VTT Technical Research Centre of Finland

Sustainable Industry X

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Published: 01/01/2020

Document Version
Publisher's final version

VTT

beyond the obvious

Sustainable Industry X –

a Cognitive Manufacturing Vision

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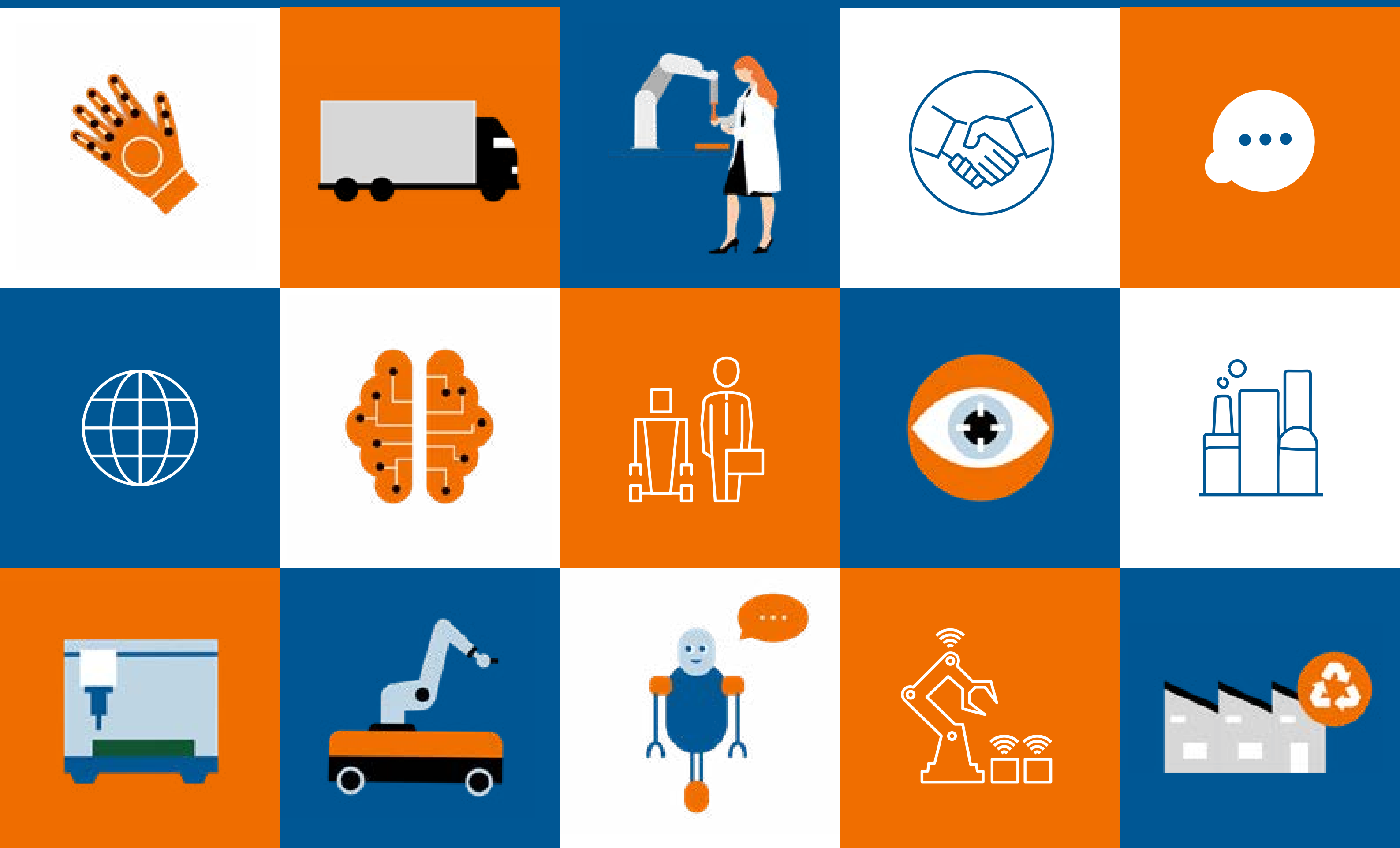

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Executive summary

The new European industrial strategy aims at green, circular and digital transformations. In line with this, **Sustainable Industry X vision** provides an overview of the future of the manufacturing industry. The vision includes three broad-level aims and three generic transitions.

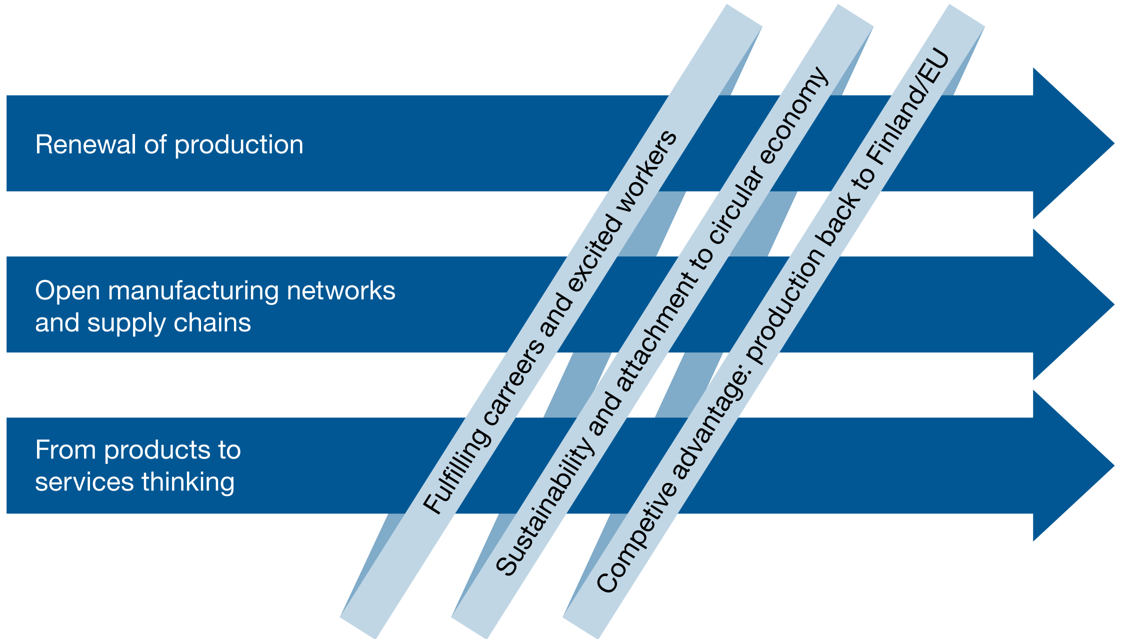
The aims are as follows:

1) fulfilling careers and excited workers,
2) sustainability and attachment to circular economy, and
3) competitive advantage for increasing production within Finland/EU.

The three generic transformations, in turn, are:

1) renewal of production,
2) open manufacturing networks and supply chains, and
3) from products to services thinking.

These aims and transitions include synergistic opportunities; that is, they support one another. The enabling technologies and tools for this transition include (but are not limited to) the following: sensing technologies, AI, big data, 5G, IoT, collaborative robotics and additive manufacturing. It is a task for the near future to revolutionise industry through a meaningful combination of digital technologies while addressing well-defined sustainability goals and creating competitive advantage – all this requires highly-skilled and motivated workers. We see that the forthcoming industrial revolution draws from collaboration between various research and technology providers. Developments within the fields of AI/ICT, telecommunications, human factors, service design, robotics, logistics and automation should converge to create the much-needed transformations within the manufacturing industry.



Introduction

The Industry Sustainable X Vision provides broad sketches for the evolution of industry. The vision draws on existing conceptualisations of technology development and syntheses, along with generic notions of Industry 4.0 and 5.0. This is coupled with risk management, sustainability and circular economy approaches and examples.

All this reflects the notion that new opportunities arise from the progresses within ICT and telecommunications: AI-driven solutions, new means of visualisations (AR, VR), collaborative robotics, the Internet-of-Things (IoT) and hyper-connected factories. 'Cognitive manufacturing' is a term that broadly describes the fusion between novel ICT and telecommunications with the manufacturing industry. These new progresses, in turn, fuse with new production methods, such as collaborative robotics and additive manufacturing, which will provide competitive advantage in the near future.

In today's global economy, companies are inextricably linked to their supply chains (Bowersox et al., 2016; Christopher, 1998). The primary goals of cross-company integration are the reduction of waste, the cutting of costs and the building of relationships that allow all parties involved to achieve mutual improvements.

The synergy created when operating across organisational boundaries cannot be achieved by a single – at least hypothetically isolated – company. Operational integration therefore leads to efficiency gains in many respects. Furthermore, an isolated optimisation of a specific functional area without considering cross-functional impacts and requirements is unlikely to lead to integrated performance (Bowersox et al., 2016).

The more tiers of suppliers and customers a supply chain has, the more complex and difficult it is to monitor actions and processes in the nodes of the network. For many companies in the manufacturing industry and other production sectors, this leads to an increase in sustainability and continuity-related supply chain problems. The dependency on specific materials and sources and the connected significant risks requires active management. Consequently, sustainability performance must be judged over the whole supply chain.

Transparency – knowing what is happening in the chain – requires efforts to use adequate technology. The move towards a circular supply framework based on transparency involves the comprehensive use of Industry Sustainable X technology solutions, such as sensor technologies and IoT, data analytics and 5G as the enabling infrastructural technology.

In particular, the Industry Sustainable X Vision aims to create synergistic benefits by combining the following:

- activities and solutions that allow and promote the circular economy, and
- new intelligent technologies that are foreseen to contribute to the near-future evolution of industry

The vision for the manufacturing industry builds upon a shift towards sustainability and a circular economy in order to reduce resource use, waste and emissions as well as supply risks

As noted above, the vision for the manufacturing industry builds upon a shift towards sustainability and a circular economy in order to reduce resource use, waste and emissions as well as supply risks. The new European industrial strategy (European Commission, 2020) strives towards green, circular and digital industrial transformation. The goal of the strategy is to empower industry and small and medium-sized enterprises as well as to keep Europe competitive and sustainable. In its aspiration to become the world's first climate-neutral continent by 2050, the European Commission has launched The European Green Deal (European Commission, 2019) as a new growth strategy.

To finance this transition, the European Green Deal Investment Plan pledges to mobilise at least €1 trillion in sustainable investments in both the private and public sectors over the next decade. In addition to financing, the plan will also provide tools for investors and offer practical support to public authorities and project promoters. The Just Transition Mechanism ensures that investments will be targeted in a fair manner to the most affected regions, such as those relying on the fossil fuel value chain (European Commission, 2019).

In addition to government-led investments in sustainability, manufacturing companies remain committed to further investment in digital technology. According to CapGemini (2019), the market for smart factories, for example, is estimated to be worth approx-

The proposed vision should also be seen in the light of increasing resilience to sudden shocks such as the COVID-19 epidemic.

imately $154 billion in 2019 alone. Digital technologies that form the basis for smart factories include connectivity (IoT), intelligent automation (e.g. advanced robotics) and cloud-scale data management and analytics (e.g. predictive analytics/AI). These technologies will significantly improve productivity, quality, flexibility and service, as 'closed-loop' and self-optimising operations add effectiveness.

The proposed vision should also be seen in the light of increasing resilience to sudden shocks such as the COVID-19 epidemic. The coronavirus and the restrictive measures undertaken by governments force the economy into turmoil and impact strongly on employment and people's wellbeing. Many companies in the manufacturing industry are, for example, affected by the impact on their global supply chains, which were hit both by the early spread of the pandemic as well as the resulting measures.

Therefore, to recover from the COVID-19 crisis, the European Commission is targeting funds, mostly in the form of grants, to reach the EU's objectives of climate neutrality and digital transformation. Its proposed economic stimulus plan amounts to €750 billion along with a budget of €1.1 trillion during the EU's next seven-year budget period (European Parliament, 2020).

Technology investment in times of crisis will accelerate recovery while simultaneously enhancing economic competitiveness. Thus, green recovery has the potential to transform the situation into an opportunity (Pantsar & Tynkkynen, 2020). This is especially important due to path dependencies of decisions taken in the past. When choosing the path of traditional recovery using carbon-intensive technologies, this will effect development in the long-term. Thus, the opportunity to support and speed up the transition to a circular economy with fewer emissions as part of the economic recovery will positively affect the sustainability problem.

This paper addresses the question of what kind of shared vision might pave the way towards a sustainable industrial revolution. A crucial element here is the workforce – in order to realise all this, the manufacturing industry must be able to provide fulfilling careers and attract a talented workforce. We will first go through the background literature and then outline the Sustainable Industry X Vision. The vision involves synergistic elements, that is, transformations that support one another.

Literature background

Industry 4.0

The integration of communication and information technology into objects, materials, devices and production and development environments enables the capture of the states of devices and materials. It also allows capturing external states of industrial processes in real time. This supports comprehensive improvements in production processes, engineering development, logistics and supply chain management, material planning and life cycle management. This development is known as the fourth industrial revolution, or Industry 4.0.

The concept is in line with the various industrial revolutions that have brought fundamental change in the course of industrial history (Promotorengruppe Kommunikation der Forschungsunion Wirtschaft – Wissenschaft, 2012). The introduction of mechanical production facilities at the end of the 18^{th} century accompanied the first industrial revolution, while the second industrial revolution at the turn of the 20^{th} century was enabled by the mass production of goods based on the division of labour using electrical energy. The evolution culminated in the third industrial revolution from the mid-1970s onwards. The use of electronics and IT further advanced the automation of production processes and delegated part of the knowledge work to machines.

1st	2nd	3rd	4th	5th
Mechanisation, water power, steam power	Mass production, assembly line, electricity	Computer and automation	Cyber-Physical System	Coworking

Industry 5.0

The future factory in the manufacturing sector, even if it becomes more and more automated, will not be devoid of people. Instead, specialists will take over important functions in the installation, conversion, maintenance and repair of a wide variety of systems and components. To this end, these experts must be supported by intelligent assistance systems in order to carry out the necessary work safely and efficiently and with appropriate decision support.

It is imperative to appreciate the cooperation between machines and human beings. This cooperation emerges by combining the diverging strengths of both, machines and humans, in order to create a more inclusive and in particular human-centred future in which ethical concerns are addressed (Longo et al. 2020). This is especially important, as there is a growing concern about automated machines, such as robots, taking away jobs from manufacturing and other industrial sectors.

This next stage of industrial evolution, which can be labelled as Industry 5.0 (Promotorengruppe Kommunikation der Forschungsunion Wirtschaft – Wissenschaft, 2012), should therefore also lead to a paradigm shift in human-technology interaction with completely new forms of collaborative factory work. Innovative methods and technologies will be used here to support and enable the handling of cyber-physical systems. The cognitive, i.e. learning, abilities and the natural limits of both humans and AI should be recognised. The ignorance of these limits leads to high error rates and accidents. This is important, because generally the new technologies open up possibilities to optimise any processes and to adapt them to the human being.

Industry X.0

The transition, which includes the major structural reforms described above, naturally focuses on the digitalisation and computerisation of industry. The aim is to adapt processes to flexible and dynamic needs and to strengthen overall competitiveness.

The transition process is not uniform and is experienced by companies in many different ways. Many companies use digital technologies in a fragmented way. As a result, the benefits of digitalisation do not reach all their organisations and therefore do not contribute to the transition in a comprehensive and holistic way.

The consulting firm Accenture (2020) believes that the solution to realise the potential of digitalisation and the progress in the technology area of Industry 4.0 and Industry 5.0 lies in a meaningful combination of smart and connected technologies.

Accordingly, companies must address the transition with digital technologies to reinvent their products, processes and services from a variety of perspectives, including design, engineering and support services. The convergence of technologies such as sensors, artificial intelligence, high-volume data analysis and the Internet of Things enables companies to move forward and gain competitive advantage. Accenture (2020) calls this approach Industry X.0.

Need for sustainability

Ecological problems, which are reflected in a scarcity of natural resources as well as a deterioration of resource quality, have led to the industry being increasingly confronted with the social consequences of environmental and ecological problems. This can have far-reaching consequences, as both the original ecological problems and the associated environmental protection requirements can change the competitive environment of companies. It is therefore extremely important that companies in the industry address the issue proactively. Otherwise, it is possible that tighter environmental legislation will lead to the loss of competitive advantages. This would be devastating, at least for parts of the industry (Schulte, 2013; Grant et al., 2015).

The concept of sustainable development, as conceived by the Brundtland Commission over 30 years ago, has been extremely influential concerning proactive responses to environmental issues. According to the Commission, ‘sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs’ (UN World Commission on Environment and Development, 1987). We can extend this to other systems, including social systems such as companies or the economy as a whole, and state that a system should be used in such a way that its main characteristics are maintained in the long term.

In practice, sustainability is conceptualised by the triple bottom line approach (Elkington, 2004; Hourneaux et al., 2018). Sustainability involves three aspects, these being economy, ecology and society. Ideally, all three dimensions are appropriately weighted. However, the economy is usually seen as an overarching goal, but this includes little controversy given the above-mentioned European Green Deal (European Commission, 2019) incentives.

Circularity

Although production is often perceived as efficient, the consumption and use of natural resources and material goods is associated with a high volume of waste. Depending on the supply chain, most of the materials used are incinerated or disposed of, while a smaller part is reused or recycled.

The reasons for this are numerous, but are often linked to the comparative costs of sourcing from new materials compared to sourcing from recycled materials. This means that reusing or recycling materials is unfortunately still often more expensive than using new resources.

One answer to this problem is to focus on supply chain strategies, which can be an important factor in improving sustainability by making new ways of sourcing and procurement available (Rodrigue, 2020).

In principle, the circular economy is a feedback system whose aim is to minimise the use of resources or materials and the generation of waste that is released into the environment. It can be seen as an extension of the principles of waste management logistics into a more comprehensive framework, which we refer to here as a closed-loop system. Closed-loop systems ensure that each output of the system can be recycled to serve as input for the production of another product. Closed-loop systems are used in supply chains when companies want to recover their products for remanufacturing, reprocessing or perhaps even for sale on secondary markets (Grant et al., 2015). Thus, the closed-loop approach is a response to companies' supply needs by creating novel methods in sourcing and procurement.

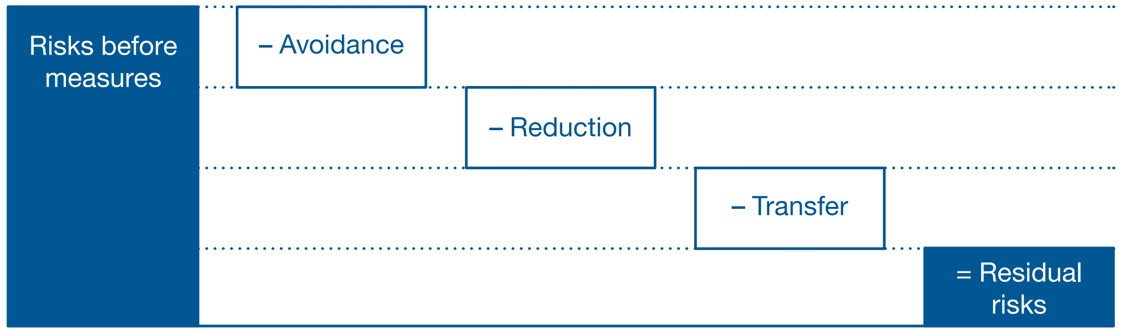
Supply chain risk management

Supply chains are generally vulnerable to risks, irrespective of whether these risks are internal or external in nature. The optimisation of supply chains generally involves the control of risks. This is achieved through stable processes, the use of the latest information and communication technologies and sustainable partnerships, especially with suppliers and customers.

Risks are unexpected events and developments that have a negative impact on set targets and associated expectations. Every business activity is associated with risks. The problem is therefore not the taking of a risk, but the uncontrolled existence and failure to control risks. The most successful companies are those that have their risks best under control and take advantage of the opportunities that arise from them (Schulte, 2013).

Typical relevant risks include supply risks, operational risks, political risks and resource and sustainability risks. Supply risks refer to uncertainty or disruption in the supply

Figure1. Risk management: multi-stage model (Buderath, 1999: 25)



based on, for example, breakdown at the supply sides, price fluctuations, shortages or shipping issues. Consequences include breakdown of own production. Operational risks may refer to breakdown of operations, inadequate production planning or process variability. Consequences include the inability to supply downstream supply chain actors or high costs when trying to find alternative capacity. Political risks include changes in policies at the national and international level, e.g. concerning trade restrictions, taxes and tariffs and licence requirements. Consequences of political risks may include changes to market access, tax advantages or escalating costs, increased competition and loss of market share. Resource and sustainability risks refer to potential shortages or even the depletion of vital natural resources, such as metals, minerals and biological resources. It may also refer to natural catastrophes or the risks involved in sourcing resources from politically unstable regions. The consequences of such risks include the increasing costs of acquiring relevant resources and possibly frequent supply shortages. In addition, when operating in politically unstable regions, the risk of operating according to bad business practices could increase (Grant et al., 2015: 178–179).

Risk management is to be seen as a comprehensible control cycle that encompasses all company activities and includes a uniform and permanent procedure. Within the framework of a company's risk strategy, the basic handling of risks and the responsibility for risk management are defined. This includes company-wide principles and guidelines. The purpose of risk identification is the early recognition of developments that could jeopardise the continued existence of a company. These developments include particular risky business processes that have a significant impact on the net assets, financial position and results of operations (Schulte, 2013).

As part of risk management, decisions must be made regarding how to deal with the relevant risks. Risk management is intended to actively influence the risk position of the company. The aim is to use the instruments in such a way that a balanced relationship between opportunity and risk is achieved. The set of instruments comprises measures aimed at reducing the probability of occurrence of causes of risk and which serve to improve the result when risks occur and to reduce, limit or compensate for damages and losses (Schulte, 2013).

Using a multi-stage model, a distinction can be made between measures that avoid (e.g. decision against a remote supplier) or reduce (e.g. sharing assets with another company) risks, or at least transfer them in part (e.g. having insurance), and those that are taken on completely (accepting a risk completely) (Buderath, 1999).

Together, the circular economy and Industry 4.0 could help to realise the vision of an environmentally sustainable economy.

Circular economy and Industry 4.0

There are links between Industry 4.0 and the recycling industry. This means that the respective concepts can fully exploit their advantages for the economy, society and the environment in synergy.

A company's internal resources, expertise and skills form the basis for competitiveness. These must be constantly developed and expanded in order to create sustainable competitive advantages. In our case, therefore, there are not only technologies that create competitiveness within the framework of Industry 4.0, but also digital technologies that enable a circular economy and support and underpin the corresponding corporate strategies. This approach makes it possible to name specific Industry 4.0 technologies and their economic and ecological advantages that result from their application within the framework of production systems, supply chains and a circular economy.

From a political decision-making point of view, economic development and environmental sustainability can be reconciled in the context of ecological modernisation. This is based on the assumption that development through technological innovation leads to an increase in resource and energy efficiency. In this context, the question can then be addressed, for example, as to how innovation policy contributes to Industry 4.0 and how this policy is coordinated with the principles of the circular economy (Lopes de Sousa Jabbour et al., 2018).

In a blog post on Industry 4.0 and the circular economy, Knudsen & Kaivo-oja (2018) suggest that Finland should take the lead on linking Industry 4.0 with the circular economy to ensure that it remains competitive in the future. Digital technology and the use of large amounts of data are important prerequisites for the introduction of the circular economy. Together, the circular economy and Industry 4.0 could help to realise the vision of an environmentally sustainable economy.

There are challenges, however. For example, the advantages of interconnectivity and large data volumes can actually lead to a positive feedback loop, increase consumption and energy demand and lead to higher environmental pollution. Knudsen & Kaivo-oja (2018) also raise a double challenge: 'to build sustainable industry 4.0 and to use industry 4.0 to build sustainability'. This means ensuring that sustainability and the circular economy are part of the idea of Industry 4.0, while digital technologies that make up Industry 4.0 must be used to enable sustainable business and production systems. Each research agenda should be consistently focused on areas that are still unexplored in the process of linking Industry 4.0 and the circular economy (Knudsen & Kaivo-oja, 2018).

Green jobs

None of the industrial revolutions mentioned here would have taken place without human labour. The transition to sustainable production implies that the manufacturing industry will include, more than today, 'green jobs'. These jobs minimise waste and pollution and/or increase material and energy efficiency (ILO, 2016). An empirical study describes the differences between green jobs and non-green jobs in terms of skills and human capital – the results suggest that high-level abstract skills, higher levels of education, work experience and on-the-job training describe green jobs as opposed to non-green jobs (Consoli et al., 2016). The researchers suggest (p. 23) that this may be because 'environmental technologies are still at an early stage of the life cycle, where cognitive skills such as design and problem solving are essential for guiding future developments'.

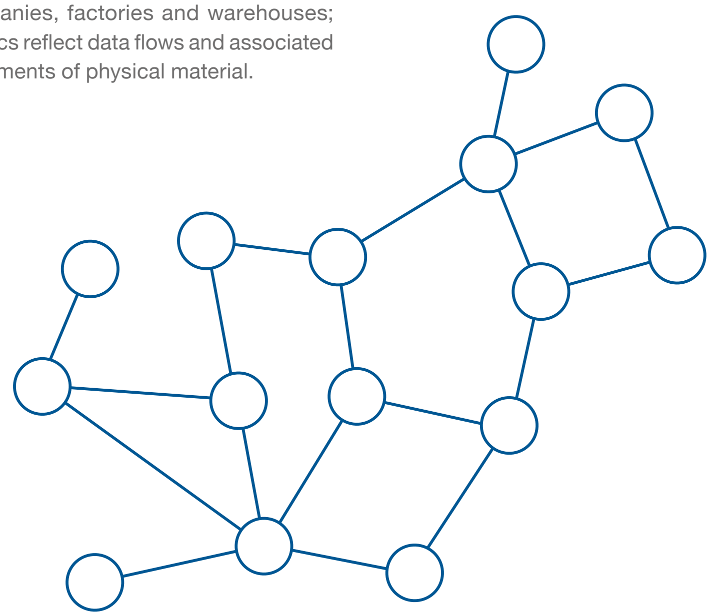
In turn, a study of American college students suggests that perceived sustainability increases the attractiveness of companies to potential applicants (Presley, Presley & Blum, 2018). This has implications for the manufacturing industry: taking sustainability objectives into account could make it easier to attract good workers.

Hyper-connected Factories

Taking into account the trends and needs described in the introductory sections of this paper, and in view of the sustainability objectives, it is possible to identify the need to integrate devices, production lines and factories leading to intelligent manufacturing and new environmentally friendly work tasks. One integrative concept is so-called hyper-connected factories. Hyper-connected factories combine the technologies typically associated with developments in Industry 4.0 with the necessary human perspective. For example, the technology elements involved can be summarised as follows (Frontoni et al., 2018):

1) connectivity and sensors within physical components,
2) a high degree of automation,
3) different forms of networking,
4) integration of several data points that differ in space and time, and
5) dynamic reconfiguration mechanisms.

The perspective of humans in hyperconnected factories requires further study, but we believe that this will be accompanied by an increased level of trust (Fastems, 2020) within the multi-company factory network and new ways of working. These new working practices intertwine with technological possibilities, for example, when factory network participants



The Hyper-connected Factories model in the form of a generic supply/value chain: The nodes represent a variety of companies, factories and warehouses; the arcs reflect data flows and associated movements of physical material.

use tools such as AI-based prediction, digital twins or augmented reality.

Indeed, people should not just be passive recipients of information within hyper-connected factories. Instead, they are actively involved in decision-making processes. It must be possible to integrate diverse and complex data from a variety of sources. Hyper-connected factories also include data-driven products and services so that innovative solutions can be offered (Big Data Value Association, 2018).

Hyper-connected factories thus enable a number of features, including adaptable and evolving factories capable of small-scale production, and the combination of flexibility, efficiency, precision and zero-defect production. In addition, hyper-connected factories aim to ensure a high level of resource efficiency, resulting in significant reductions in energy and water consumption and low emissions. Sustainability and the circular economy are essential aspects. Attractive and secure jobs are also an important feature (Haerick & Gupta, 2015).

The theme of the fusion of digital and physical reality also applies to the concept of hyper-connected factories. Then the focus is more on processes at the level of integrated systems or networks than on isolated environments. This requires coordination throughout the network, involving both human and artificial intelligence and distributed throughout the entire structure (FG-NET-2030, 2018).

Therefore, an infrastructure such as one that is 5G-based is needed, which is able to transfer data faster and more reliably between physical devices, machines and robots to support productive and, if desired, largely autonomous operations in a secure way.

This paper focuses on several dimensions and use cases that include functions of hyper-connectivity. These include traceability technology to track shipments in the supply chain or even individual products throughout their life cycle, remote maintenance using sensor technology in machines or production lines, and process optimisation of operations through distributed manufacturing based on advanced IT infrastructure, additive manufacturing and collaborative robots.

Sustainable Industry X Vision

The vision here builds on three main challenges within the manufacturing industry. Firstly, we consider the need for personnel within manufacturing.

For example, in Finland there is a noticeable shortage of skilled workers. Consequently, nearly all newly graduated professionals in the field get employment (Ollila, 2018). This means that the manufacturing industry must be able to attract talented employees. In order to achieve this, there is the need to provide a sense of excitement and professional meaningfulness for the workers. Secondly, as discussed earlier, sustainability and circularity are needed for a variety of reasons, including supply chain risk management and serious threats such as global climate change. Sustainability considerations also allow tapping into the forthcoming investments aiming at technology for reducing carbon footprint. Thirdly, our vision aims at strengthening the economy and giving companies a competitive advantage using digital technologies. This will retain and may even bring back production from offshore locations. Bringing production back, onshoring or nearshoring it where sensible could also contribute to increasing resilience against any unforeseen impacts that prevent global supply chains from operating.

The manufacturing industry must be able to attract talented employees. In order to achieve this, there is the need to provide a sense of excitement and professional meaningfulness for the workers.

Overall, the future of the manufacturing industry must include the following three features:

Sustainable Industry X

- **Fulfilling carreers** and excited workers
- **Sustainability** and attachment to circular economy
- **Competive advantage** and resilience with digital technologies

How then to address these aims? The background concepts, including Industry 4.0, Industry 5.0 and Industry X.0, all entail certain shared elements. Firstly, they involve what has continued throughout the history of manufacturing industry, that is, **renewal of production**. Autonomous and collaborative robots as well as new developments within additive manufacturing are among the concrete means of new production.

The existing literature also involves the widespread use of sensor-controlled and interconnected machines and devices, that is, the utilisation of the Internet-of-Things. Along with developments such as digital twins and digital spare parts (concretised through additive manufacturing), the Internet-of-Things concept creates **open manufacturing networks and supply chains.** This way, companies are able to share information collected by sensor-controlled machines and objects in a transparent way. In addition to sensor data, manufacturing networks and supply chains may even be covered by artificial intelligence algorithms, helping to predict and advise on next steps in decision-making. In concert, artificial intelligence and the Internet-of-Things remove friction and allow companies to plan, coordinate and synchronise activities more efficiently.

Through the developments above, new business-models emerge: with digital and data-based capabilities, manufacturing companies will be able to sell more services instead of only physical products. A good example is services surrounding predictive maintenance, i.e. techniques that help determine the condition of equipment, machines, production lines and infrastructure in operation in order to estimate when maintenance should be performed. This transformation is called **from products to services thinking.** Its exact characteristics are a matter of creativity, with a wide range of possibilities. However, this thinking involves companies providing comprehensive turnkey solutions for customer needs: rather than producing and selling a product to the customer, the aim is to understand what the customer needs and to fulfil these needs. This means that given products may be cared for over their entire lifetime, including their installation, maintenance and, if suitable, their reuse, recycling or remanufacturing – in line with the circular economy strategy.

Overall, the vision involves the following three transformations:

Sustainable Industry X

- **Renewal** of production
- **Open manufacturing networks** and supply chains
- **From products to services** thinking

We will next go through the technology solutions and concepts involved in the vision. Then we will consider synergistic opportunities; that is, how the aims and transformations support one another.

With digital and data-based capabilities, manufacturing companies will be able to sell more services instead of only physical products. This transformation is called from products to services thinking.

Enabling technologies overview

Sensing technologies

A sensor is a device that provides predictable, consistent and measurable feedback on a physical process or substance. In the context of this paper, sensors are part of advanced platforms with integrated technology such as microprocessors, memory, and diagnostic and connectivity tools that turn traditional feedback signals into digital insights. Sensors can provide timely and valuable information, which in turn can improve costs, performance or customer experiences.

Typical sensing technology in supply networks include RFID tags, sensors on environmental parameters and mobile communication devices. The devices that contain these sensors may all be linked through wired or wireless communication networks and interact with each other.

The combination of sensors (or 'sensor fusion') and increased computing power enables new ways of data analysis and valuable information to improve many areas of operations. This results in responsive and agile production processes that ensure and improve performance in a number of industrial sectors, with corresponding impacts on supply chain and circular economy processes (Wang & Pettit, 2016).

Artificial Intelligence (AI)

Min (2010) writes that AI could be defined as the use of computers to think, recognise patterns, learn or understand certain behaviours from experience, acquire and retain knowledge, and develop various forms of reasoning. AI is used to solve problems in decision-making situations where optimal solutions are usually too difficult or impossible to achieve by other means.

Supply chain management and circular economy approaches are highly information-intensive, which requires an understanding of complex, interlinked decision-making processes and the creation of intelligent knowledge bases that are crucial for joint problem solving, especially with regard to joint demand planning and forecasting processes.

AI therefore offers enormous advantages. In particular, efficient analyses of large amounts of data could be improved and meaningful simulations and notifications could be made available. This will improve the efficiency of a supply chain as well as the circular flows, increase resource and energy efficiency, reduce emissions, significantly improve responsiveness, i.e. agility within the supply chain, and thus also ensure the security and optimal risk management of a supply network.

Systems that are able to deviate from their line of action in response to some unforeseen events are called autonomous. Examples are autonomous vehicles and machines, autonomous manufacturing processes, autonomous knowledge generation and cognitive automation (Watson & Scheidt, 2005).

Some consider that the fundamental goal of AI is the ability of machines to operate independently with little or no human interaction. In this sense, the technology of autonomous systems is comprehensively transformative and has enormous potential for increasing the efficiency of processes and reducing risks, and can also enable work in environments where people cannot work for physical reasons.

Data analytics has become a competitive necessity as it has a positive impact on the efficiency and effectiveness of operations and thus on financial performance.

Autonomous systems are an important part of the technological vision and future development in mechanical engineering as presented in this paper. As tasks and job content change and new professions are created, many ethical issues related to artificial intelligence arise. According to current thinking, it is therefore often desirable to focus on semi-autonomy, which implies a strong human control over AI routines (Ailisto et al., 2017).

Big data

The management of supply or circular value chains and manufacturing networks as the coordinated effort in optimising the delivery and return flow of goods, services and information is naturally based on comprehensive data processing. Traditionally, their management has been founded on experience and past data, stemming from companies' internal controlling systems, for example. Big data goes beyond that.

Big data refers to data that contains high variety, occurs in increasing volumes and changes at great velocity. Therefore, it is about large data sets that are, for example, too large, too complex, too fast moving or too weakly structured to be evaluated with manual and conventional methods of data processing. Examples include increasingly used sensor data, data from devices (IoT) and social data.

The analysis of large amounts of data can profoundly change the way manufacturers work and is increasingly recognised as a critical value for the sustainability of companies (Li & Liu, 2019). Potential applications highly relevant for chains and networks include forecasting, inventory management, transportation, maintenance and human resources, all of which can make use of big data in order to create more efficient, effective and sustainable management processes (Waller & Fawcett, 2013; Wang & Pettit, 2016).

Data analytics

Until recently, business intelligence was mostly limited to the analysis of existing data collected from own or internal systems of supply chain partners. Nowadays, the focus is on information that is not simply based on data from the past, but on complex analyses to support decision-making, problem solving and forecasting.

Today's enterprise networks generate huge amounts of data, increasingly involving real-time data sources. Analytics makes sense of all this data and uncovers patterns to create useful information. Different types of analytics include descriptive analytics that helps understand data in terms of informational content across chains and networks, predictive analytics that helps understand future developments, likely scenarios, etc., prescriptive analytics that helps solve problems, and cognitive analytics that uses advanced technologies like AI to solve complex problems based on understanding, reasoning, learning and inference (IBM, 2020).

Data analytics has become a competitive necessity as it has a positive impact on the efficiency and effectiveness of operations and thus on financial performance. It can also have a positive impact on the social and environmental aspects of sustainability, such as in reducing risks or undesirable impacts that can be caused by business and supply chain operations (Hazen et al., 2016; IBM, 2017).

5G

5G ('fifth generation mobile communications') is the name of a standard for mobile internet and mobile telephony. This standard enables significantly higher data rates than before – in real-time transmission, for example, the standard is intended to make 100 billion mobile phones simultaneously accessible worldwide – as well as lower latency, i.e. response times.

As a further development, 5G technology is geared towards several different application scenarios. These applications include the ability to provide mobile devices with the highest possible data rates as an extended broadband connection; to enable as many connections as possible to devices within the framework of the Internet of Things; and to ensure extremely reliable and low latency, for example to enable applications within the framework of Industry 4.0 or autonomous driving.

In the context of our paper, 5G is the foundation in the form of the infrastructure necessary to realise all the applications presented in the Sustainable Industry X Vision. With the help of 5G, devices and applications such as 3D systems, cobots, data analyses and new services for industry and manufacturing can be networked with each other and sustainable supply chain and circular economy processes are made possible.

IoT

The Internet of Things (IoT) describes the network of physical objects, which are embedded with sensors, software and other technologies to connect to and exchange data with other devices and systems over the internet.

In an industrial context, IoT technology can be applied in particular to the instrumentation and control of sensors and devices via cloud technologies. For example, machine-to-machine communication can achieve wireless automation and control. In this way, it is possible to connect devices, management systems, materials and logistics. Since the connected objects provide feedback, IoT helps to make decentralised decisions practically in real time (Oracle Corporation, 2020; Manavalan & Jayakrishna, 2019).

In general, connected objects enable the routing of entire fleets of trucks, ships and trains that carry the required inventory,

making logistics processes within supply chain management more efficient. Materials or production facilities can be equipped with sensors to measure when production could be impaired. This enables fast response times to counteract negative consequences and reduce waste and operating costs (Oracle Corporation, 2020; Manavalan & Jayakrishna, 2019).

IoT plays an important role in facilitating Sustainable Industry X. The circular economy aims to minimise waste by reusing, repairing, reconditioning and recycling materials and products, and also deals with long-lasting design and durable construction. IoT is seen as a key element here, helping to extend utilisation cycles, increase resource utilisation, provide information on the availability, location and condition of resources, and regenerate and recirculate assets (Circular Economy and Internet of Things (CEIOT) consortium, 2020).

Cobots

Collaborative robots, or cobots, are robots that work in direct interaction with human workers while performing tasks, for example in manufacturing.

The ability to work alongside humans is of great importance and has increased the use of collaborative robots in companies on the way towards Industry X. Therefore, they are not intended to replace humans. In fact, cobots are used in processes where the ability of humans to perform complex activities is important. Here, it is primarily a matter of combining the core competence of a robot to repeat the same task with the sensitivity and sensory input of humans. The overall process thus has higher productivity, quality and safety (Djuric et al., 2016).

Different levels and forms of collaboration can be seen (Aaltonen et al., 2018): working at the same space 1) at the same time or at different times, 2) on the same or different tasks, and 3) being part of the same or different process. Compared to the usual industrial robots, cobots could be more approachable for small manufacturers because they require less space and do not require heavy protective measures. Optimally, they will feature easy programming by hand. For safety, maximum loads and speeds are very limited, however. (Some possibilities of cobots are discussed below in 'Synergistic opportunities'.)

Additive manufacturing

Additive manufacturing (AM) or 3D printing is a technology that allows the manufacturing of products by printing layer upon layer using a variety of different materials. These include, for example, metal and plastics powder, binders or granulate.

AM is used in industrial manufacturing applications, but still quite often on a limited basis. In contrast to mass manufacturing solutions, the cost for the 100,000th item produced with AM is essentially the same as for the first. Nevertheless, AM is a technology that enables local manufacturing and a lot size of one. This has profound implications for any supply chain and its economic and environmental impact (McKinnon & Whiteing, 2015).

As part of a circular economy framework, AM technology has even more pronounced sustainability benefits. For example, AM can utilise recycled material based on reprocessed waste. Impacts include continuity of manufacturing operations by reducing supply risks and greater resource and energy efficiency through recovering, remanufacturing, waste reduction and recycling. This is to be achieved in the production and use phases during all manufacturing processes. Further, extended product life and more sustainable socioeconomic patterns can be realised when the AM circular economy connection is embedded in an extended local economy, with shorter and potentially simpler supply chains. All these elements are important steps towards zero-waste manufacturing by maximising material utilisation and reducing operational carbon footprints of manufacturing for many different parts along the supply chain (Oros Daraban et al., 2019; Cruz Sanchez, 2020).

Synergistic opportunities

In combining the elements above – the three aims (i.e., 'fulfilling careers and excited workers', 'sustainability and attachment to circular economy', and 'competitive advantage and resilience with digital technologies') and the three transformations (i.e., 'renewal of production', 'open manufacturing networks and supply chains', and 'from products to services thinking') – opportunities for synergies can be recognised.

The aims and transformations provide mutual support: they are stronger together than individually. In the following, some of the most evident synergy-benefits are presented.

Firstly, synergy effects can be identified between the goals of fulfilling careers and sustainability. By setting sustainability targets, the manufacturing industry can improve its public image. In addition, there are people who want to achieve environmental goals in and through their careers. This can increase the motivation of employees as suggested above on 'green jobs'. Furthermore, it is assumed that the faster network connections provide new opportunities to work remotely rather than on the factory floor. This might increase the attractiveness of industrial work as well.

Secondly, there are synergies between service thinking and the circular economy, as already indicated above. This is especially true when it comes to business models that aim for turnkey solutions. This means that the service provider looks after the products throughout the entire product life cycle: old products can be returned to the factory for reuse, remanufacturing or recycling.

This practice allows the service provider to collect data on the life cycle of the products and parts, which enables even better products and services – wearing parts can be replaced before the end of the life cycle, so that the customer never experiences the failure of equipment, machines or entire production lines.

Thirdly, possible synergies between the renewal of production methods and recycling management can be identified. For example, it could possible to create products from waste through additive manufacturing (see 'additive manufacturing' above). Furthermore, collaborative robots enable work in smaller production units. These are space saving, as humans and robots could work side by side. This, in turn, might allow smaller production units in city centres rather than beyond city limits where space is less expensive. Since both the city-based customer and the city-based producer could thus be physically closer to one other, personal one-to-one encounters between the two could be established efficiently. This could nurture feeling of trust and togetherness between the producer and customer. In principle, this could lead to a situation where the customer is more willing to pay more for the product, while the producer is more willing to maintain the products and ensure quality, resulting in much longer product life cycles. Similar proximity and production in a small space can also be achieved with additive manufacturing. Jobs in central city locations thanks to the smaller production unit sizes can also be advantageous to attract workers.

Fourthly, there is a connection between the objectives of open production networks and supply chains on the one hand and the circular economy on the other, since transparent material flows could be regarded as enabling factors for the circular economy: A closed loop can be achieved by monitoring the flow of materials and exchanging information. This means that at the end of their life cycle, products can be recycled, reprocessed and reused via an efficient aftermarket for this material, which would otherwise be considered waste. Here, for example, a virtual catalogue of discarded products could be accessible to everyone. The aftermarket would use the Internet of Things, powerful AI-based search engines and automated negotiation and procurement methods to enable circular supply chains.

Fifth, and this refers to the previous point, open supply chains clearly offer a competitive advantage. More data enables better operational and synchronised planning. This concerns all parts of the economy, from logistics and production to marketing and research and development. AI-driven optimisation can take place within an open network of companies.

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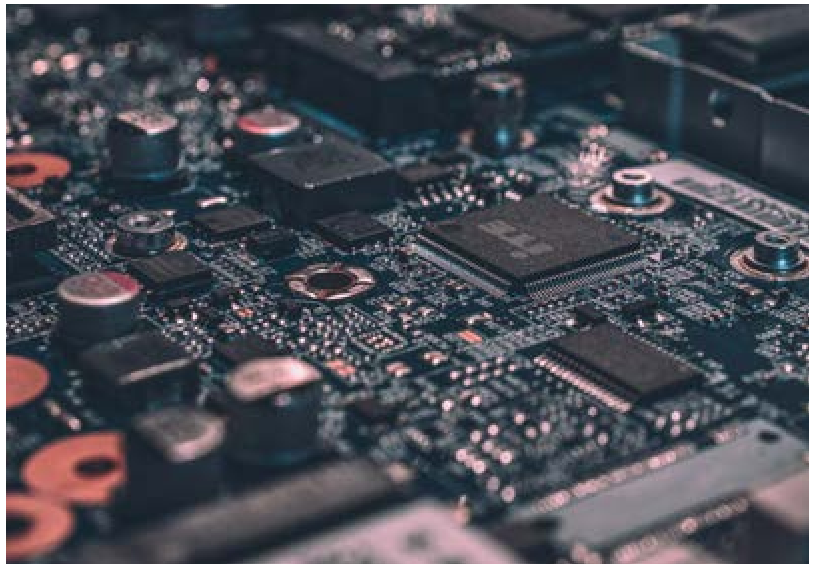


Vision summary – platform for R&D use cases

In summary, the vision comprises three general objectives and transitions. These are illustrated by the considerations shown in Table 1. In line with the synergistic possibilities and ambitions mentioned above, it is possible to map potential research and case studies in the matrix provided here. The technologies studied can also be considered here.

Generic aims \ Generic transformations	1. Renewal of production	2. Open manufacturing networks and supply chains	3. From products to services thinking
1. Fulfilling careers and excited workers	Collaborative robot operations	Shared analysis of open IoT for a network of companies	Digital maintenance and installation service
2. Sustainability and attachment to circular economy	Use of waste in additive manufacturing	Transparent material flow: low-carbon circular economy manufacturing	Sustainability through leasing-services within B2B
3. Competitive advantage: production back to Finland/EU	Increased level of production autonomy	RFID & 5G enabled – infrastructure development	Solving the clients' problems with a network of companies

Table 1. Sustainable Industry X Vision summary: case-study examples by generic aims and transformations

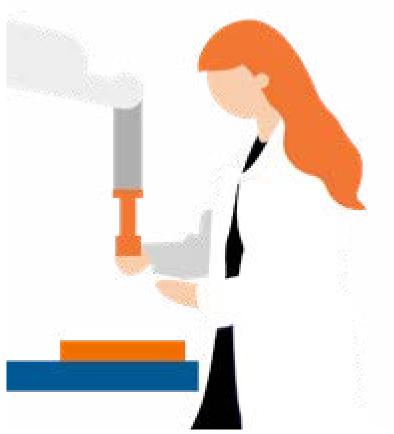
Professions of the future – examples

Use case 1: Cobot operator

Leena is an independent collaborative robot (cobot) operator. She works from her own garage, but in tight collaboration with a network of other cobot operators and additive manufacturing companies. Leena is not a programming expert, nor does she have a technical education background. The cobot device is so well designed that it can be easily programmed or, rather, "taught" through hand gestures.

Leena, a former musician, enjoys the creative aspects of using the cobot. She meets clients face-to-face regularly for customised products, but also works for others within the aforementioned manufacturing network.

Leena's clients enjoy the maintenance, repair and return policy that lasts throughout Leena's own lifetime – if the products break, Leena will fix them. Leena applies recycled material in creating the new products.



Aims:
- Sustainable circular economy manufacturing
- Small networked production units
- Competitive advantage through high quality and customisation
- Products designed collaboratively with the client

Technologies:
- Networked objects (IoT)
- Big data
- Artificial intelligence
- 5G infrastructure

Challenges:
- Clients need to pay premium price for high-quality customised products
- Need for networked business models

Outcomes:
- Customised products that outlive the clients' lifetime made from recycled materials

2020–2025
- Human and robot work at the same time and within the same space
- Open manufacturing networks allow networked business models and small production units
- Safety through slow motion and round/soft edges

2025–2030
- 'Responsive Collaboration': the cobot responds in real-time to the worker's motion and human and cobot work on the same task at the same time
- Cobot as an extension to operators imagination akin to musical instrument
- Cobot can be taught/programmed easily with hand gestures
- Efficient yet safe cobot through reliable sensors and highly functional neural networks

Use case 2: Logistics and supply chain analyst

Aino is a logistics and supply chain analyst who uses a variety of traditional methods and planning tools, such as enterprise resource planning software, mathematical methods for demand forecasting and inventory management and geographical information systems for effective spatial planning. Her aim is to ensure the continuity of material and information flows across the supply chain.

In today's global economy, Aino faces many issues such as demand fluctuations, uncertainty of supply, operational inefficiencies and many other disturbances involving economic, geopolitical, technological and environmental risks. With better data and decision-support, these issues can be analysed and managed. How can Aino be helped here?

Aims:
- Supply chain risk management
- Sustainability of material flows and information communication
- Increasing the resilience of supply chain operations

Technologies:
- Networked objects (IoT)
- Big data
- Artificial intelligence
- 5G infrastructure

Challenges:
- Meeting demand in terms of quantity, quality, place and time of delivery
- Analysing potential supply disruption
- Past data and friction in information sharing

Outcomes:
- Digital technologies generate instantaneous data for real time monitoring and communication
- Advanced analytics and decision-support improve visibility and allow comprehensive orchestration of global supply chains
- Enables flexible and agile supply chains

2020–2025
- It is possible to map supply chain issues and risks and develop alternative routes and options in advance.
- Any unforeseen incident improves the available data and approaches.
- Real time analytics becomes more common but is obviously restricted to available data sources, e.g. social media data that influences logistical options. Supply management issues are still mostly a matter of strategic management.

2025–2030
- The widespread application of IoT technology allows increasingly comprehensive monitoring.
- Advances in AI and big data analytics allow the tracking of unforeseen events in a timely manner.
- Choosing alternatives in the supply chain becomes a tactical question and can increasingly rely on AI.
- As a result, supply chains have become ever more resilient.

Use Case 3: Cyber-physical remote maintenance team

Matti is a service technician for a production line manufacturer. In his work he focuses on consultation and customer support, obtaining information about a given situation or machinery state, clarifying problems, finding and analysing faults, and maintenance and assembly of replacement parts. Matti's aim is to make sure that his company's production lines operate smoothly at their customers' sites without much downtime, increasing a line's operational lifetime, and ensuring that customers are satisfied.

Increasing market fluctuations, the need for agile responses and world-wide service offerings broaden the complexity of knowledge and activities required to deal with customer and maintenance demands. Ideally, Matti could do all this remotely. By relying on digital technology, which provides a comprehensive picture of the problem at hand and allows guidance of local personnel and resources, Matti could concentrate on soft skills, showing understanding and acting in an advisory and empathetic manner. What technology solutions exist to make Matti's work easier?

Aims:
- Reducing downtime
- Satisfied customers
- Cost-effective maintenance
- Extending operational lifetime of machinery

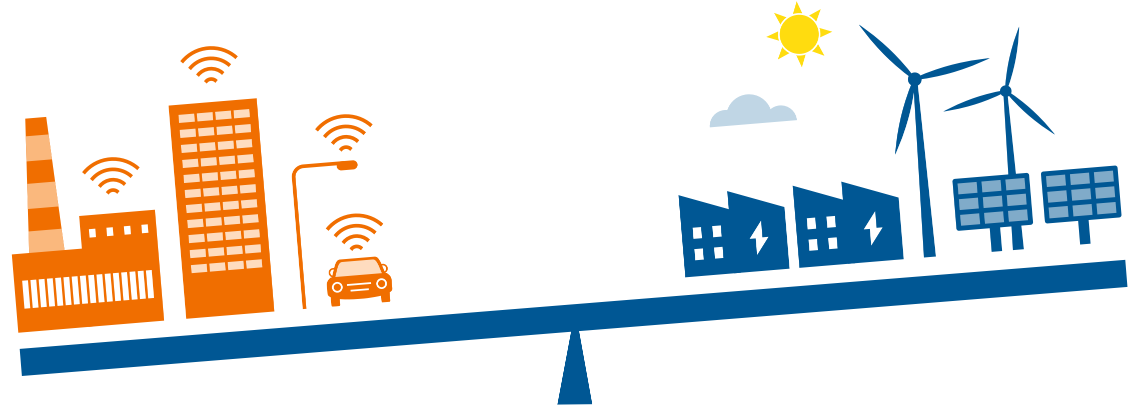
Technologies:
- 5G
- Sensors and IoT
- Digital twin
- Augmented reality
- AI

Challenges:
- At times high work volume
- Risk of losing customers
- Not having an answer to a problem – deep knowledge of resources available required
- Understanding what customers want

Outcomes:
- Unmanned operation or maintenance
- Fast service on site
- Serving multiple customers
- Significant increase on the service level
- Learn about new innovations and research in the technology sector

2020–2025
- Remote maintenance and maintenance done by autonomous robots becomes common place, but still with significant service personnel in the field
- Communication infrastructure develops so that sensor technology and IoT allow remote machine state detection and diagnosis
- Digital twin and augmented reality technologies employed in high value facilities
- Artificial intelligence provides decision support and reduces complexity for service personnel

2025–2030
- Digital twin technology widely used in remote control and maintenance
- Augmented reality works fluently to assist local personnel in factories as digital guides
- Artificial intelligence widely employed for automatic detection, notification and ordering of supplies and replacement parts
- Cyber-physical systems operate across supply chains to include many companies and production lines for advanced detection of delays and bottlenecks in supply



Future profession examples in view of the circular economy aspects

The circular economy (Ellen MacArthur Foundation, 2020) consists of the following activities: Firstly, maintenance ensures the operability of a product. This also includes possible upgrades. Secondly, reuse stands for the use of a product by a new user. Third, remanufacture means the manufacture of a new product from similar products after it has failed due to damage or wear and tear and the reintroduction of the product into the supply chain. Finally, recycling involves the collection of various materials that can be used in the manufacture of new products. The overall aim is to create a closed loop system that aims to achieve the highest utility and value from products, components and materials at all times.

The above-listed future profession examples can be considered with regard to these aspects within the recycling economy: Table 2 summarises and illustrates these considerations. Certainly, numerous other examples and their relation to the circular economy can be thought of here.

Aspect within circular economy	Implications for manufacturing	Key technology enablers	Future profession example
Maintenance	Product design for maintenance, maintenance-driven business models and services	Predictive maintenance (AI, big data, IoT, 5G), remote maintenance (AR, digital twins)	Cyber-physical remote maintenance team
Reuse	Networked business models, product design for spare-part aftermarket	Exchange of information within product life-cycle (IoT, 5G)	Logistics analyst / cobot operator
Remanufacture	Service-driven business models: leasing instead of selling	Predictive maintenance (AI, big data, IoT, 5G)	Cyber-physical remote maintenance team
Recycle	Using waste as a resource	Smart bins / recycle centres (IoT, 5G), additive manufacturing	Logistics analyst / cobot operator
Coordinated closed-loop material flow	Networked business and production models, connected factories and recycling centres	Optimised logistic chains (IoT, AI, 5G)	Logistics analyst

Table 2. Sustainable Industry X Vision use cases and circular economy aspects

Final remarks

The vision 'Sustainable Industry X' provides an outline of the next industrial revolution, taking into account Europe's ambitions to reduce carbon emissions, with particular emphasis on creating a more circular economy. This includes the idea that a future manufacturing industry should apply recent and future advances in ICT and telecommunications, that is, a shift to cognitive manufacturing will take place. In addition to the sustainability objectives, these new technologies, if properly applied, will enable the creation of interesting careers within the manufacturing industry, which is necessary to attract talented people. All this represents a competitive advantage that will allow production to be significantly strengthened in Finland and the EU.

In our vision, the forthcoming industrial transition includes, first, the renewal of production through collaborative robots, additive manufacturing, sensor systems, AI and other appropriate technological developments. In addition, new advances in telecommunications and ICT/CI will be used to create a common Internet-of-Things. Open production networks and supply chains could be used to plan and optimise operations within a vast network of companies. Within these transitions, there are many opportunities for new service models, which also support the creation of a circular economy.

However, all this requires intensive efforts in research and development. Large-scale R&D ecosystems are needed, where telecommunications and ICT/AI developers work with existing manufacturing industries. This process, involving both applied research organisations and universities, should create new collaborations and businesses. Although the first outlines of a future industrial revolution have been sketched out here, hard work is needed to make the vision a reality, and much research is needed. Our aim is that this vision of Sustainable Industry X, which was developed by researchers mainly on the basis of literature research, will be further discussed and reformulated with industrial partners – this will enable the real common path to the next industrial revolution.

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