistics throughput is growing faster than what today’s facilities can provide. Certain well-indicated special targets exist, e.g., the last mile problem, i.e., taking the items from the last logistic node to private homes. Drones may be a partial solution, but some work is still required to realize this vision.

*It should be noted here, as in many other places in this document, that well-designed semiautonomous solutions may be the most realistic, viable and trusted solution, for decades to come.*

f. 5G factory

The 5G technology differs from the earlier communication technologies in significant ways. First, it is fast both as providing outperforming throughput and as causing almost negligible delays, for most industrial applications. 5G networking operates via 5G base stations, as the earlier generations, but the ranges of 5G radios are smaller, meaning a denser network of base stations is necessary. What is distinctive, is that there is a huge computing capacity, expandable, at each base station, taking care of both the 5G communication management and leaving room to a considerable amount of local computing, for applications. A 5G base station is
thus essentially a powerful edge node, on one hand, capable of communicating both to intelligent devices via the 5G radio and to the internet or cloud and, on the other hand, executing computing intensive functions or tasks distributed locally and close to the machinery or more centrally in the cloud.

Thus, the 5G infra installed in a factory site provides a versatile communication and computing infra, the actual application software system must be engineered on top. Nevertheless, the computing and communicating environment gives a strong platform for the applications.

The Nokia Bell Labs Future X for industries architecture

Figure 20 Ref: Networking solutions for the new age of industry, a Nokia white paper, 2018.

g. Human-machine collaboration

“Human-machine collaboration means human and machine or robot agents working together to achieve shared goals”.
The earlier idea to automate was to increase productivity compared to labor intensive production. Today, many more modes of automation or robotization prevail or are envisioned.

- High-degree tailoring of products, one-of-a-kind production, niche production of few expensive products, etc., do not allow long periods of time needed to develop a capable automated production line. Often the challenges for automation may be unrealistically high, whereas educated and experience human workers may easily outperform a poorly performing automated production.
- It is often worthwhile to divide production tasks flexibly into manual, automated, or semiautomated tasks.
- Simple and repetitive tasks become easier and reliably automated. Speed, accuracy, use of strength may often call for automation. Similarly, some tasks may be hazardous or dangerous for people.
- Traditionally, robots or automated machines must be kept separated by fences, etc., from human workers. Since task become more and more mixed between human and robots, the concepts where humans and robots could operate together, have become tempting. The first concepts have been to use so small and weak-powered robots that injuries are inherently prevented in unexpected error-conditions. In more advanced settings, robots are equipped with extensive sensors and cameras so that injuries are reliably anticipated making also heavier robotic operations possible. Or, at least by intelligent measurements, safety margins may be made narrower or changing dynamically according to tasks at hand.

**h. Manufacturing as a Service (MaaS)**

This is a recent business model where companies either do not have their own products or do not concentrate on product development or ownerships but are targeting to offer manufacturing subcontracting to other companies. Their competitive edge is based on wide readiness to receive manufacturing orders, or a strong engineering capability to ramp up any kind or any volume manufacturing, depending on contracts. Such companies typically need a strong engineering
department to respond to outsourced manufacturing and, to a higher extent, participating in the particular product or production design.

MaaS is a concept allowing companies to specialize in expertise and skills and relieving non-optimally utilized capital and labor investments to companies specializing to such subcontracting. Plenty of match-making or flexible request-order transactions may happen over internet or cloud. A lot of engineering data and knowledge need to be discussed, as well as information about dynamic market pull connected to production conditions in the supply network. Although MaaS vendors seldom own their products in the traditional sense, their product is actually the MaaS capability.

i. Industrie4.0

In around 2011, the famous Industrie4.0 was published implementing or envisioning the wider scope the manufacturing, listing the preferred or accepted subsystems and their mutual interactions or standards, and thus defining a single gigantic digital framework for all kinds of manufacturing systems. Industrie4.0 was introduced as a national initiative for German discrete manufacturing industry, especially for car manufacturing. The strategy involves the strong customization of products under the conditions of highly flexible mass-production. Throughout following years, nearly all European countries started to guide their respective national initiatives according to Industrie4.0. The latter part of 2010’s, also saw extensions of Industrie4.0 to continuous processes. The degree and extent of digitalization has been so massive and significant that the era of 2011 and beyond is called the fourth industrial revolution.
In 2011 in Germany, the first drafts of the emerging concept of Industrie4.0 were edited. Fig. 2 in above, actually represents RAMI, The Reference Architectural Model for Industrie4.0 [3], indicating the dimensions of modern factory system (hierarchy levels, life cycles, and physical extents starting from product or device and enlarging to enterprises or even the connected world). In overall, RAMI defines the business processes, functions, data, communication, integration, and interactions with the physical world. Topic wise, the contents of Industrie4.0 can be summarized as in Fig. 14. The middle layer of topics indicates the central properties of Industrie4.0 based systems, e.g., service orientation and product personalization. The bottom layer lists the most significant enabling technologies that are needed to implement these properties, e.g., simulation and modeling, cloud computing, and cybersecurity. There are many presentations of topics and technologies for the digitalization of industries; here they are all in one picture.

j. Industry5.0, Cognitive production

After 10 years of intensive engineering and development, the industrialization domain is regarded a fifth revolution in itself, Industry5.0. (see, e.g., [4]). Fig. 6 below, outline the transfer of topics or emphases. One might argue that Industry5.0 represents rather a continuum from Industrie4.0, just highlighting sustainability, human-system interaction, and the so-called resiliency. The combination of the newly emphasized technologies is often called “cognitive production”.

k. Carbon-free production

Nearly 200 countries have committed to the Paris Agreement on climate change to limit global warming to below 2°C. Rapid transformation out of greenhouse gases (CO₂, etc.) or fossil use in all sectors is required. Many countries have set even more ambitious targets. Climate awareness is so widespread that industries...
do not want to spend any more time in the old ways of doing. If technology allows, shifts to carbon-free production and products will occur faster than anticipated, although at the same time we must admit that hard research and innovations are desperately needed at certain points. Environmental effects cannot be achieved by a single means and by optimizing discharges pointwise. Global value chains need to be considered thoroughly. Probably progressing towards zero emission conditions do not occur simultaneously, so net-effect analyses and controls may offer temporary significant flexibilities. Carbon-free production means replacing coal in different forms as a raw material, either totally or engineer an extensive recycling in place.

“Should carbon be an unavoidable discharge, industries should be looking for various kinds of carbon capture technologies to avoid leaking CO2 into atmosphere”.

Often production processes are very energy intensive, and the industries must make sure the electricity does not come from powerplants burning coal, wood, oil, or gas. Usually this means that existing processing need to be replaced by new ones. Should carbon be an unavoidable discharge, industries should be looking for
various kinds of carbon capture technologies to avoid leaking CO\textsuperscript{2} into atmosphere. Most of the intended processes of today are expensive and difficult to control or manage. A lot of careful, knowledgeable, experienced, and modern automation or digital technologies must be employed and developed to achieve acceptable and reliable performances.

Some examples of ongoing developments:
- carbon-free steel production
- replacing cotton by cellulose, as a raw material for clothes
- food production without farming

I. **Solid foundations in the past, also relevant and necessary in the future.**

![Figure 15 Remembering Industry’s Past](image)

“In the hype of digitalization generations, we must not ignore many remarkable engineering concepts from the past”.

Manufacturing companies are often cautious to new ideas, with a reason, although the progresses often happen with recent technologies. Legacy technologies often still need considerable developments or be connected with the newer ones.

- **Feedback control** is probably still the most significant achievement in automation engineering. What causes the most difficulties these days, are ill-designed or out of tune controllers, although controller monitoring has evolved quite a bit. Issues
with controllers cause quality problems, waste discharges, energy and material losses, damages, etc. Often a careful management of controllers in the plant may account more than half to the CO2 footprint of the plant. – Advanced control methods which still need R&D attention include, e.g., model-based control, adaptive control, AI or image-based control. A lot of R&D attention or piloting has been concentrated on control structures with wireless elements due to recent IoT, edge-fog-cloud, etc., architectures.

- **Alarm systems** are generally easy to implement and are necessary or even obligatory in every installation. They are easy to design for constant and stable conditions (and generate alarms on deviations) but very difficult to implement for dynamic conditions. It is still commonplace that on regular start-up or shut-down occasions, during grade changes, or in mildly severe deviations, the control screens are flooded with unnecessary alarms. Reliable intelligent plantwide alarming remains an R&D target.

- **Standardization.** Although the need for standards, open interoperability, etc., is an old discovery and there have been standardizing efforts for decades. Indeed, every large digitalization or automation project in industry will have a key focus on interoperability. The problem is not the lack of standards, but in the proliferation of standards themselves. Standards exists at many different levels including, country or continent wide, application sector wide, they may be vendor specific, they may be end-customer dictated, and some standards originate from the research arena and may lack industrial credibility or visibility. The choice of standards is often determined by agreements in projects. A lot of expectations today are invested in semantic interoperability, a powerful principle but is demanding to implement. The progresses of technology gradually outdate old interfaces creating the need for updating older standards, and perhaps too often inspire new groups to initiate a totally new set of standards, surely filling some gaps but too often reinventing the wheel with the obvious needs for connectivity to legacy systems.

- **Old solutions ported to new platforms.**

  Opportunities solved in the recent past: PC, internet, busses, web browsing, PADs, mobile phones. Future opportunities and challenges: mixed reality glasses, edge-cloud platforms, digital platforms, 5G infra

- **Useful reference architectures, supported by tools and platforms.**

  Industrial systems have been and still are critical and complex. The word ‘complex’ carries several meanings. If a system is simply large, it deserves the word complex. If there are huge number of dependencies between items of a large system, that will make a system more complex. Then the items themselves may be complicated, etc. To deal with these inherent complexities, the engineers have developed several useful reference architectures, accumulating the knowledge and experience on designing, implementing, and running such systems. Although the technologies underneath are changing, new or advanced older functions emerge, it is more than worthwhile to learn the wisdoms of the older legacies.
Figure 16  ISA 95 Levels (ref: https://isa-95.com/)
Enabling Technologies Portfolio
5. Enabling Technologies portfolio

5.1 Artificial Intelligence

Artificial Intelligence (AI) as it is understood today is, on one hand, the most celebrated technology family we have, but on the other hand, it is a very good example of a promising concept of decades spent steadily growing but disappointing in terms of breakthroughs. In the 1970’s, AI became widespread in research, but it primarily meant expert systems, rule-based system, LISP programming, etc. The 1980’s saw the rise of Artificial Neural Networks, leaning on effective data-driven machine learning. In the past ten to twelve years, data-driven technologies became more mainstream, and the technology family got the name Artificial Intelligence. When the volume of data increased (across time series, image, video, free text, etc.), the term ‘big data’ was adopted.

Condition (or quality) monitoring and AI control have been the first and most widespread applications in industry. In condition monitoring, AI methods offered a means to provide maintenance services to industrial customers based on remote measurements, remote analytics, remote predictions, etc. AI will impact several main areas:

▪ By weaving AI into the design, manufacturing, production and deployment processes, productivity can be improved.
▪ By using AI to increase autonomy, higher operational flexibility can be achieved.
▪ By using AI to improve usability of products and services (e.g., by allowing greater variations in the human-machine interaction), the user value can be increased.
▪ By using AI for supporting complex decision-making processes in dynamic environments, people can get help in situations of rising complexity (e.g., technical complexity, increasing volatility in markets).

"Computation platforms for AI are undergoing dramatic change".

The near-process intelligence is being built both on smart IoT cards or more generically, on local edge computing hardware interacting directly to the physical process and to the internet, or recently to or as part of 5G. What is not meaningful to compute locally will be computed centrally in the cloud infra. An extreme application for the future will be supporting autonomous driving locally
in the edge computer(s) embedded in cars, 5G node computers in the communication network base stations, with the rest in the cloud. Similar experiments are being prototyped in factories. – AI algorithms are becoming more easily available in software libraries. Special hardware is being developed for ever faster AI computations, in the future perhaps in quantum computers.

Despite remarkable progress, advances are often slower than expected. Few reasons can be pointed out:

▪ AI algorithms remain a black box. It is often difficult to understand and manage their behaviour and performance, especially when things change, or new data arrives. Their so-called transparency is weak. The algorithms are often tuned to maximum but to achieve reliably a predetermined performance is not distinctive to AI.
▪ AI modules are often isolated from their wider industrial context. The industrial standards define seldom statistical entities or uncertainties. AI experts often have little knowledge and experience on industrial processes, manufacturing, businesses, or mindsets.
▪ AI algorithms should be more commonly combined with other methods or engineering, as a genuine part of them, not as an isolated subsystem on the side.

5.2 Digital twins, mixed or augmented reality, telepresence.

A digital twin is a dynamic digital representation of an industrial asset enabling companies to better understand and predict the behaviour and performance of processes. Nowadays, connectivity to cloud allows us an unprecedented resource. Simulation capability is currently a key element to European process, manufacturing, and machine industry to increase competitiveness. In Industrie4.0, modelling and simulation play a key role. A holistic engineering approach is required to span the different technical disciplines and prove the end-to-end engineering across the entire value chain.

Telepresence technologies can be considered as the predecessor for Extended Reality (XR) presence. The combination of XR and 5G offers a great innovation potential. The main driver is the enhancing of competitiveness through better productivity, improved worker safety, and better quality. The industrial applications have followed the prospects created by the gaming industry and consumer applications.

Beyond virtual commissioning, modelling and simulation responds in a broader fashion to many kinds of digitalization challenges:

▪ Understanding, explaining, and visualisation of physical or real-world phenomena of products, production, businesses, markets, etc.
▪ Helping designers to perform their core tasks, i.e., studying alternative designs, optimising solutions, ascertaining safety, providing a test-bench for automation and IoT solutions.
▪ The effects of changes can be safely and more extensively experimented in advance in a virtual domain than by using real plants, equipment or even mock-ups.
Simulators offer versatile environments for user or operator training.

Simulators may be used online and parallel with its real counterpart to predict future behaviour and performance, to give early warnings, to outline alternative scenarios for decision-making, etc. Despite years of research, such tracking simulators are still in their infancy, at least in the industrial context.

The idea of modelling and simulation is not new, but it is not complete yet, or reaching out industries is in the halfway. Some observations for future research or development are due:

- **Virtual commissioning**: It often takes substantial amount of time and effort to build a comprehensive dynamic model for the entire plant, production line, machine, or the simulator modules for the whole. For most purposes, today’s modelling and simulation techniques can be accurate enough, and the special hardware for obvious increased computation complexity is available, if ordinary PC is not fast enough. With good understanding, simulation granularity can be adjusted, and partial simulations are also useful.
- **Tracking mode simulation**: Possible today but needs good models, professional engineering and usually extra computing power.
- **Generating simulators** from other design documentation or measurement data (laser scanning, etc.). Speeds up simulator design, and the technology has recently become available.
- Digital twins combined with data-driven (AI, etc.) models. Development and piloting needed, but holds promises for increased performances.
- **Interoperability** remains a challenge. Modelling and simulation can be an isolated exercise in a company. In the context of design tools (CAD, etc.) interoperability does exist. When developing simulators, interoperability must be kept in mind, and conversely, when designing processes and machines, engineers must bear in mind that the target they are working on, will sooner or later be simulated, too.

*Figure 17 Virtual commissioning in process industry.* (ref: VTT)
5.3 Design and Architecture

Digitalization has become ever more vital. It has also enabled the creation and exploitation of the digital continuum of engineering and operative computer-based systems. For instance, requirements analysis and conceptual design are carried out with the aid of specific computer-based tools. Product and system design are carried out by a multitude of software tools, often referred to collectively as CAD (computer-aided design) tools, with each application field (oil and gas, energy, pulp & paper, discrete, etc.) using its own variations of tools.

Engineering software has also steadily evolved into extensive product life cycle management (PLM) systems with CAD and product data management (PDM) subsystems at their core. Engineering is, in lifecycles, followed by manufacturing or construction and delivery, managed again by specific engineering or manufacturing control software. Thereafter, the product or system enters its intended industrial use and, depending on the case, effective operation is governed, for example, by sensor or actuator systems, machine or process control systems, wider automation, condition monitoring, or quality management systems.

At a higher level, production planning, enterprise resource management (ERP) systems, and even cross-machine management systems and networked business management systems, may be used. This continuum of engineering and operative computer-based systems provides the foundation for the digitalization of industry. Nevertheless, it is more acute than ever to really talk dually about virtual plants or machines and real plants or machines. The volume, value and importance of the digital, virtual realm is increasing dramatically compared to physical plants and machines.

Two overall assets are essential in design and engineering: (1) effective architectures and platforms at all levels of the design hierarchy and (2) structured and well-adapted design methods and development approaches supported by efficient engineering tools, design libraries and frameworks. Future systems will be intelligent (using methods from Artificial Intelligence or else), highly automated and even autonomous and evolvable, meaning their implementation and behaviour will change over their lifetime. Such systems will be connected to, and communicate with, each other and the cloud, often as part of an integration platform or a system-of-system.

Design and engineering projects are challenged by pressures of time (faster throughput), increased complexity (extent, volume, interactions, multi-technology), and design quality.
Virtual engineering. Design processes must be expanded to enable virtual engineering on all hierarchies. Central to this approach are “digital twins”, which capture all necessary behavioural, logical and physical properties of the system under design in a way that can be analysed. This allows for optimization and automatic synthesis. Supporting methods include techniques to visualize V&V and test efforts, as well as sensitivity analysis and robustness test methods for different parameters and configurations. Test management within such virtual engineering processes must be extended to also cover all layers of the design hierarchy and be able to combine virtual and physical testing. To substantially reduce design effort and costs, a second set of supporting methods deal with the automatic generation of design artefacts such as design models, automatic scenario, use-case and test vector generation, generative design techniques, design space exploration, etc.

System and component design (methods and tools). To fully enable virtual engineering, design processes have to switch completely to model-based processes where models may be constructed using data-driven methods.

Lifecycle-aware holistic design flows. Closing the loop, i.e., collecting relevant data in the operation phase, analysing it and feeding it back into the development phase. Professional design is not possible without a legion of digital tools and the underlying framework that enables smooth switching, interaction and communication. Again, interoperability and standards are essential. A lot of expectations have been laid on the European digital single market which is difficult to achieve. We continue to read industrial reports explaining how much extra work is wasted for incompatibilities, to justify the standardization initiatives. On the other hand, engineering industries are used to dealing with the issue: they choose compatible tools and applications, or they have tested and proven interaction software(s). Often, it is the knowledgeable paying customer who has strong opinions about standards, etc., and then the service providers must adapt. Managing with standards is also an obstacle for newcomers, start-ups, etc., to join big projects, or vice versa, a questionable business tactics for those who are so-to-say in or have market shares to protect.

Digital twins are commonly characterized by modelling and simulation (the finite element method, FEM, computational fluid dynamics, CFD, etc.) or virtual or mixed reality techniques, and their numerous applications. However, the product
processes, manufacturing design and management of the operative lifetime of a product or factory is much broader. Typical examples of these are: managing the multi-technologies (mechanical, electronics, electrical, software); safety, security and reliability engineering; managing interactions with the contexts of the target (humans, environment); managing testing and quality; the various types of discharges or footprints; managing projects, logistics, supply chains, etc. These tasks are increasingly being managed by software tools and systems, and through the use of standards, regulations and engineering handbooks, which generally require extensive domain knowledge and experience.

The respective engineering disciplines are well distinguished, developed and understood. Key examples here – such as factory design, electronics design, engine design and car design – are well known and significant as regards success. These disciplines are going through a tremendous and demanding digitalization process and are sometimes called the “other twins” to underline their importance and high value. A narrow focus on digital twins will certainly play a growing role in implementing the concomitant increase in types of “other twin”.

There is also a notable discipline called “systems engineering”, which describes the instantiated subfields such as factory design and engine design. Similarly, many notable software tools – such as product lifestyle management (PLM), supply chain management (SCM) and CAD – are actually families of tools with significant versions for the actual subdomains:

- parallel joint engineering of products, processes, safety, security, cybersecurity, human factors, sustainability, circular factors, etc.
- mastering the deep linkage and complexities in multiple engineering domains and technologies, along with product and process lifecycles in the digital domain.
- multiplying the engineering extent, efficiency and quality in the digital world.

5.4 Software Engineering

Software clearly represents an enabling technology for process, manufacturing, and machine industries. Software has become a core, and the staff of engineering offices or departments of companies are mostly software or automation engineers. A company may have made a strategic decision not to get involved in software engineering but instead to outsource everything or at least to buy software as tools, modules, libraries, or as services. Or conversely, software has become a growing asset of company’s technology base. Even though, we have had computers for over 50 years, recent thinking is focused on the digital transformation [16]. Even though there are outstanding position papers, strategies and visions about today’s digitalization, in the end there is no common definition for digital transformation. But it certainly means architectures, processes, and technologies. Digital transformation is not something that you get, but is rather something that every company must define for itself.

The intention here is not to define a complete doctrine or profession for software engineering, directed to industrial needs. Besides the sole software engineering itself, it should include knowledge and experience on industrial engineering of the sector of the company, on the businesses, on customers, etc. This is clearly much
more than any university degree can accommodate, which give rise to the requirement for lifelong learning. Something companies must understand and cherish. As for individuals, it is also more than true that becoming competitive as a company needs years of attention and evolution in software engineering, and it is never ready. Modern software used in products such as cars, airplanes, operation robots, banks, healthcare systems and the public sector comprises millions of lines of code (growing). To produce this level of software, many challenges must be overcome.

How do we develop this software and simultaneously manage its complexity? How do we ensure the correctness and security of this software, as human wellbeing, economic prosperity and the environment depend on it? How can we guarantee that software is maintainable and usable for decades to come? Finally, how can we construct the software efficiently, effectively and sustainably? Even though such software impacts everyone everywhere, the effort required to make it reliable, maintainable and usable for longer periods is routinely underestimated.

A choice of software engineering topics that would need R&D attention, is extracted from the recent SRIA of ECSEL and includes:

- **From software engineering to systems engineering.** Developing professional software is multi-disciplinary. There is a whole ecosystem of models (e.g., physical, mechanical, structural, software and behavioural) describing various aspects of a system.
- **Integration of software.** It is necessary to place greater focus on integrating embedded software into a fully functional system.
- **Using abstraction and virtualization.** Generating software from higher-level models can improve maintainability and decrease programming errors, while also improving development speed.
- **Resolving legacy.** So-called legacy software and systems still constitute most of the software running in the world today. New software developed with novel paradigms and new tools will not run in isolation, but rather have to increasingly be used in ecosystems of connected hardware and software, including legacy systems. There are two main areas for innovation here. First, we need to develop efficient ways of improving interoperability between new and old. Second, we must innovate how to (incrementally) migrate, rejuvenate, redevelop and redeploy legacy software, both in isolation and as part of a larger system.
- **Lifecycle management of software.** Industrial systems have a long lifetime, often up to 30 years. If software is not effectively maintained, the software becomes overly complex until it is no longer sustainable. Practical challenges that require significant research in software sustainability include: (i) organizations losing control over software; (ii) difficulty in coping with modern software’s continuous and unpredictable changes; and (iii) dependency of software sustainability on factors that are not purely technical.
- **Digital platforms.** It is fair to assume that most future software applications will be developed to function as a part of a certain platform, and not as standalone components. In some domains, this idea has been a reality for a decade (e.g., in the AUTomotive Open System ARchitecture (AUTOSAR) partnership, which was
formed in 2003). However, guaranteeing quality properties of the software system (e.g. in safety and security) is a challenging task, and one that only becomes more complex as the size of software applications grows. - Europe is facing a great challenge in the lack of platforms that are able to adopt applications developed by individual providers into an ecosystem. Or, to put it the other way around, there are several (too many) platforms emerging, both from industrial software vendors or departments and from series of big public funded projects.

5.5 Quality, Reliability, Safety, Cybersecurity and Trust

“Increasingly, industrial technologies are being regarded as critical applications by law, meaning that extensive validation, verification, testing and licensing procedures must be in place”.

Security must also be embedded in all engineering tools, which strongly reminds us that safety is not achieved by testing alone but should be built in or integrated into every lifecycle stage. Security and cybersecurity are the other side of the coin in the distributed, remote or networked applications that contemporary communication technologies effectively employ. Since safety or security are difficult to achieve and prove, industries prefer to talk about trust and how they expect (and assume) safety and security will be in place for their business partners. In short, there must be no nasty surprises between trusted partners in terms of security issues.

As regards privacy, there is much well-meaning urging by researchers, software enthusiasts, etc, for open data and open software. However, certain data must be kept private by law. In addition, critical applications have be sealed and protected once they have been finalized, otherwise their safety, security, functionalities, etc., cannot be guaranteed. Most industrial applications also involve a great deal of engineering effort and creativity, are very extensive and constitute the core asset of companies that must be protected. Competitive business situations could therefore result in a cautious attitude towards open data and software. Nonetheless, industries sometimes do not entirely know what data, etc., it is beneficial to keep private and what should be open. In the era of AI, it may be a challenge to know in advance what could be discovered, for example, in the vast amount of factory or machine data.

The realm of critical applications has been expanding over the years. Application sectors that have been considered critical include: nuclear industry, certain
chemical and petrochemical industries, medical and food, health-care instruments, moving machines, transportation, aviation, and space. The list has been expanding over the year and is expected to grow, since more and more applications will be dealt with law and authorities. At the same time, quality in general has become a necessity in practice and, therefore, techniques and procedures developed for critical applications become relevant wider.

Risk, dependability, and reliability were originally developed for mechanical or electrical system and the core concepts were gradually adapted to software which proved to be most challenging. Software engineers were not accustomed to regard their modules, etc., as critical that had to be ascertained and proven, too. Whilst good progress has been made in this space, it is a challenge that remains, particularly with the expanding use of software in an array of realms.

In the past, critical software should always be small and simple so that the required reliability could be achieved and proven. Also, the hardware underneath should be ascertained. Critical systems must be kept isolated from less critical parts. When entering the extensive, complex, highly communicative systems, with criticality characteristics, the following challenges and opportunities are foreseen:

- Dependable connected software architectures
- Software reliability in the face of infrastructure instability.
- Dependable edge and cloud computing, including dependable and reliable AI/ML methods and algorithms.
- Dependable communication methods, protocols and infrastructure.
- Formal verification of protocols and mechanisms, including those using AI/ML.
- Monitoring, detection and mitigation of security issues on communication protocols.
- Quantum key distribution (“quantum cryptography”).
- Increasing software quality by AI-assisted development and testing methods.
- Infrastructure resilience and adaptability to new threats.
- Secure and reliable over the air (OTA) updates.
- Using AI for autonomy, network behaviour and self-adaptivity.
- Dependable integration platforms.
- Dependable cooperation of system-of-system (SoS).
- Dependable software and virtualization technologies
  Changing or updating software by retaining existing hardware is quite common in industrial domains. However, keeping existing reliable software and changing the underlying hardware is difficult. By decoupling software functionalities from the underlying hardware, softwarisation and virtualization are two disruptive paradigms that can bring enormous flexibility.
- Combined SW/HW test strategies
- Trustworthiness
- Ensuring cyber-security of systems, including AI.
- Defining different methods and techniques of trust for a system, and proving compliance to a security standard via certification schemes.
- Defining a method for multiple standards via the composition of certified parts.
- Enabling developers to have a flexible means to demonstrate security capabilities.
- Developing technologies, methods and techniques to ensure cyber-security at all levels.
- Definition and future consolidation of a framework providing guidelines, good practices and standards oriented to trust.
- 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.

### 5.6 Digital platforms

As noted earlier, most future software applications are developed as a part of a particular digital platform. One cannot do without them. A digital platform is an operating system like complex software entity by which application pieces of software, or modules, or objects can communicate, work together, etc. A platform offers a means for lower-level data and control signalling, tools and means for compound application composition and configuration, managing cybersecurity, i.e., all extra software engineering one would need to build extensive applications like factory or enterprise systems. Some platforms are intended for end-to-end engineering and business processes, whereas, some others are dedicated to modelling and simulation, maintenance management, etc.

![Figure 19 FIWARE digital platform for manufacturing (ref: The Open Source Platform for our Digital Future – FIWARE)](image-url)

Many software houses build their offering on top of a growing digital platform. Platforms are also sold as a backbone for customer’s expanding digital applications’ portfolio. The advent of Industrie4.0 gave a model for most of the digital platforms for manufacturing or production, and throughout the 201X’ies,
they all started to converge towards Industry4.0 definitions (platforms are big software so changes do not happen immediately).

![Image: Evolution of digital frameworks in EU funded projects.](ref: ECSEL SRIA 2020)

There has been a number of EU funded big projects, or series of projects, where several digital manufacturing platforms have been evolving. Project acronyms such as SOFIA, ME3GAS, IoE, ARROWHEAD, PRODUCTIVE4.0, AFarCloud, and FIWARE are famous, they have spent 100M€+ EU funds each, and reached on the order of 1000 European companies, universities, etc. The major European software and engineering companies are developing their own platforms (Siemens, ABB, Schneider – as examples of the large). US, Japan, China, Korea have their own significant initiatives. Also the Factories of the Future project cluster for ‘Digital manufacturing platforms for Connected Factories’ are currently developing a whole range of pilots enabling zero-defect manufacturing, dynamic value chains, human-centered manufacturing and circular economy (see also [www.connectedfactories.eu](http://www.connectedfactories.eu)).

Almost five years ago, European Commission declared its Digital Single Market vision [8], meaning every company or stakeholder, big and small, should have a viable opportunity and means to connect to any manufacturing or industrial application or project, as part of the growing European ecosystem. This vision has evolved in 2021 with the “Digital Decade” communication, which underlines the important role of the digital infrastructures and platforms not only for businesses, but also for the entire society. However, digital platform landscape is still very
fragmented, with open and closed, vertical and horizontal platforms in different developments stages and for various applications. There is a strong need for interoperability / standardisation and orchestration / federation of platforms. The trend towards agile, composable, plug and play platforms and more decentralised, dynamic platforms supporting AI at the edge, needs to be encouraged and supported. With particular emphasis to be given to practical accommodation of SME uptake and deployment.

Like standardization (also an important part of platforms), there are too many platform developments ongoing. Perhaps there are too many businesses or personalities who want to differentiate. Automation has also been a sector where ‘semi big’ companies dominate, i.e., big in a big country or big in a subsector – but not superiorly big globally or even in Europe, at least in contrast with certain global IT sector players (Microsoft, Google, Amazon, etc.). Industry applications are also extensive and complex, differ from sector to sector, and therefore one size does not fit all. Even the EU projects seem to concentrate in a certain way. Some are Mediterranean bound, some are Northern bound, or there are just clusters of old acquaintances among partners. The projects are also up limited of partners.

Existing gaps can still be found in the following topics:

- 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 its manufacturing and engineering dimension.
- Long-range communication technologies optimized for machine-to-machine (M2M) communication and the large numbers of devices – low bit rates are key elements in smart farming, for instance.
- Solving the IoT cybersecurity and safety problems, attestation and security-by-design. Only safe, secure and trusted platforms will survive in 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.

5.7 Edge and cloud computing, 5G

The computing platforms have been under significant transition during recent years, and this will probably require a transition from the prevailing factory information and automation system architectures we have had since 1980’s, cf. above. Thanks to the intensive autonomous driving R&D of the car industry, these schemes are also penetrating to machine industries. It is now envisioned that already near future (piloted today) system architectures consists of three layers of
computing devices, see Fig. 17. 1) Embedded computing reside very close or attached to the machinery or process. They can be seen as a legacy of the near past IoT devices connecting directly to hardware, process material, etc., performing some embedded intelligence and communicating to and from the here called Near Computing nodes (computers), either wirelessly or wired. These Near Computing devices (2) are often called edge computers, routers, or local servers. Near computer nodes are powerful computers themselves and communicate both to the embedded computing cards and to the cloud (3) via the internet. Obviously, there will always be a need for many kinds of more centralized computing, where the so-called cloud computing has been a kind of mainstream, at least on the R&D frontiers. But many kinds of central servers, etc., fit easily into the concept. – The term “edge” got its name due to the fact that it refers to something at the edge of the internet or cloud. Some people propose to place a layer of special computers to coordinate, etc., the edges. They are called “fog”.

A specific boon to the space comes from the 5G technology. The 5G communication technology executes edge-to-cloud and edge-to-edge communication which will be faster than anything before. The 5G base stations are no longer mere antenna poles but equipped with very powerful computing nodes, and the densely installed 5G base stations will take the role of edge computers.

Figure 21 Emerging computing architecture of embedded computing, near computing and central computing. [6]
These new computing architectures are now being piloted in various applications, including autonomous driving or bringing advisory or pleasure features to vehicles, smart buildings, pilot factories, etc. Advanced condition monitoring and management, telepresence, and other remote service business applications are also technologies of significant interest here.

Although touted as a revolutionary technology, this concept seems to appeal to industry. Looking from distance, it does not look very different! Automation systems have always had local and short cycle-time computations, line and factory level computations, and then central or remote computations. Without the need to change the overall mindset. The computing and communicating capacity seem relatively unlimited and appeal to all latest enabling computing and communication intensive technologies discussed in this paper.

Responsible and experienced industrial engineers do have concerns and questions here:

- Critical automation applications have been implemented on dedicated PLC and DCS hardware for decades, with dedicated design methods, tools, and languages. A lot of engineering experience is embedded in these. Do they easily port to the new paradigm? What needs to be ported? What comes extra or instead? Are the new devices and software reliable enough? Can I keep my assets of previous designs?
- Is wireless communication safe and secure? Or if and as we want to keep the old and proven solutions, can we operate stand-alone if the 5G connection is missing?
- Industrial systems have anyhow long lifetimes, often 30 years, and their automation is typically renewed every 10-15 years.

Despite the above concerns, it is better to stay open-minded and look forward to the opportunities of this partly new paradigm.

### 5.8 Responsive and smart production

“The ability to react quickly to changes, efficient work allocation, predictable quality, fair circulation of tasks, and the ability to tailor tasks for individuals are important targets for responsive and smart production”.

Agile factories and networks are required to deliver products with a high degree of personalization (high-mix low-volume, lot size one, highly customized manufacturing). Therefore, to make a manufacturing plant more constructible, adaptable, and dependable, improved, scalable approach to adaptivity and resilience is needed. This approach must be general, cohesive, and consistent.
across all interconnected lifecycles of the system components. Many European initiatives and reports cover this topic:

1. EFFRA calls for “Agile value networks design, manufacture and deliver innovative products with a high degree of personalisation”
2. SMART-EUREKA mentions “Intelligent and adaptive manufacturing systems” as a main research and innovation domain.
3. ManuFuture: “Factories will adapt and become resilient to foreseen and unforeseen changes in the market and in technology.”
4. World Manufacturing report 2018 indicates that rapidly responsive manufacturing is a disruptive trend, to “…react quickly to and take advantage of changes in market conditions, customer preferences, manufacturing conditions and social demands.”
5. Attention for further development is still needed as follows:
6. Robust optimal production, scalable right first-time production. Manufacturing should become more robust, even when facing disturbances. This will require advances in self-healing and redundant automation systems, first-time-right, zero-defect manufacturing, and predictive maintenance.
7. Mass customization, personalized manufacturing, or customer-driven manufacturing. Mastering the complexity of products, processes and systems. Progress towards lot-size-one manufacturing and personalized product design will continue.
8. Resilient and adaptive production, including supply chains. Shortening supply chains. Modular factories. Resilience is a critical property for a system that can absorb change and adjust its functional organization and performance, so that it can maintain the operations necessary to accomplish its mission in varying conditions.
9. Cognitive production. Cognitive production looks to deploy both natural and artificial cognition to enable new analyses and learning that can enable responsive and sustainable adaptable production.
10. Manufacturing as a service.
11. Standardisation. One cannot easily beat the legacies of many standards and their installed base. Instead, focus on bridging systems of diverse standards. Develop semantic technologies as a vehicle to master diverse and multitude of standards. Develop middleware or translator software, or platforms that enable effective connectivity, on high application level. Develop respective digital test and development environments. Develop licensing. Ensure wide acceptance and support of software vendors, engineering offices, end-users.

5.9 Sustainable production

Nearly 200 countries have committed to the Paris Agreement on climate change to limit global warming to below 2°C [13]. Rapid transformation of all sectors is required. Many European countries have set even more ambitious targets. Digitalization can have a great bearing in reducing environmental impact. The vision of SPIRE (Sustainable Process Industry through Resource and Energy Efficiency, [7]) breaks down the higher-level goals into more concrete actions:

1. Use energy and resources more efficiently within the existing installed base. Reduce or prevent waste.
2. Re-use waste streams and energy within and between different sectors, including recovery, recycling and re-use of post-consumer waste.
3. Replace current feedstock by integrating novel and renewable feedstock (such as bio-based) to reduce fossil, feedstock and mineral raw material dependency while reducing the CO2 footprint of processes or increasing the efficiency of primary feedstock. Replace current inefficient processes for more energy- and resource-efficient processes when sustainability analysis confirms the benefits.

4. Reinvent materials and products to achieve a significantly increased impact on resource and energy efficiency over the value chain.


Directions for future research and development are:

1. **Life-cycle assessment.** Life-cycle assessment (LCA) is a prerequisite for holistic environmental evaluation, and is a simple but systematic method. However, it requires extensive experience and comprehensive models and data. In practice, mixed combinations often need to be employed – for example, missing measurements must be compensated for by models or standard data. LCA software must also be better integrated into other automation systems.

2. **Monitoring flows of energy, materials, and waste.** It is already commonplace in many sectors (e.g. food, medicine) that material and energy streams need to be completely traced back to their starting point. Flows need to be monitored. Sustainable manufacturing needs comprehensive environmental and other measurements that may not at all be in place when a particular manufacturing or production was initiated. On the other hand, this is a very typical application of many kinds of IoT sensor and system that can be informed by a careful LCA. Discharges or losses mostly happen when production does not occur as planned, as is optimal, due to mistakes, bad condition of machinery, unskilled operation, and
so on. Human factor causes most of the variation in running continuous processes. There should be focus on how to AI assistant or AI optimizer could be used to help operators by giving advices and preventing not optimal changes.

3. **Human-centered manufacturing.** A higher level of formal training may be required for workers in production and maintenance. Greater specialization is constantly introducing product, process or company-specific extra training.

4. **Green Deal.** Policy initiatives aimed at putting Europe on track to reach net-zero global warming emissions by 2050 are put forward in the European Commission’s European Green Deal [14]. The Commission plans to review every EU law and regulation in order to align them with the new climate goals.

---

**5.10 Autonomous systems, robotics**

The most famous fully autonomy target today is autonomous driving. All major car manufacturers have extensive projects. Progress is defined to advance by levels of autonomy, that is we are going to have 1-5 levels of autonomous vehicles, where level 5 is the 100% autonomy, which seems to be years ahead. But the new car models do have more and more driver assistant features that are quite intuitive.

The autonomy target has also spread to working machines, where we already have autonomous mines and harbours, i.e., where the work site is more structured. However, autonomous forest machines may remain years ahead.

There is a long-lasting trend towards higher degrees of automation level in factories. Hydro power plants for example have been fully automated for decades. There are also pilot factories or concepts for full autonomy. A more common trend is to have fully autonomous or automatic unit processes, production lines, etc. Again, car manufacturers have fully robotized production cells or lines. However recent studies emphasize a more effective human-machine or human-robot collaboration, so various degree of semi-autonomous machines and plants should be regarded as a realistic vision.

Machines are more precise and efficient than humans. Thus, replacing, or aiding work processes susceptible to human errors, quality defects and safety issues will have an impact on quality and redundant waste. In some industries, such as construction, aerospace, automotive, critical infrastructures complex systems, and utilities, quality issues and the prevention of hidden defects in structures and/or any mechanical and electrical components are extremely serious. Therefore, substantial losses in terms of legal aspects, safety, potential stresses under critical situations of vehicles and aircrafts, substandard end products and quality costs in general – for part of the consideration.

The main aims and evolution trends of robots and autonomous systems in the digital industry are oriented toward:

1. **Production efficiency, speed and reduced costs,**
2. **Higher precision and quality,** and
3. **Safety in the working conditions.**

However, between the two extremes of entirely manual or fully autonomous, there will probably always be a large area of semi-autonomous equipment, units,
machines, vehicles, lines, factories and sites that are worth keeping somewhat below 100% autonomous or digitized. The reasons for this include:

- a fully autonomous solution may simply be (technically) next to impossible to design, implement and test
- if achievable, it may be too expensive to be realized.
- a fully autonomous solution may be too complex, brittle, unstable, unsafe, etc.
- a less-demanding semi-automatic solution may be easier to realize to a fully satisfactory level.

When automation and digitalization degrees are gradually, reasonably and professionally increased, often portion by portion, they may bring proportionally significant competitive advantages and savings that strengthen the position of digital industries overall. However, since automation or digitalization degrees remain well below 100%, the negative effects to employment are either negligible or non-existent. On the contrary, an increased market position could increase the need for more people in the respective businesses.

5.11 Industrial service business, lifecycles, remote operations and teleoperation

The volume and value of industrial services are increasing by 5-10% year-on-year. The share of services has exceeded the share of machinery for many machine, system, and service vendors, not just for a final assembly factory but also for companies in supply chains. Companies are willing to take larger shares of their customers’ businesses, at first as a spare part supplier, later about remote condition monitoring, and extending to a number of other tasks that were considered in the past as customer core businesses. From customer point of view, such a shift in business models is called outsourcing.

As businesses have become more global, some services are provided locally, while other services are provided centrally from the original vendor or companies specialized to services. Similarly, as there may be extensive supply chains behind the vendor companies, the respective services may extend to supply chain companies. The industrial era of the past is becoming a service era, enabled by high-end ECT/KDT technologies. This distributed setting is also conveniently fitting to modern edge-cloud architectures as computing and communicating platform.

The importance of service business in the future is evident as the service business enables a revenue flow after the traditional product sales and, more importantly, the service business can be more profitable than the product sales itself. The service business markets is becoming more and more challenging, while the high-income countries are focusing on high-skilled pre-production and on life-cycle stages. Fortunately, in the global service business market, Europe can differentiate by using its strengths: highly skilled workforce, deep technology knowledge and proven ICT capabilities, but the success needs new innovations and industry level changes.

Key focus areas for future development include:
Industry4.e whitepaper

- **Collaborative product-service engineering, life-cycle engineering.** Extending R&D to consider that products and systems will be integrated to the industrial service programme of the company. Possibly obtaining knowledge to give services for other similar products (competitors!)

- **Training and simulation.** Complex products like aircrafts, drones, moving machines and many teleoperated machineries will need a simulation environment for training of the human driver/operator.

- **Condition monitoring, condition-based maintenance, anomaly detection.** Performance monitoring, prediction, management. The traditional service business sector, still encountering major challenges in practice. An extension to the above, as targets of services are expanded to other topics in customer businesses than spare parts or condition monitoring.

- **Remote engineering and operations, telepresence.** Operating or assisting in operations of industrial systems from remote sites.

- **Decision and operations support.** In most cases decision making is not automatic but is based on remote expert assistance or extensive diagnosing (AI based, etc.), engineering, and knowledge management systems.

- **Local and global services.** Organizing services locally close to customers and centrally at vendors’ site.

- **Fleet-management.** Obtaining knowledge and experience from number of similar components and machines in similar or different conditions.

- **Edge-cloud solutions.** Implementing distributed service applications on effective edge-cloud systems.

- **Full life cycle tutoring.** Monitoring activities, level of stress and performance-oriented behaviour during the entire product life to anticipate its end of life, to properly handle its waste(s) and recycling and for an improved redesign of next product generations.
Ground work for Success
6. Groundwork for Success

As part of the initial work done in setting up the structures of the I4.E Lighthouse, we commissioned a CSA (I4.E CSA) to support the work being undertaken. The main focus of the CSA activity was to build a message for the lighthouse into the wider community, carry out an environmental scan of the various digital frameworks and roadmaps in the wider EU research ecosystem and to help build connectivity across these disparate communities.

The CSA partners were Irish Manufacturing Research (Coordinators), Mondragon Inibertsitatea, Aquatt, Steinbeis 2i and VTT. The focus for this work centred on building connectivity and support for industry 4.0 digital research projects and developing public engagement as part of an overarching outreach program. The lighthouse initiative then invited flagship projects to join the Lighthouse activities and this has been building over the past three years.
The connectivity and visibility of these lighthouse projects to both one another and to the wider community has been a very positive first step in determining the collective impact (and indeed gaps in collective impact) across the research activities of the wider ECS community. One very useful tool developed by the CSA and LAISE activities in this phase of our evolution was the deployment of the Industry4.E Project Portal (figure below).

Figure 25  I4.E Lighthouse Project Portal (Screenshot)
The project portal allows project information to be easily uploaded and tagged, so that data retrieval, cross-referencing and information pertaining to the wider activities of a group of projects can be easily managed. It is also linked automatically to the Twitter feeds and other dissemination channels for the partner projects so that it remains up to date using the latest digital technologies. The portal has been a very important aspect of the development of the connectivity part of the Lighthouse journey. Other highlights of the work done to date include over 1000+ digital network followers (LinkedIn, Instagram), 1000+ people participating in digital workshops, a communications and dissemination e-book published to help practitioners to navigate the EU project landscape and the development of this whitepaper. This work to date, in line with the development of the structures underpinning the Industry 4.0 Lighthouse have been a basis to start the journey, but now the real work begins.
Conclusion
7. Conclusion

The challenges facing European industry are significant as we transition to an industry 4.0 world. Challenges such as standardisation, interoperability and the requirements for the green agenda mean that practical supports to enable industry to take these important steps towards a meaningful digital transition are more critical than ever before. Often these transitions will require upskilling and re-training of personnel. In more cases, practical investments in connectivity and interoperability at a company level, all the while keeping a strategic overview of the progress being made and anticipating future needs at an EU level. For example, we know that over the coming years we will need to systematically digitise European industry. For this to happen we will need to embed all sorts of clever and innovative technical components and systems into machines and factories across all industrial sectors. The need will be as relevant in medical devices as it is in agri-food and the automotive sectors.

In a very practical sense, all these systems need to be manufactured, assembled, and deployed, which in turn will put constraints on the relevant supply chains and value chain networks that exist in Europe (and beyond) right now. Such constraints need to be considered in future R&D&I planning and investment. We need to be mindful of these types of consequences for our digitisation aspirations and anticipate the strategic requirements to ensure this type of problem does not become a block to European progress in the future. The interconnectivity of various supply chains and industrial ecosystems is convoluted and complex, which often extends beyond the borders of the European Union. It is important that Europe maintains a strong (technical & business) presence internationally, so it is well positioned at a global level, in order to minimise potential impacts from global trade (or political) fluctuations. It is against this backdrop that the I4.E Lighthouse LIASE have presented this whitepaper.

The work of the Industry4.E Lighthouse Initiative, led by the LIASE will continue to provide concrete recommendations through the introduction of the KDT and the launch of the next phase of EU Research and Innovation funding (Horizon Europe). We will look to expand the LIASE group, to include more industry partners, more women, and a wider research stakeholder representation. We will also work with the various agency and commission partners to grow the influence, connectivity, and effectiveness of the I4.E Lighthouse Initiative. Our focus will remain on the higher order direction and influence of activities across the broad range of EU funded research. The LIASE is committed to making sure the I4.E Lighthouse Initiative is providing the ecosystem with pertinent, valuable, and impactful perspectives, actions, and proposals on where EU research investment needs to be focused, in order to maximise the resultant impact and enable Europe to execute effectively against its key twin transition policy objectives.