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Unlocking the potential of Industry 4.0 to reduce the environmental impact of production

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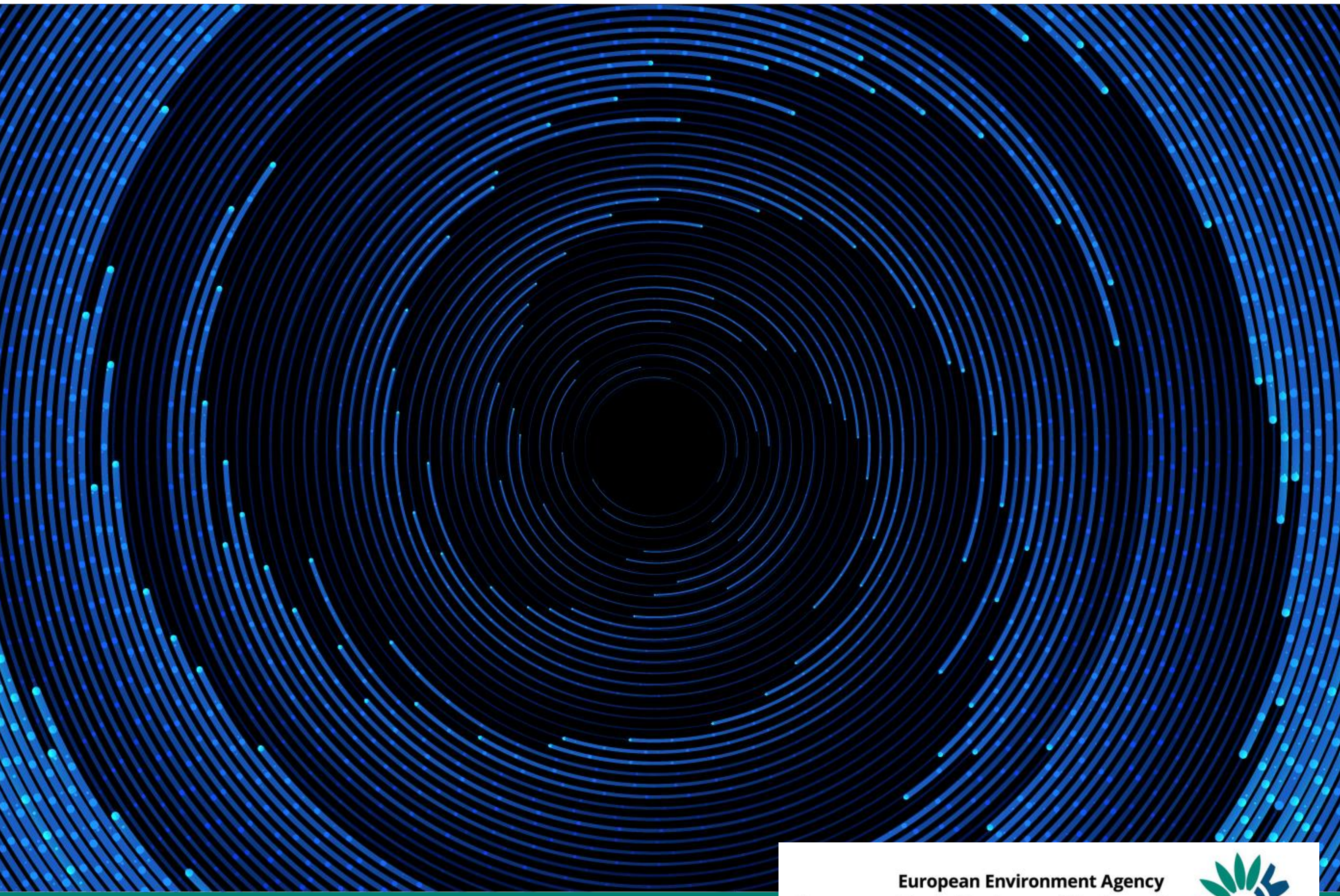

European Environment Agency
European Topic Centre on Waste and
Materials in a Green Economy

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Executive summary

The digital sector can contribute to the European Green Deal and to the reduction of the environmental impact of manufacturing. It can be both a source of clean technology solutions and of the reduction of digitalisation's own carbon and material footprint. This is reflected in the New Industrial Strategy for a globally competitive, green and digital Europe, which was conceived by the EU to help Europe's industry lead the twin transitions towards climate neutrality and digital leadership (EC, 2020b).

In light of this, the aim of this report is to analyse the opportunities of Industry 4.0 to reduce the environmental impact of manufacturing. Circular economy strategies are key ingredients for this. They can create resource effectiveness and minimise resource extraction and emissions. However, they require distinct and high amounts of information to be applicable. The ability of digitalisation and Industry 4.0 as a systemic approach to digital manufacturing to collect, analyse and transfer data into information, knowledge and wisdom is foundational for this.

Potential benefits of Industry 4.0 applications can be grouped into direct and indirect effects. *Direct effects* concern benefits achieved in the production process. They relate to improved resource or energy efficiency due to leaner production systems and material savings, as well as the reduction of excess or production waste. *Indirect effects* can be characterised as benefits enabled through Industry 4.0 technologies outside the manufacturing process itself. They can *inter alia* concern the increase of resource and energy efficiency as well as measurement and monitoring along the value chain. Exemplary applications for all of these benefits exist and prove the feasibility of the concept. Yet the application of most of them is not widespread. Moreover, their use can potentially be intensified or applied to other fields.

A specific ingredient for a digital circular economy is the digital product passport (DPP). The DPP is a solution foreseen by many EU strategies that allows the recording and management of all information related to the composition and lifecycle of a product. The concept of the digital twin is pivotal to the realisation of such a passport. It could therefore be the basis of circular strategies such as repair, refurbishment and recycling. Industry 4.0 can, however, have negative impacts on the environment as well. Digital obsolescence, technology lock-ins and the energy demand and waste streams arising from digitalisation are examples of this.

Various case studies in this report show how Industry 4.0 is already applied to reduce environmental impact. The cases are presented in a standardised format which covers the technology as such, its output for sustainability, the underlying technologies and required preconditions as well as its state of development and whether similar solutions already exist. Different topics such as the digital twin, marketplaces for recycled materials or agricultural solutions are featured to illustrate the variety of existing approaches.

The circular economy community is seeing Industry 4.0 and related digital developments as major game changers in the circularisation of products, components and materials in the manufacturing industry. A literature review and expert interviews show, however, that awareness of circular economy and sustainability topics are only just emerging in the Industry 4.0 community, while its current development is actually technologically driven and largely agnostic to both subjects. To enable a synergy between the digital transformation and the introduction of a resource-effective circular economy, implications were identified for politics, the systems level and the company level, with a focus on small and medium-sized enterprises (SMEs).

Key messages

The twin transition needs guiding and the co-creation of an integrated approach towards sustainability

- The green and digital transitions of the EU industry are today characterised as a twin transition, which should be seen as one challenge in the industrial transformation towards sustainability. It needs to rely on an integrated approach, based on co-created transformation pathways. If not considered as one single challenge, the opportunity of reaching both climate neutrality and EU industrial competitiveness will be missed.

- Awareness for the circular economy is only just emerging in the digital community of Industry 4.0 manufacturing, while the sustainability community already has high hopes that digital technologies will accelerate the transition to a circular economy. A close and continuous dialogue between manufacturing, information and communications technology (ICT) industries, and sustainability communities, together with a and strong push of the Industry 4.0 landscape towards environmental impact reduction, is required.

- The technological requirements for a synergetic convergence of green and digital transitions specified for a circular economy and Industry 4.0 need to be met. Creating standards for data interoperability, standardised interfaces and a clear definition of the DPP are among the immediate requirements for this, as well as the provision of a dedicated and functioning ICT infrastructure.

- The twin transition is systemic. Efforts need to be made at all levels, and transformation pathways need to be created with and for industry, research and public authorities as well as societal and sectoral actors.

Digitalisation for transitioning to more sustainable production systems

- Digitalisation by Industry 4.0 has the potential to provide the overall architecture, concepts and technologies for enabling circularity and transitioning to a more sustainable production system. Such approaches, however, need further research and development, while existing approaches need scaling.

- Industry 4.0 and its digital technologies can provide the conceptual and technological basis for the DPP as envisioned by the EU. The DPP is a key ingredient to enable circular economy and sustainable decision making.

- Without digital technologies, the circular economy will not be able to be meaningfully scaled up, especially not in a digital world. At the same time, Industry 4.0 without a clear focus on a circular economy is indeed a danger to climate protection and impact reduction goals.

- The window of opportunity is open now to initiate this technological development in the current decisive decade. Any delay will cost precious time in solving urgent challenges related to climate change and circular economy. Moreover, the risks of disadvantageous lock-ins, stranded assets and sunk costs increase with the rapid advance of digitalisation without a clear link to environmental impact reduction.

Need for further research

- Digitalisation has its own considerable environmental risks. General problems concern the respective technologies' needs for resources and energy. These need close monitoring and additional research to understand their environmental impacts. Ensuring the sustainability of digital manufacturing is key. Any rebound effects need to be prevented. Environmental assessment methodologies need to evolve and provide the basis for future indicators in the quantification and measurement of actual (and net) benefits.

- The progress of digitalisation and the transition to a circular economy in Europe needs to be understood and measured to ensure cohesion. Relevant metrics and data streams need to be identified.
- The speed of digitalisation and the imminence of many environmental challenges – climate change, toxins, plastic pollution, etc. – may require new strategies for fast and effective intervention from political and administrative decision makers.
- Digital circular business models need to be better understood and enabled. As digitalisation will facilitate the shift towards a more service-based manufacturing, the viability of integrating circularity parameters that enhance the service value proposition should be further investigated.
- The progress of digitalisation and the transition to a circular economy throughout European countries and in Europe needs to be measured and understood as a whole to ensure cohesion.

1 Introduction

1.1. Political background

Two parallel developments are deeply affecting the European economy, the advanced digital transformation of industrial systems and the need for a transition to a more sustainable economy. Since 2011, the advancing digital transformation of manufacturing was conceptualized as Industry 4.0. The term conveys the idea of a fourth industrial revolution taking effect (Figure 1.1). Currently, the impact of this transformation and its implications, as well as the opportunity for a transition to a greener economy, receive increasing attention.

Over the last years this development and the progress of digitalisation in general has also been acknowledged by the European Union's (EU) and started to appear in environmentally oriented strategies and action plans. In 2019, the European Commission (EC) released the European Green Deal, a new growth strategy that aims "*to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use*" (EC, 2020). The European Green Deal acknowledges and aims to address the linked challenges of the necessary European ecological and digital transformations. Characterised as a twin challenge, in March 2020 the EC concomitantly published a new Circular Economy Action Plan (CEAP), together with A New Industrial Strategy for Europe (EC, 2020d) for reaching EU Green Deal's objectives. Simultaneously, both Communications on the European Green Deal and the EU Industrial Strategy consider digital technologies as a "*critical enabler for attaining the sustainability goals of the Green deal in many different sectors*". In parallel, the European Data Strategy acknowledges the need for digital technologies to contribute to sustainable development (EC, 2021a).

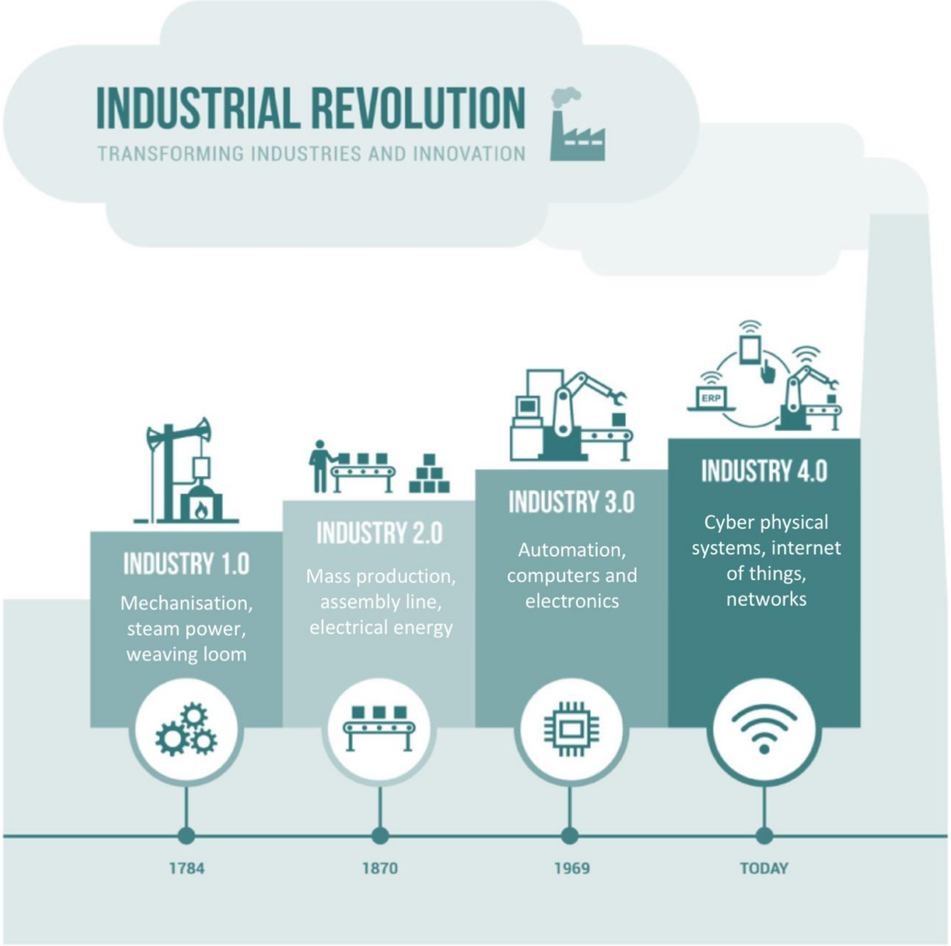


Figure 1.1 Industrial Revolution – transforming industries and innovation
Source: IIoT (2018)

Further illustrating this increasing awareness for an integrated approach connecting these two parallel developments, EU-related activities have started to push the convergence of the digital-industrial field with the principles of sustainable development to reduce the environmental impact of the European production and consumption system. The European Parliament, for instance, stressed

- *the need for better understanding of how artificial intelligence technologies can support a circular economy by encouraging their applications in design, business models, and infrastructure;*
- *the importance of treating digitalisation as an enabler of the circular economy, notably when it comes to product passports or material information in the context of an EU-wide dataspace;*
- *that improving data accessibility and sharing will be key;*
- *while ensuring active collaboration between stakeholders to make sure that new approaches remain fair and inclusive, and safeguard privacy and data security.*

(European Parliament, 2021)

Even more concretely, for batteries in industrial applications and electric vehicles with a capacity higher than 2 kilowatt-hours (kWh), a new EU regulation aims to introduce a *digital battery passport* to trace and understand battery use and specifically improve after-use management (EC, 2020e). The chance of digitalisation benefitting the environment was also emphasised within Germany's presidency of the Council of the European Union (eu2020.de, 2020). Furthermore, several databases related to the circular economy, environmental effects and toxicity have been established or are emerging – respectively the European Product Database for Energy Labelling (EPREL) and the Product Environmental Footprints (PEF) and Substances of Concern In articles as such or in complex objects [Products] (SCIP) databases. Until now, however, the emergence of a full-fledged integrated approach broken into specific measures to hone the full potential of industrial digitalisation to the means for achieving the Green Deal goals is still in its infancy.

1.2. Study aim

In support of the implementation of the objectives of the 8th Environment Action Programme and the Green Deal, and to inform the policy-making process in the alignment of these currently independent and parallel transformations, the EEA has recently started building knowledge on digitalisation for achieving sustainability goals. Published in 2021, the EEA briefing *Digitalisation and waste management* (EEA, 2021b) and its underpinning ETC/WMGE report (Berg et al., 2020) provided an overview of the potential for a digital transformation of the European waste management sector.

Digitalised manufacturing is bringing about a wide range of changes to manufacturing processes, outcomes and business models. The aim of this study is therefore to provide the necessary knowledge base to realise the potential of digital industrial solutions to advance the circular economy and subsequently increase resource efficiency, optimise resource use (energy, raw materials, water, etc.), monitor and abate emissions, reduce waste generation, reduce greenhouse gases (GHG) and other emissions to air, water and soil and reduce the overall environmental impacts associated with European production activities.

2 Industry 4.0 definition and overview

“*Industry 4.0 refers to the intelligent networking of machines and processes for industry with the help of information and communication technology*” (Plattform Industrie 4.0, n.d.). It has become an international synonym for the digitalisation of industry but also represents a strategy and architecture for this process. The term first emerged in 2011 as a future-oriented project within the framework of the German High-Tech Strategy (BMBF (LS 5), n.d.).

It is not confined to traditional industrial sectors. Smart factories and production methods have also found their way into such fields as agriculture through the digital networking of agricultural machinery. The interplay of four principal aspects characterises Industry 4.0 and is enabled by digitalisation:

1. horizontal integration within value networks refers to new concepts being implemented across the whole value chain with the result that the entire value network can profit from increased connectivity, improved information flows and processes and suitable information technology (IT) infrastructure (i-Scoop, n.d.);
2. vertical integration, for example, within a factory/manufacturing plant, is the process of simultaneously addressing all layers of the automation pyramid, such as connecting physical products through sensors, digitalising and optimising internal processes, increasing connectivity, and rethinking business models and the ways of collaboration (i-Scoop, n.d.);
3. lifecycle management and consistency of engineering are concepts that guarantee the consistency, traceability and interpretability of information throughout the value chain (Fraunhofer IOSB, 2020);
4. people act as conductors in the value network; they supervise processes of value creation and ultimately bear the responsibility. (Verein Deutscher Ingenieure e.V and Zentralverband Elektrotechnik- und Elektronikindustrie e.V, 2015)

Before further elaborating this connection between these four principles (Section 2.3), some background information on the central concepts (Section 2.1) and technologies (Section 2.2) are provided.

2.1. Central concepts for Industry 4.0

Advances in sensor technology, computing, data storage, networking and miniaturization have laid the technological foundations for the current industrial digitalisation process. In the Industry 4.0 context, they allowed the development of the central Industry 4.0 concepts: Cyber physical production systems (CPPS), the Reference Architectural Model Industry 4.0 (RAMI 4.0), digital twins, and the asset administration shell (AAS). These are explained below.

Cyber physical production system (CPPS): A CPPS is a system of several autonomous and collaborating computational entities, i.e., subsystems, that are in intensive connection with the surrounding physical world, such as machines, and its ongoing production processes (Monostori, 2014). These subsystems interact with each other depending on the situation, at and across all levels of production, including all processes, machines, and production and logistics networks. Within CPPS, physical assets, such as machines and products, are represented in a digital form. In the Industry 4.0, three concepts are fundamental to creating these systems: RAMI 4.0, the digital twin, and the AAS. In 2019, the companies Ericsson and Comau presented a 5G-enabled digital twin that represents multiple physical machines used in an automotive plant and allows for central observation at all times of the production processes through sensors. Another example of CPPS are automated guided vehicles (AUG) (Sabella, 2019).

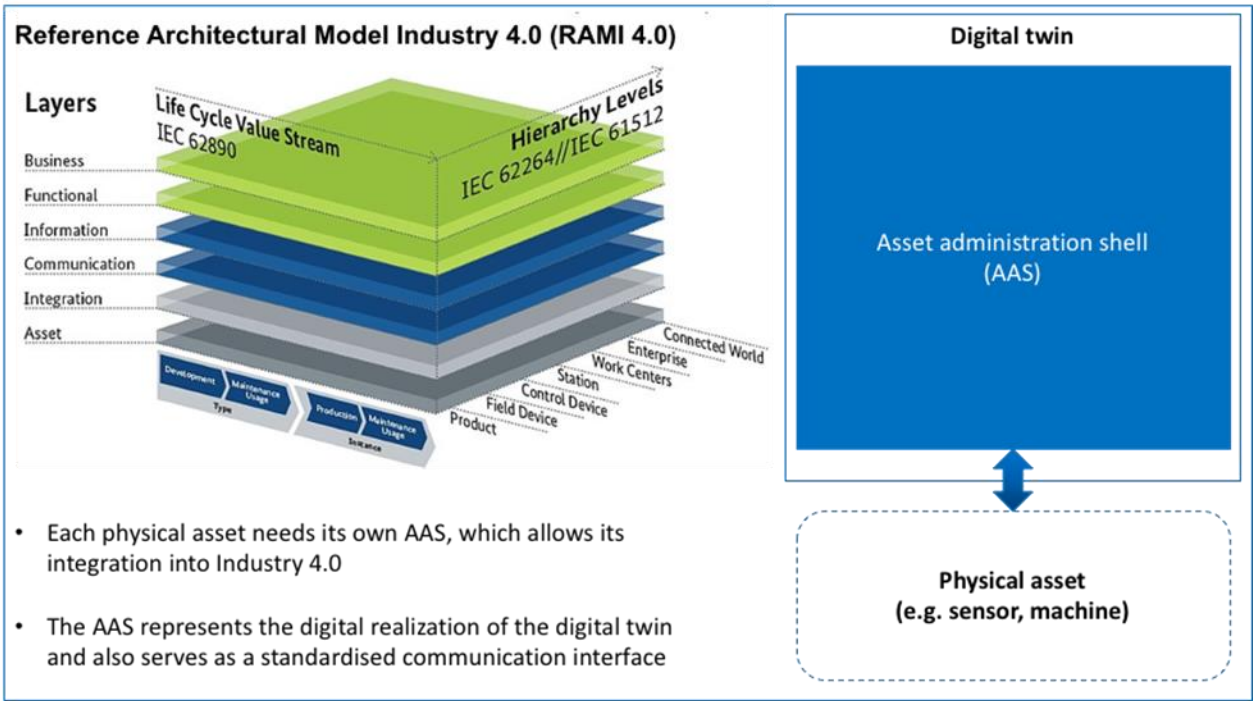
Reference Architectural Model Industry 4.0 (RAMI 4.0): RAMI 4.0 (Figure 2.1) represents a reference framework for digitalisation in industry (Plattform Industrie 4.0, 2018). It is a three-dimensional map that displays and orders the most important aspects of the Industry 4.0 architecture. These three dimensions are the following (Figure 2.1):

1. Architecture Layers represent six different aspects of business including the organisation of business processes, the aspired functionality of the asset, the output of data, the communication technologies necessary for data generation and treatment, and the development of the asset itself and its connection with digitally controlled processes.
2. Life cycle value stream. This axis represents a product's lifecycle stage and mainly consists of the development and usage phases. In the development phase, the asset, its production or construction and the possibilities for its maintenance are planned, whereas in the usage phase the asset is produced and identified, with, for example, a serial number, and maintenance and service are ensured.
3. Hierarchy Levels. This axis reflects the hierarchical structure of the Industry 4.0 network. Since the rather flexible networks can consist of production plants, machines and products belonging to different companies, a consistent hierarchical structure is necessary for network-wide communication (Plattform Industrie 4.0, 2018).

Overall, RAMI 4.0 ensures that all participants involved share a common perspective and develop a common understanding.

Digital twin: A digital twin represents a virtual model of a process. As an example, this can be a product or a service that links the physical and the virtual worlds (Grösser, 2018). Therefore, it uses data from installed sensors in order to monitor the working conditions, the position of machines or other aspects. Connecting the virtual and real worlds in this way allows data to be analysed and systems to be monitored. Through this approach, problems can be predicted and dealt with before they even occur. This helps avoid downtime, develop new opportunities and plan for the future with the help of computer simulations.

Asset administration shell (AAS): The AAS forms the digital part and thus the actual implementation of a digital twin (Plattform Industrie 4.0, 2018). It also represents a network's standardised communication interface connecting Industry 4.0 to the physical asset while storing all data and information about the asset.



- Each physical asset needs its own AAS, which allows its integration into Industry 4.0
- The AAS represents the digital realization of the digital twin and also serves as a standardised communication interface

Figure 2.1 Reference Architectural Model Industry 4.0 for use in digital twins.
Source: Plattform Industrie 4.0. (2018).

2.2. Central technologies for Industry 4.0

The conceptual ingredients presented above are enabled by different technologies. Providing similar background information as in the EEA briefing *Digitalisation and waste management* (EEA, 2021b), the most important technologies are presented below.

Sensor technology: Sensors are the bridge from the real world to a digital production environment. The state of different variables of production machines and goods in production are tracked, logged and used for process control. Sensors are used to measure these states and transform them into digital values.

Connectivity of production machines: To transfer data from sensors to the digital realm and to control production machines, they must be connected to the data processing unit. For immobile machines and large data transfer rates, this is best achieved by a cable connection. For mobile things such as produced goods, wireless connections need to be used. The connections can range from (adapted) Wi-Fi over cell-phone networks to custom tailored wireless networks. Depending on the application, stability, speed, range, power use and other properties need to be considered for optimal performance.

Data acquisition, processing and storage: Because of the digital nature, the amount of data gathered and its fine resolution, enormous amounts of data are produced and used in an Industry 4.0 environment. The technological infrastructure to process this data and store the information extracted must therefore be available.

Edge computing: In edge computing, operations are carried out on networked peripheral devices in contrast to central data processing in a cloud or in a mainframe computer. As the peripheral devices make their own calculations without prior data transmission, the lack of communication steps and the custom-tailored processing unit can increase the speed of computing and thus reduce latency. Network load can be decreased because distilled information rather than raw data is transmitted.

Encryption and authentication: For privacy reasons, to protect intellectual property or to prevent outsiders from intercepting the production process, it is often necessary to encrypt data collected before it is stored and passed on. Identification and authentication also may need to be included in communication for the same reasons.

Additional technologies and concepts that can enhance the above-mentioned ones but are not central to the concept of Industry 4.0 include the following:

Artificial intelligence (AI): Digital systems carrying out higher level classification and decision-making tasks are termed artificial intelligence. Much of the progress that has taken place in the field of artificial intelligence in recent years has been made in the pattern recognition and classification through the application of neural networks – commonly called machine learning (ML). This enables applications such as speech or image recognition. The underlying technology is not custom tailored to a specific problem but can use different sets of training data to be adapted to different use cases. The selection and amount of training data are important factors for optimising the neural network. A drawback of this method is its black box character. The results cannot be reverse engineered making it difficult to understand the reasoning for the decisions made.

Internet of things (IoT): The term internet of things summarises the increasing spread of connectivity, sensors and actuators in all kinds of products. Connecting them to one another other through the internet or other networks makes it possible to create an increasingly accurate digital image of the real world. The sum of this information creates the possibility of predicting trends or compiling information. The basic concept of the IoT, connecting many devices that are equipped with sensors, is also used in the Industry 4.0 context.

Distributed ledger technology (DLT): In 2008, Nakamoto published his whitepaper on a blockchain and laid the foundations for distributed ledger technology (Nakamoto, 2008). This distributed ledger can be seen as a decentralised database. Read and write access is given to all users but all changes are logged in the database itself. A consensus protocol ensures that all parties agree on one version. This way data can be (ideally) stored incorruptibly and encrypted to achieve data protection of various sorts.

2.3. Industry 4.0, merging central concepts and enabling technologies

The Industry 4.0 concept includes both the framework (system architecture) and the required technologies. It is based on distinct international norms provided in Figure 2.1. The architectural approach of RAMI 4.0 helps to create a uniform understanding between all stakeholders through the two dimensions of layers and hierarchy levels (Plattform Industrie 4.0, 2018). The layers on the vertical axis describe the structural digital representation of an entity within a process or organisation. The hierarchy axis depicts the different functionalities within a plant or factory (Hankel, 2015). In particular, the hierarchy levels dimension of Industry 4.0 is very different from that of Industry 3.0 in which a hardware-based infrastructure and thus also hierarchical communication between the individual elements occurred. Industry 4.0 provides flexible systems and machines whose functions are distributed across the entire network. Within the network, all components can communicate with each other irrespective of their hierarchical levels. With regard to the concept of the digital twin, this means that each networked object –product, machine, etc. – has an associated AAS, which thus represents the digital twin. The AAS serves as a communication interface between the various network components, through which a component can be identified and controlled, and at the same time can also transfer data. In other words, the AAS collects and stores the required data and can provide that data to further processing. Through this, it is also possible to create data on the lifecycle of plants or products. It is the networked digital infrastructure that enables constant or regular data generation and analysis in real time. Depending on the network and technology, this could be extended over the whole lifetime of machines or products.

2.4. Current implications and advances for manufacturing companies

Industry 4.0 enables completely new business models and modes of production. This in turn increases the importance of software expertise and knowledge of digital technologies for a manufacturing company's success in an Industry 4.0 ecosystem.

The collection and analysis of data offers companies new opportunities for products tailored to individual customer’s needs. Industry 4.0 production is more flexible and opens up the possibility of rapid changes, for example, in product design. Newly gained insights can be used for fast iterations in product design or even customised or personalised products, such as lot-size-one production (Fraunhofer-Gesellschaft, n.d.). Data analytics also creates deeper insights and improvements in product development. This is *inter alia* enabled by analysing the use of information that a smart product collects over the course of its lifespan.

With the growing network infrastructure and exchange of large volumes of data in Industry 4.0, security requirements are increasing. Hence, cyber-security and data-privacy measures must be considered from the very beginning. Systems and products, as well as data and knowhow, must be reliably protected against unauthorized access and misuse. Additionally, the protection of the right to privacy in data processing must be taken into account.

3 The digitalization and circularity nexus – enabling the circular economy with Industry 4.0 technologies and curbing the environmental impacts of Industry 4.0 with circular economy principles

3.1. A necessary transition towards resource effective production systems

The International Resource Panel (IRP) has estimated that extraction and processing of natural resources, ranging from minerals to energy carriers and food, is responsible for around half of global greenhouse gas emissions and for more than 90 per cent of impacts associated with water stress and biodiversity loss (IRP, 2019). Projections of demand for raw materials indicate that this will more than double by 2060, compared to demand in 2011, rising from 79 to 167 gigatonnes (Gt) [1] (OECD, 2019), meaning that, unless absolute decoupling is achieved, the impacts associated with raw material extraction and processing are expected to increase at a global level. Decoupling occurs when resource use or pressure on the environment or human well-being grows at a slower rate than the activity causing it (relative decoupling) or declines while the economic activity continues to grow (absolute decoupling).

To promote a sustainable transition to a world in which economic development is pursued while negative impacts on the environment and humans are reduced in absolute terms, fundamental changes are required in current elevated consumption patterns and production activities. Having the objective of using natural resources more efficiently and keeping resource consumption within the planetary boundaries, while contributing to reductions in greenhouse gas emissions and limiting the depletion of natural capital and biodiversity loss, a transition to a circular economy is today considered an urgent and essential pathway to these more sustainable consumption and production activities, leading to resource effectiveness.

A circular economy is indeed a system-oriented approach defined as "*an economic system where the value of products, materials and resources is maintained in the economy for as long as possible*" (EC, 2015). The transition to a circular economy entails reducing the intake of virgin materials and reducing the generation of waste. The concept of a circular economy is illustrated in Figure 3.1.

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[1] Gigatonne = 1 billion (10^9) tonnes

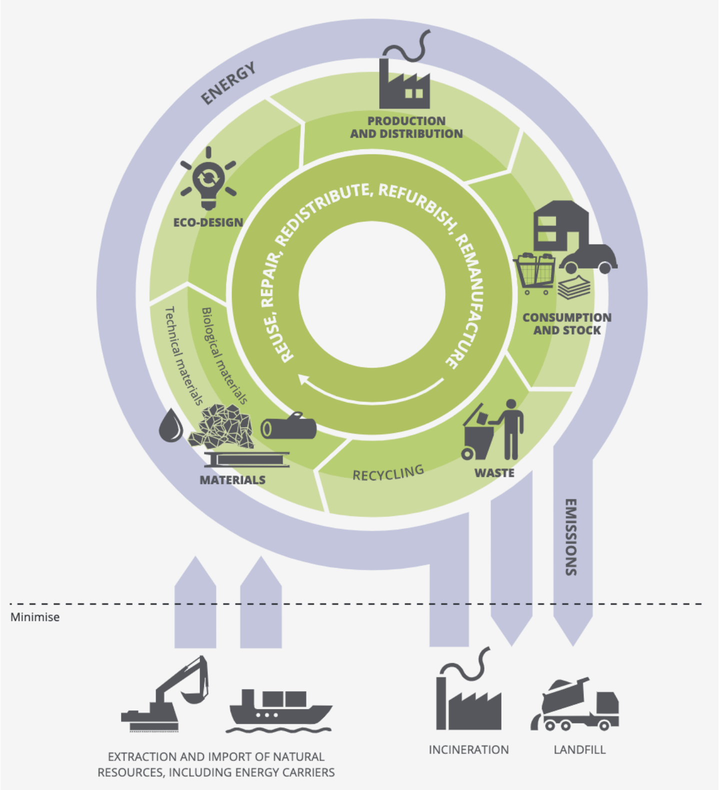

Figure 3.1 Circular economy system diagram.
Source: EEA (2019).

Also called R-strategies, the EEA typically uses the circular economy strategy categorisation defined in Potting et al. (2018). In this study, the authors defined a circularity ladder, which is based on product function and distinguishes 10 R-strategies that can be leveraged from transitioning from a linear to a more circular economy. Illustrating the above-mentioned transformation pathway and associated decoupling, Figure 3.2, also used in the Bellagio Declaration (EPA Network et al., 2021), displays the following rule of thumb: it can be assumed that circularity strategies higher up the ladder result in a stronger reduction of material use and these materials are more often derived from secondary sources.

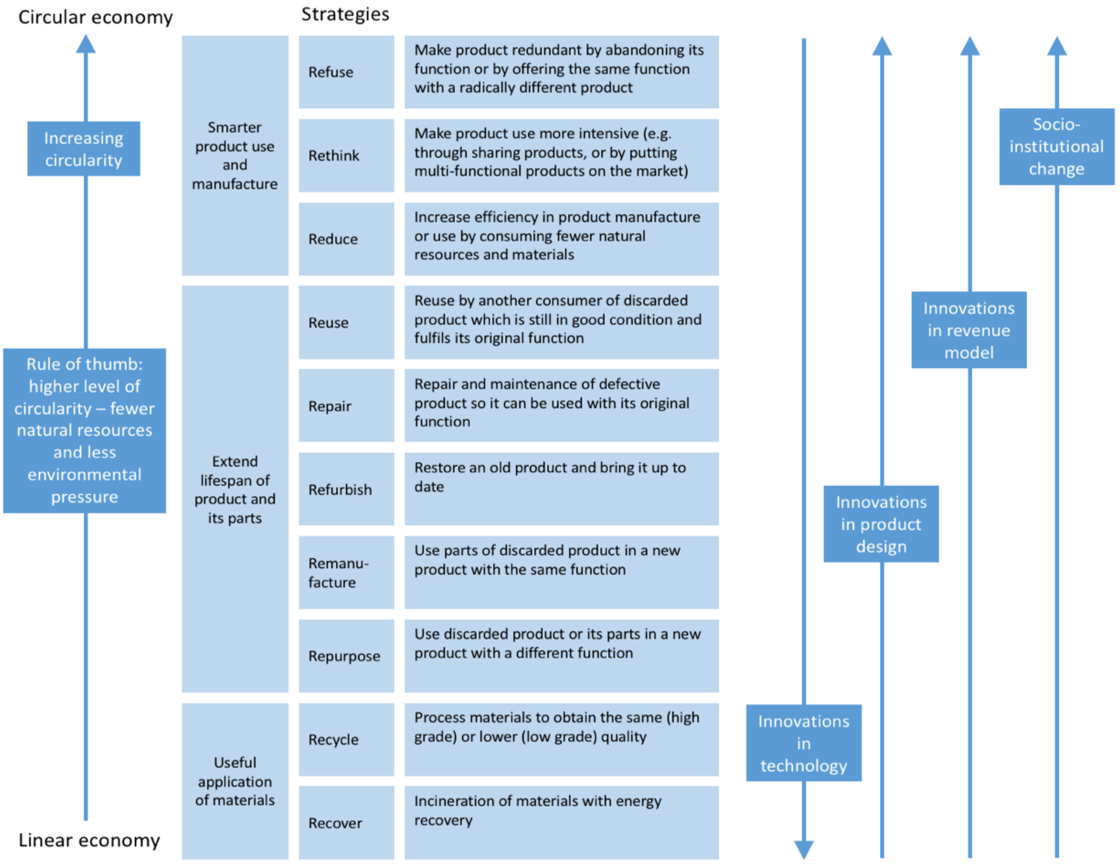

Figure 3.2 R-strategies
Source: EPA Network et al. (2021).

3.2. Advancing the circular economy through Industry 4.0 concepts

Circular economy strategies require data and information: A circular economy is more reliant on data and information than the linear one. Digital technologies can play an enabling role by providing the necessary information to unlock the potential of specific circular strategies (Berg, Le Blévennec, et al., 2020). This has been observed early on for recycling (OECD, 2006). High value recycling of, for instance, metals and plastics requires not only specific information on parameters of material composition but also market-related information such as availability and supply, which are important to reduce transaction costs (Wilts and Berg, 2017). The same holds true for other practices related to manufacturing. Rethink for example requires detailed knowledge of use patterns to enable logistics, design and distribution. Some instances of refuse can be enabled by virtual services, such as simulations, rather than material offers, but in order to gain this knowledge on the processes concerned, they have to be digitalised. Also processes, shown at lower circularity levels in Figure 3.2, that directly link back to production, such as refurbishment and remanufacturing, are information heavy. Remanufacturing of a product requires data on, for example, abrasion, use time, prior maintenance, etc. so that informed decisions on replacements and further utilisation can be made.

A structural view of the data economy: As shown in Figure 2.1, with the different layers of RAMI 4.0, the capacity to gather, process, structure and use data in decision making is increasingly seen as a source of competitive advantage for manufacturing companies. Before discussing the integration of central technologies for Industry 4.0 (Section 2.2) within the circular economy, and as developed by Kristoffersen et al. (2020) and then described by Berg, Le Blévennec et al. (2020), it is important to establish the basis of a common language and first understand the underlying ICT processes, principles and culture. Figure 3.3 conceptualises a structural view of the data economy. Moving from the outer side of the sphere towards the center (blue) provides increased structuring and production of information, whereas the central spots (green) represent knowledge building.

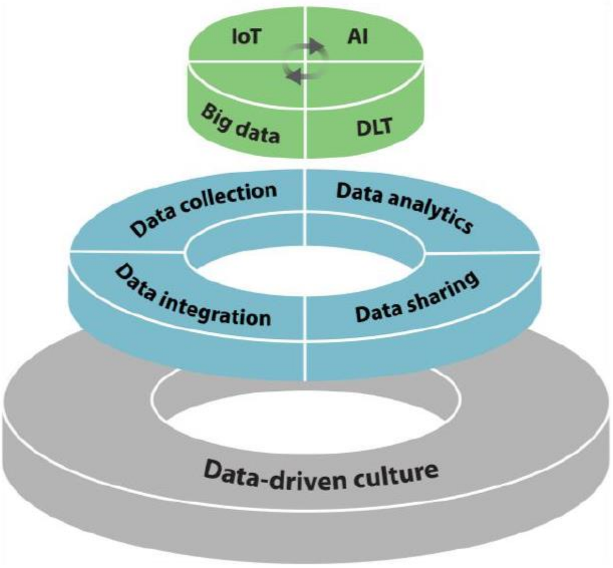

Figure 3.3 A structural view of the data economy.
Source: Berg, Le Blevennec et al. (2020), p. 9.

A framework bridging the digital transformation and resource optimisation capabilities: Kristoffersen et al. (2020) systematised this nexus between data use and processing with increasing resource optimisation capabilities for enabling specific circular economy strategies. Figure 3.4 shows this nexus and illustrates the importance of data and digitalisation in a circular economy: it is the meaningful collection, integration and analysis as well as the transfer of data that enable resource and energy efficiency gains. The green pyramid in this figure denotes a hierarchy of advancement in resource optimisation in which each level builds on the previous one. Each level has its specific merits and the higher the level, the more chances emerge for all steps (cf. Kristoffersen et al., 2020).

The descriptive level at the bottom of the hierarchy indicates how the connection of resources leads to the creation of data and information. Here, raw data is produced, collected and aggregated and context is added. Thus, in this basic step insights into the questions of what happened or what is happening to a resource, such as quantities and timing of material flows, are obtained. Hence, insights into the history and flow of resources are created, but no further conclusions for circularity can be directly drawn.
The diagnostic step adds causality to the information obtained on the prior level. Why something happened can be learned. The causes and effects behind the insights gained are captured linking them to the processes (events and behaviour) included. Based on the insights generated, needs for lifetime extending operations, can be inferred.

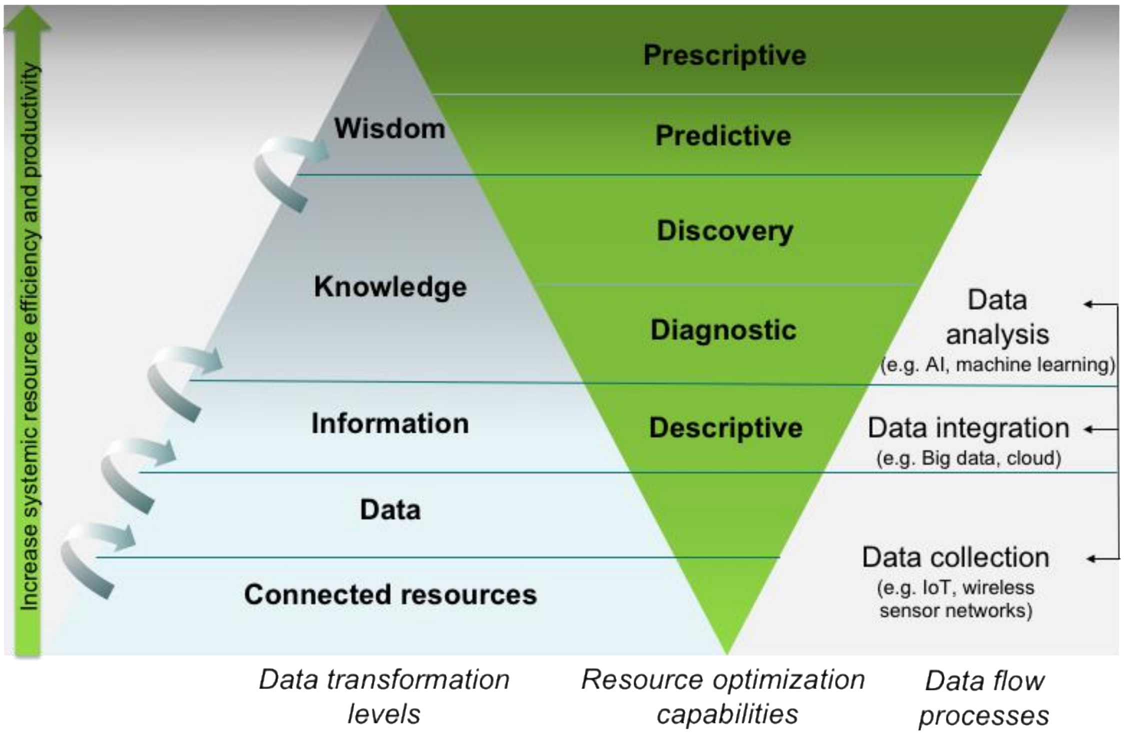

Figure 3.4 Hierarchy of data transformation levels and resource optimisation capabilities. Source: Kristoffersen et al. (2020).

It is noteworthy that the first two levels, descriptive and diagnostic, work on historic data and information, so that insights are provided on processes that have already occurred. However, the following three instances take present (discovery) or future-oriented (predictive and prescriptive), and hence more normative, approaches, respectively.

The third level - discovery – requires more intricate analytical measures. The aim is to create more detailed insights by moving from a descriptive to an analytical approach that “*employs inference, reasoning, and detection of non-trivial knowledge from information and data”* (Kristoffersen et al., 2020, p. 248). From this additional knowledge inferences on how resources may be used in a better way, given the present environment, can be created. Thus, this is the first step in which concrete measures in terms of enhanced circularity are obtainable, for instance, by increasing resource efficiency. New and more effective material cascades could, for example, be identified, end-user behaviour can be analysed to predict recyclate streams and make their use more effective.

The next two levels, predictive and prescriptive, include foresight and additional capability. In informatic terms they hence move from a stage of knowledge to a stage of wisdom. The predictive level projects future probabilities and trends, so that likelihoods for future development can be identified. From such projections, inferences for a better future resource use can be drawn. Predictive maintenance where repair and replacement are based on extrapolated real data is a point in case here.

Prescriptive methods mark the highest level of the hierarchy and also introduce a higher level of technological autonomy. This step also relies on the insights obtained on the previous levels and turns them into a dynamic approach to future resource use. Decisions can be made based not only on extrapolations, the predictive level, but on generated future scenarios so that emerging future opportunities are identified and can be seized, or imminent risks can be dealt with. Moreover, the prescriptive level can include the enablement of digital technologies to involve autonomous decisions to some extent, machines can, for example, predict *and* schedule measures for maintenance or other life-extending operations themselves (Kristoffersen et al., 2020, p. 248).

These analytical steps thus enable the refuse, rethink and reduce strategies portrayed in Figure 3.2. While the reduction of resource use can be seen as a straightforward effect represented at all levels of the hierarchy, rethink and refuse demand higher level analytical work. They are hence more associated with the wisdom-categories of the predictive and prescriptive resource optimisation capabilities. It is these steps that then also enable *resource effectiveness.*

While this section provides a framework and discusses the mechanisms for aligning the use of Industry 4.0 technologies and resource optimisation capabilities for accelerating the transition to a circular economy with the use of digital technologies, Chapter 4 discusses the potential of reducing environmental impacts of production activities based on this integrated approach in more detail. The categorisation of the different levels of resource optimisation is also used in the case study description in Section 5.2 to indicate their level of advancement and impact. Before this is done, however, the diffusion of digital technologies by Industry 4.0 also requires some critical thoughts, which are provided in the next section.

3.3. Curbing the effects of digitalisation

As discussed in the previous section, the scaling up of the circular economy would benefit from the deployment of digital technologies to fill its information deficit gap. An absolute decoupling will never happen, however, if sustainability is not put at the heart of the Fourth Industrial Revolution. Digitalisation and Industry 4.0 has its own, considerable environmental risks. General problems concern the respective technologies' needs for resources and energy. These technologies, for example, require materials – specifically metals – the production of which is resource heavy, may cause severe environmental damage and may also include violations of human rights and harmful working conditions in the extraction process. Table 3.1 shows that, with the projected increased application of digital technologies, demand for metals will rise accordingly, with even more concomitant severe long-term effects. At present, many of the appliances also do not lend themselves to circular economy practices such as repair or recycling due to, for example, miniaturisation and short use cycles. The data centre industry has also grown rapidly. This in turn leads to a fast-increasing stream of waste from electrical and electronic equipment (WEEE), which has become one of today's most problematic waste streams (Bahn-Walkowiak and Wilts, 2020).

Metal	Demand of future technologies (metric tonnes)		Demand for metal (worldwide production ratio)		End-of-Life recycling rate (%)
	2013	2035	2013	2035	
Lithium	610	110,000	0.0	3.9	< 1
Heavy rare earth metals	2,000	7,400	0.9	3,1	< 1
Light rare earth metals	29,000	64,000	0.8	1.7	< 1
Tantalum	500	2,100	0.4	1.6	< 1
Cobalt	5,000	120,0000	0.0	0.9	> 50
Germanium	60	120	0.4	0,8	< 1
Platinum	0	110	0.0	0.6	> 50
Tin	180,000	150,000	0.6	0.5	> 50
Palladium	20	100	0.1	0.5	> 50
Indium	230	360	0.3	0.5	< 1
Gallium	90	130	0.3	0.4	< 1
Silver	5,800	8,300	0.2	0.3	> 50
Copper	120,000	300,000	0.0	0.3	> 50

Table 3.1 Demand of future technologies by metals
Source: Pilgrim et al. (2017) p. 18.

Moreover, digitalisation and the use of the internet has grown to an extent that it has become a major consumer of energy and therefore also a major source of greenhouse gas emissions. Worldwide, consumption of energy by the internet is, depending on source, calculated to be about 5 per cent of the global total energy demand and is projected to increase to 21 per cent by 2030 (Jones, 2018).

Digitalisation and the use of digital appliances therefore urgently require solid management according to circular economy principles to curb adverse environmental effects and to ensure that digitalisation is developed within planetary boundaries (Berg, Le Blévennec, et al., 2020). Further risks stemming from Industry 4.0 directly are discussed in the Chapter 4.

4 Reduction of environmental impact of Industry 4.0 technologies

4.1. Setting the scene for avoiding further effects of the linear economy

Chapter 3 introduced the nexus between the fundamental drivers of Industry 4.0 and the circular economy, explaining that undeniably, using Industry 4.0 is crucial to accelerating the transition from a linear to a circular economy while a socially useful and sustainable Fourth Industrial Revolution cannot be envisioned without advancing the circular economy. Section 3.1 particularly indicated that advancing the circular economy is only the route that leads to resource effectiveness and ensures more sustainable consumption and production activities. While discussions on the links between digitalisation and the environment have gained momentum in recent years, only an absolute decoupling of resource use and pressure on the environment from economic activity growth can be envisioned for achieving European climate objectives. In other terms, it is crucial that environmental savings associated with the deployment of digital technologies (largely) overcome the environmental impact associated with their implementation. In order to further illustrate the risks and challenges associated with deriving the actual net benefits of using Industry 4.0 technologies for the circular economy, a qualitative description of their potential, together with anticipated pitfalls, is provided in this chapter 4.

4.2. Potential benefits of Industry 4.0

Potential benefits of Industry 4.0 applications can be grouped into direct and indirect effects. *Direct effects* concern benefits achieved in the production process relating to improved resource or energy efficiency due to leaner production systems and material savings, as well as the reduction of excess waste or production (Bai et al., 2020). The following are examples of benefits from direct effects.

- **Impact reduction by design**
  Industry 4.0 related technologies enable constant feedback loops from the production and use phases back to design and construction (Brandmeier et al., 2016). The knowledge generated by this can help to improve existing products, for example, in terms of longevity by redesign of parts or processes that show unexpected weaknesses in the use phase. Moreover, new products can be improved based on such data and the use of Industry 4.0 technologies. The application of AI in an Industry 4.0 context can, for example, help to speed up circular design processes and prototyping, and also arrive at new choices and suggestions for resource and energy efficient design based on the processing of large data samples (Ghoreishi and Happonen, 2020).
- **Tracking of emissions**
  Manufacturing related emissions can be measured and tracked using digital technology. The frequency of measurement points can be increased, reducing the time between anomalies and reaction or even revealing emissions that would have otherwise gone unnoticed. An example is the tracking of methane emissions, which are often caused by oil, gas and other heavy industries all over the globe, by the European Space Agency's Copernicus Sentinel 5P satellite (ESA, 2020).
- **Extending manufacturing equipment lifetimes**
  Predictive action in manufacturing can be based on data analytics enabled by the Industry 4.0 schema. Maintenance in the manufacturing process is a case in point. It implies using sensors in machines and data analysis models to predict failure of machine parts before they actually occur. Senseye software is an example that works in various production environments, including the automotive industry. This concept of predictive maintenance can reduce downtime, avoid greater damage to machine parts and leads to lifetime extension, thus saving resources through the application of circular economy principles (Senseye, n.d.).
- **New insights through data**
  Aggregated data from the production process give a clearer overview of material and energy flows and the use of production capacity. This can help derive new insights into resource and energy use in the production process itself. Increases in resource and energy efficiency can be realised from this. Furthermore, high quality management and control can be enabled so that

material and energy losses are minimised early, quickly and effectively. Real-time data analysis within the production process, for example, can help detect anomalies like changes in temperature and material flows very early on, which in turn can help detect failures in products and enable fast reactions so that fewer defective products are produced and resource efficiency increases. An example is Blackbird, a company that allows real time monitoring of production processes using visual information (Blackbird, 2021).

- **Avoid unnecessary (physical) activities**
  Developed for enabling more reliable and economic development processes, digital testing and prototyping activities reduce the need for their equivalent in the physical world and thus have the potential to reduce resource use such as water and energy, minimise waste, and reduce carbon dioxide emissions at early manufacturing stages. Safety considerations in car design, for instance, are evaluated using digitally simulated crash tests.

Indirect effects can be characterised as benefits enabled through Industry 4.0 technologies beyond the manufacturing process itself. They can, *inter alia*, concern the increase of resource and energy efficiency as well as measurement and monitoring along the value chain.

Removing intransparencies and information deficits
Industry 4.0 principles have the potential to overcome barriers to the circular economy caused by intransparencies and information-deficits (Wilts and Berg, 2017). The continuous tracking of data during a product's production and lifetime can provide information needed for meaningful reuse and refurbishment and enable recycling by way of providing information on a product's ingredients and disassembly.

- **Enabling new business models**
  Digital technologies enable the emergence of new circular business models. As-a-service models, for example, can be enabled through improved knowledge of use time, abrasion and wear out, for instance, leading in turn to improved economics (EEA, 2021a; Geissdoerfer et al., 2020; SAP SE, 2017). An example is the convenient access to bike-sharing in many bigger cities through smartphone applications.
- **Information for consumers and recyclers**
  Cyber physical systems and digital twins can inform product passports as the ones foreseen for batteries to allow informed decision making for maintenance, remanufacturing and recycling. They can also be used in the design process of products or to support end-consumer choices for more sustainable products.
- **Low footprint of digital goods**
  In a similar way, the resource use involved in reproducing and copying software and data is much lower when compared to conventional products. Consequently, if a service is created as data or software, it helps to decouple growth and resource use, through dematerialization ([2]). Digital books on an e-book reader and digital music are examples from the consumer sector.
- **System information as basis for decisions and improvements**
  With regard to resource and energy efficiency, the data that can be obtained on Industry 4.0 approaches can for the first time give detailed and real-time insights into the processes and functionalities of a whole system, industry or production process. Based on such insights, these processes can be optimised in part or in whole for sustainability. Similarly, political decisions can also be based on improved information when Industry 4.0-related technologies are used to

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[2] Unfortunately, this positive effect can be counteracted by a pronounced rebound effect (Section 4.3). The low resource use and thus low costs for multiplying data and software leads to massive increases in the use of digital products the increase in the number of pictures taken with digital technology compared to analogue photography, the number of e-mails compared to the number of handwritten letters sent or the number of songs in digital music collections compared to analogue ones are all examples from everyday.

monitor industry or environmental data. Agricultural production of various crops, for example, has been monitored using satellite data since the 1990's in the United States and made public in the Cropland and CropScape data layer (USDA, 2021). Using this and combining it with further data, different farming practices such as environmentally-friendly conservation tillage can be judged not by individual experiments but by the combined real yields across all fields (Deines et al., 2019).

- **Keeping track of natural stocks**
  Industry 4.0 monitoring principles and technologies can also track stocks and changes in stocks of natural resources such as forests, ice, water, deserts, etc. to detect changes, and potentially their causes and effects, and thereby enable early action to protect them. The water levels of many European rivers, for example, are available online and the German state of Baden-Württemberg even supplies hourly data on temperature, dioxygen (O_2) concentration turbidity and other parameters for their main rivers (LfU BW, 2021).
- **Open information for the public**
  Lastly, the data and knowledge created can also be easily and cheaply used to provide information to the wider public to raise awareness of sustainability and on measures and policies to promote it. The composition of the German energy mix and its emission factors, for example, is made available online on an hourly basis (Agora Energiewende, 2021).

Box 4.1 Digital product passports

Digital product passports are projected to be decisive enablers of the circular economy, *inter alia*, by diminishing the information deficits that currently hinder the upscaling of circular economy strategies. Currently, DPPs are still in a conceptual phase and still need to be fully developed. Their introduction has been suggested in several EU strategies including the European Green Deal (European Commission, 2019), the New Circular Economy Action Plan (EC, 2020a), and the European Parliament's resolution on the New Circular Economy Action Plan (European Parliament, 2021). The introduction of the frst DPP, for batteries with a capacity of 2 kWh and above is planned for 2026 (EC, 2020e). Hence, there is a strong drive towards their introduction by European policy makers.

Definition and aim of the digital product passports

A concise definition of DPPs was devised by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU).

> *"The digital product passport is a set of data summarising a product's components, materials, chemical substances and/or information on reparability, replacement parts and proper disposal. The data originates from all phases of the product lifecycle and can be used for various purposes in all its phases (design, manufacture, use, disposal). Structuring data in a standardised, comparable format enables all stakeholders in the value and supply chain to work together towards a circular economy. At the same time, the digital product passport is an important basis for reliable consumer information and sustainable consumer choices in both stationary and online retail."* (BMU, n.d.)

The 2021European Parliament's resolution on the New Circular Economy Action Plan (European Parliament, 2021) has meanwhile adopted a similar view and an analysis of intentions expressed in the several European strategies that mention DPPs revealed a similar concept of the European Commission (Götz et al., 2021).

The definition illustrates huge ambitions for DPPs. They are to be seen as a file or set of files that collects and provides all-encompassing information over a product's entire lifetime. The DPPs should function as points of information for manufacturers, retailers, and end-consumers. In particular, they should act as a point of reference for informed and sustainability-oriented decision making and for public administrations to monitor and steer the progress of circular economy.

Digital product passports and Industry 4.0

DPPs in their current conception are very ambitious as they are intended to satisfy several purposes as described above. Their comprehensive conception requires very extensive, if not continuous,

collection of data along a product's value chain to analyse and incorporate the information needed. In this, Industry 4.0 and RAMI 4.0 can serve as conceptional frameworks to support the establishment of a common technical understanding of DPPs. More precisely, the concept of the digital twin can serve as the technological basis for DPPs. This would imply that DPPs provide a specific view of the data and information, tailor-made for various target groups that are stored on the underlying digital twin.
Open issues
With DPPs being at a very early stage of development, many questions are still open for the full-fledged approach. To mention a few, the following challenges may be illustrative: the technological architecture, including interfaces and interoperability, needs to be addressed; at which level(s) of the product hierarchy, including substances, materials, components and products, DPPs will work also needs to be clarified; and, furthermore, safe data storage and provision have to be ensured, as well as sufficient data quality and validity.

4.3. Anticipated pitfalls

Currently developed for cost savings, improved availability of assets, optimised logistics, etc. the direct effect on sustainability is not yet a driver in the deployment of these new digital technologies (Haapanen and Tapio, 2016). To ensure the net environmental benefits associated with their development and implementation, it is also essential to consider their impact. The most important of these counteracting effects or pitfalls are listed in Box 4.2.

Box 4.2 Counteracting effects and pitfalls

- **Energy demand and greenhouse gas emissions**
  The use of energy by digital technologies is steadily rising and the related greenhouse gas emissions are a major contribution to the man-made climate crisis.
- **Increasing waste streams**
  The use and disposal of electronic devices results in enormous amounts of waste that are hard to recycle.
- **Driver for economic growth**
  Digitalisation drives economic growth and output (Katz and Koutroumpis, 2013), which can be counterproductive for sustainable development if this growth occurs in industries/markets that are harmful to the environment, such as increasing fossil fuel use (Schneidewind, 2018, p. 54 ff.)
- **Rebound effects**
  Efficiency gains in production processes will most likely lead to higher production volumes (Golde, 2016, p. 4) and thus have a lower positive impact than expected or even have a negative one.
- **Faster product iterations**
  Digital technologies can cut development time for new products and facilitate the adoption of production processes for these new products. Product iterations are thus speeded up resulting in more production and more waste, which is contrary to sustainability goals.
- **Digital obsolescence**
  Digital devices often cease to work and become outdated when newer versions of the software they require are no longer compatible. This is the most common reason for the disposal of digital devices and is not related to malfunctioning of hardware parts (Harris, 2020).
- **Lock-in effects**
  Software and technologies using proprietary formats are not compatible with other software. Especially in a connected digital world, this poses the risk of not being able to choose between competitors because these are not compatible with machines or software already in use. This leads to decline in competition and poses the risk of monopolies and oligopolies.
- **Over-complex software**
  The use of dependencies and of legacy systems is common in the software industry and as such

not a problem. Nevertheless, it results in software becoming more and more complex. In contrast to physical objects, this complexity is easy to create but can lead to inefficient, failure-prone codes (Mens, 2017).

- **Cyber security issues**
  Another drawback of over-complex software and even more complex systems of connected software is the security issues that arise. While for some this is a risk that can be accepted as a trade-off to a new function, especially for critical infrastructure, medical devices, government infrastructure and devices that store valuable information, it is of high concern (Alenezi and Zarour, 2020).
- **Data privacy issues**
  Gathering of (personal) data that can be sold and then used without explicit consent of the owner has become widely accepted in business. This puts the privacy of the individual at risk. Therefore, regulations such as the EU’s General Data Protection Regulation (GDPR) (EU 2016/679) must be introduced and compliance with them ensured to protect the privacy of the individual (Esteve, 2017).
- **Cloud storage**
  For data stored in the cloud with no local copy there is always a risk of losing access to this data. Should the cloud provider decide to cancel the account – access to particular data may become impossible. As with cybersecurity issues, the advantages might be worth the risk for some, but it should not be taken for important applications (Neumann, 2014).
- **Technological dependence**
  AllEEA member countries lack the technological infrastructure to produce the required digital infrastructure. Theoretically, since these capabilities are located in only a few countries, they are in a position of power and can endanger others’ technological independence (Hobbs et al., 2020).
- **Learning**
  Fast product iterations in digital products make life-long learning a necessity for everybody working with these technologies. This is likely to put some people who have not been accustomed to this in their childhood, at a disadvantage. Teaching digital skills in the education system is therefore important to level out these differences.
- **Taxation**
  Social or medical welfare and other services are partly financed by taxes on work instead of taxes on profit or sales. This financial basis can partially be lost with work being moved from people to machines in a digitalised world (Acemoglu et al., 2020).

5 Case studies of existing applications

5.1. Selection process and case presentation

To illustrate this nexus (Chapter 3) as well as the necessity of ensuring net benefits (Chapter 4), Chapter 5 discusses concrete existing applications. A collection of example cases was compiled through a literature review, an internet search and from the pool of solutions known from previous work in this field. This collection was then qualitatively assessed using a standardised approach. The authors also chose to add some cases differing from manufacturing, two from agricultural and one from the construction sector. Agriculture was added for several reasons. Firstly, in many areas industrial agriculture is one of the world's most automated industries based on or linked to Industry 4.0 principles, so that spill-over effects into manufacturing are possible. In effect, the differences between the application of digital principles in these two sectors are much smaller than the communalities, making a combined analytical approach richer than a strict differentiation. Secondly, the biosphere and bio-oriented technologies tend to be neglected in circular economy research and discussions, although they form an important part of the economy and need to be subject to circular economy principles as well to creating resource effectiveness and efficiency. These two findings hint at a third point, namely that the lines between these sectors in a more developed circular economy are likely to be far less rigid than in a traditional one. Indeed, these lines are expected to be blurred, with findings from and principles in each sector reaching into and being adapted by the other.

Cases from the agricultural and construction sectors were added for three reasons. Firstly, to show that Industry 4.0 applications related to impact reduction can be applied across industries and sectors. Secondly, because the biological part of the circular economy, is increasingly intertwined with the so-called technosphere through, for example, bio-based products, and, in the case of industrial agriculture belongs amongst the world's most automated industries. Thirdly, as especially shown in the construction sector, the relevance of data and information storage and collection for industrial purposes does not end with the production process, but in the case of the urban mine, for example, needs to be continued so that future circular production processes, including recycling, can be meaningfully enabled.

Specific cases that address the lowering of energy use or greenhouse gas emissions, enable water protection, contribute to improving resource efficiency through waste prevention, life prolongation and recycling, the reduction of hazardous substances and the reduction of risks to health as well as improvements in land use, soil degradation and food production were investigated. From amongst an array of relevant example cases, the most suitable ones were picked so that each of these fields was covered with at least one example. This process resulted in a list of ten standardised example cases, which are presented here. The individual example cases often do not concern just one of the areas mentioned above (lowering of energy use, etc.), but rather serve several purposes. Where this occurs, it is made clear in the respective example.

The examples are presented using a standardised format (Annex 0) to allow for a quick assessment by the reader and facilitate comparison of individual aspects across the cases. The cases chosen and their area of application are given in the following list as an overview as presented.

Table 5.1 Cases chosen and their area of application

Case	Area of Application
Digital twins in product development	Lowering energy use/greenhouse gas emissions
Digital twins in manufacturing and production planning	Lowering energy use /greenhouse gas emissions
Digital twins for a smarter product use	Lowering energy use /greenhouse gas emissions
PT1	Water protection
Electronic passport for construction products	Improving resource efficiency (waste prevention, life prolongation and recycling)
Plastics cloud	Improving resource efficiency (waste prevention, life prolongation and recycling)
ARXUM®	Hazardous substances (substances of very high concern), reduction of risk to health
Marketplace for excess soils	Land use/soil/food
Autonomous field robot	Land use/soil/food
Agri-module smart system	Land use/soil/food

5.2. Case studies

5.2.1 Lowering energy use/greenhouse gas emissions

Digital twins in product development

Resource efficient design, testing and prototyping operations

During the design and development phases, digital twins are being developed to bridge the gap between design, testing and reflecting the expectations in the designer's mind, and the constraints of the physical world. This virtual representation enables designers to optimise the products by iteratively improving the design models. Additionally, digital twin driven verification can validate the performance of the product under real-life circumstances. Taking advantage of digital twins can result in the reduction of production lead times and the need for expensive tests and physical prototypes.

- Spirent Communications, a global leader with expertise and experience in testing, assurance, analytics and security, serving developers, service providers and enterprise networks collaborates with the University of Warwick (UK), and will deploy a 5G digital twin technology that simulates 5G networks for testing connected vehicles in a controlled environment, within a 3D drive-in simulator operated by automotive manufacturers. Virtual tests, compared to real world ones, can reduce the number of physical miles required to be driven and enables the modelling of a multitude of complex what-if scenarios and environmental conditions. According to Spirent, connected vehicles provide more convenience, safety, and infotainment options than ever before. With the digital twin, all aspects of the vehicular communication system that supports the transfer of information from a vehicle to moving parts of the traffic system that may affect the vehicle (C-Vehicle to Everything) connectivity can be tested, refined, and optimised to deliver the experience that modern drivers and passengers demand.
- The recently started Innovative Future-Proof Testing Methods for Reliable Critical Components in Wind Turbines (INNTERESTING) EU-funded project (Olave Irizar, 2020), has the objective of extending the lifetime of future wind turbine components by developing innovative testing methods for prototype validation such as pitch bearings and gearboxes. The current product development process (PDP) relies on a validation method that

combines physical and virtual testing. While more advanced virtual modelling techniques are becoming available, it is still necessary to perform large-scale (full-size) physical tests to demonstrate reliability of new and larger wind turbine components. These full-size physical tests are the final step and the most expensive and time-consuming part of the PDP. To deal with bigger wind turbines, such critical tests require increasingly larger and more expensive test benches. • A US-based digitalisation consultancy, Black Swan Textiles is working in close collaboration with Siemens with an aim to accelerate clothing development and manufacturing through the implementation of Industry 4.0 and digital twin technologies. They are developing a digital twin model of product design and development using virtualisation software to replace old-fashioned product development tools.	
Output/goals for improvement	**Underlying technologies**
Developed for enabling faster, more efficient and reliable testing and prototyping operations, the deployment of digital twins in design and development phases has the potential to reduce resource use such as water and energy, minimising waste, and reducing carbon dioxide emissions.	• Multi-physics simulation. • Data analytics. • Machine learning.
Data transformation level ↔ resource optimization capability	**Requirements and preconditions**
Wisdom → prescriptive	• Access to high-quality data. • Skills in modelling, analytics and visualisation. • Multi-stakeholder collaboration.
Other aspects	
n/a	
State of development	
Described solutions are currently under development. Aimsun Next software provides a set of tools for investigation into the use of vehicle-to-everything connectivity. The extensible V2X software development kit can help researchers design innovative new systems based around connected vehicles and allow them to test future urban traffic management systems, in-car information tools and autonomous vehicle controls.	
Sources	
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Digital twins in manufacturing and production planning
Predictive maintenance of manufacturing equipment Production can be optimised by creating product digital twins of (all) manufacturing equipment. To reduce costly downtime in production, a virtual representation of manufacturing equipment combined with data analytics is currently being developed and implemented for enabling predictive maintenance. Based on an integrated real-time operational status of the equipment, and the health status of the components, a digital twin can support the prognostics and health management decision making. Sensor data from machines are analysed to detect failures. Once processed and classified this data can be used to detect failure occurrences and types. Based on the real-time data from a physical machine and historical data, the manufacturing equipment digital twin is then able to accurately predict the machine’s remaining life, faults, etc.

- A partnership between Xilinx and Aingura IIoT to support Etxetar Group, a Spanish federation of industrial manufacturing companies, plans to implement machine learning on its computer numeric control machines for enabling predictive maintenance. These machines are used to build automotive powertrain parts, including crankshafts, camshafts and connecting rods, which require a high level of precision delivered at high speed. It has been estimated that providing a supervised learning algorithm could provide a 20 per cent increase in improved asset availability, estimated at an additional three hours of use per day.
- In the United States, General Electric (GE) is providing Predix, an asset performance management software and service solution designed to help optimise the performance their customers' (GE and non-GE) assets. Examples of customers' use include:
    - sensors installed on critical turbine assemblies transmit real-time data to a secure computing resource, building a digital twin of each component and assembly. The digital models are enriched with situational data such as system load, ambient temperature and air quality. By building an individual digital twin for every critical turbine assembly, and continuously analysing each model using advanced statistical tools, plant operators can bring turbines down for maintenance predictively, eliminating the costs of unnecessary downtime and mitigating the risks of unplanned outages.
    - Severstal, an integrated steel and steel-related mining company, analysed the condition of its maintenance system, created a solution design, completed module and integration testing, trained 390 users and administrators, installed software packages to the users' personal computers, tested six pilot machines and completed a criticality analysis of 17,000 machines. Between 2013 and 2015, Severstal reduced its unscheduled maintenance delays for core equipment by 20 per cent, which was particularly helpful as the company also reduced its maintenance budget and personnel.

Virtualisation of production centre for more efficient industrial processes

As part of the Horizon 2020 IoT4DigitalTwin project, Geprom Connecting Industries and Gefasoft GmbH have formed a consortium to introduce a digital twin in CELSA, a private Spanish multinational and leader in the metallurgical sector, and advance Industry 4.0 with more flexible, personalised and efficient processes. During the 13 months of the project, pilot tests in CELSA's processes have been developed, generating a link between the real factory and a virtual platform. Not only concerned with the status of manufacturing equipment, all relevant data for the digital twin, such as order information, asset positioning and process values, are provided in real time through the system. The result of the project is a flexible and scalable digital twin model, which enables new production scenarios to be validated without altering the existing manufacturing process and more secure decisions to be made based on reliable, real-time data. With this virtual factory, CELSA will be able to predict production processes by avoiding production stoppages, to test modifications without introducing changes to the plant, increase the efficiency and productivity of operations and optimise logistics and production parameters.

Output/goals for improvement:	**Underlying technologies**
Developed for enabling faster, more efficient and reliable operations, the deployment of digital twins in manufacturing and production planning has the potential to reduce resource use such as water and energy, minimise waste, and reduce carbon dioxide emissions.	• Multi-physics simulation. • Data analytics. • Machine learning.
Data transformation level ↔ resource optimization capability	**Requirements and preconditions**

Wisdom → predictive	• Access to high-quality data from machines and/or factory operations as a pre-requirement. • Skills in modelling, analytics and visualisation. • Multi-stakeholder collaboration.

Other aspects

n/a

State of development

- Partnership between Xilinx and Aingura IIoT, from pilot factory to demonstration.
- GE Predix asset performance management solution – technical readiness level (TRL) 9.
- Siemens, ABB, Schneider Electrics, etc. also provide TRL 9 solutions:
  - ABB (Switzerland) digital twins and simulations for managing solar asset performance with connected analytics
- Umlaut (Germany) has developed a digital twin for virtualising a production. process, from concept through engineering to manufacturing and aftersales, already in use in the aerospace industry. Their enhanced virtual training solutions enable cost-efficient simulations of complex situations – damage, emergency situations, etc.

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Digital twins for a smarter product use

Energy-efficient design and continuous operational optimisation

IES, a private UK consultancy, has developed the Intelligent Communities Lifecycle (ICL) solution, providing digital twin technology that connects distributed energy networks, renewables, master plans, building design, operations and retrofits with an aim of decarbonising the built environment. By integrating machine learning and AI, the ICL creates dynamic 3D models that reflect real-life performance, delivering resilience, cost savings and water and energy efficiency for buildings, campuses, communities and cities.

- IES was contracted to deliver a 3D master-planning and visualisation model, along with virtual testing and building performance optimisation for Nanyang Technological University's (NTU; Singapore) 250-hectare flagship eco-campus. Delivered in two phases, the project used IES' innovative ICL technology to provide high-level visualisation and analysis of testbed energy-reduction technologies on site, before delving into detailed simulation and calibrated modelling of 21 campus buildings.
- As part of the Innovate UK funded project, CEDISON, IES created an intelligent virtual network (iVN) model of Eday, one of the Orkney islands. The analysis aimed to determine ways in which the island could reduce its reliance on grid imports and fossil fuels, whilst also identifying steps towards making Eday a zero or positive energy community.
- Using the iSCAN platform, IES facilitated data monitoring and analysis at Glasgow's Riverside Museum (Scotland) to achieve savings of GBP 52,300 (approximately EUR 61,000) per year by uncovering zero/low-cost energy-saving interventions.

Potential to reduce environmental impacts	**Underlying technologies**
Digital twins developed for decarbonising the built environment: • NTU Singapore's goal is to reduce their energy, water and waste footprints by 35 per cent by 2020, and in the process become the greenest campus in the world. • On Eday,. it was found that near zero energy building (NZEB) status could be achieved through a combination of retrofit measures which would result in 76 per cent total energy savings and the elimination of fossil fuel consumption on the island. The payback for achieving NZEB status was determined as 5.6 years, or less if homes were found to be eligible for retrofit funding under schemes such as the energy company obligation (ECO) scheme. • IES was able to achieve significant energy savings in both gas (26 per cent) and electricity (18 per cent) at the Glasgow's Riverside Museum. The savings in gas energy were validated using a measurement and verification (M&V) technique to ensure that the savings were not due to difference in weather conditions.	• Multi-physics simulation. • Data analytics. • Machine learning.
Data transformation level ↔ resource optimisation capability	**Requirements and preconditions**
Wisdom → prescriptive	• Access to high-quality data. • Skills in modelling, analytics and visualisation. • Multi-stakeholder collaboration.
Other aspects	
n/a	
State of development	
Implemented	
Sources	
• https://www.iesve.com/digital-twins • https://www.iesve.com/icl/case-studies/2572/riverside-museum-glasgow • https://www.iesve.com/icl/case-studies/4711/eday-orkney-islands • https://www.iesve.com/ntu-singapore	

5.2.2 *Water protection*

Hydro-powered monitoring units
According to studies, an average of 30 per cent of treated water worldwide is lost through leaks. A major problem for water suppliers is that pipe damage and water losses are caused by overpressure, and there are still too few metering points and remotely controlled valves installed to perform optimisation, since a reliable and economical energy source is not available everywhere. PYDRO is a German-based start-up company that offers PT1 hydro-powered monitoring units, self-sufficient systems to support sustainable water resource management by deploying it in water

<table>
<tr><td colspan="2">intake wells, district metering areas, and custody transfer measurements of potable water (PYDRO GmbH, 2021). The units’ energy-autonomous multi-sensors are placed in the flange connections of the pipes. The sensors supply themselves with energy by means of a turbine driven by the flow in the water pipes and are thus immediately able to measure data such as flow, pressure and temperature in real time according to the water-to-data principle. This information is transmitted to a cloud, where it is processed, analysed and made available to the customer.</td></tr>
<tr><td>Output/goals for improvement:</td><td>Underlying technologies</td></tr>
<tr><td>PYDRO's energy-autonomous multi-sensors with real-time data transmission monitor drinking water pipes, thus ensuring resource conservation through less water and energy loss and strengthening supply security. It delivers data to manage smart water networks, to reduce water leakage and to prevent pipe bursts.
PT1 enables direct environmental benefits. It helps to maintain a sustainable water management by flow-, pressure- and temperature sensors that is independent from external power supplies as it harvests energy with its integrated hydro-power turbine and stores it in an internal battery.</td><td>• Measurement technology.
• Sensors:
▪ real-time transfer.
• Software including:
▪ data analysis;
▪ cloud computing.</td></tr>
<tr><td>Data transformation level ↔ resource optimisation capability</td><td>Requirements and preconditions</td></tr>
<tr><td>Knowledge → diagnostic</td><td>• Installation of sensors.
• Sufficient hardware and software to access the data.
• Pipes that fit to the size of the sensors.</td></tr>
<tr><td colspan="2">Other aspects</td></tr>
<tr><td colspan="2">• PYDRO offers innovative business model approaches such as sensing-as-a-service and hardware-as-a-service, as well as the service of a digital twin, to operate networks efficiently and predict or quickly find anomalies in the future</td></tr>
<tr><td colspan="2">State of development</td></tr>
<tr><td colspan="2">• The company was founded in 2016 and in 2020 Gigahertz Ventures GmbH provided seed investment together with shareholders GENIUS Venture Capital GmbH and Thomas Clemens.
• Looking for early adopters.
• Similar solution: Lisios, an alarm system to detect water damage, which is still development but can be pre-ordered from https://www.lisios.com.</td></tr>
<tr><td colspan="2">Sources</td></tr>
<tr><td colspan="2">• https://www.pydro.com
• https://start-green.net/netzwerk/gruenes-startup/pydro/
• https://gruender.wiwo.de/pydro-wir-finden-die-lecks-in-wasserleitungen/
• https://www.dbu.de/123artikel38693_2430.html</td></tr>
</table>

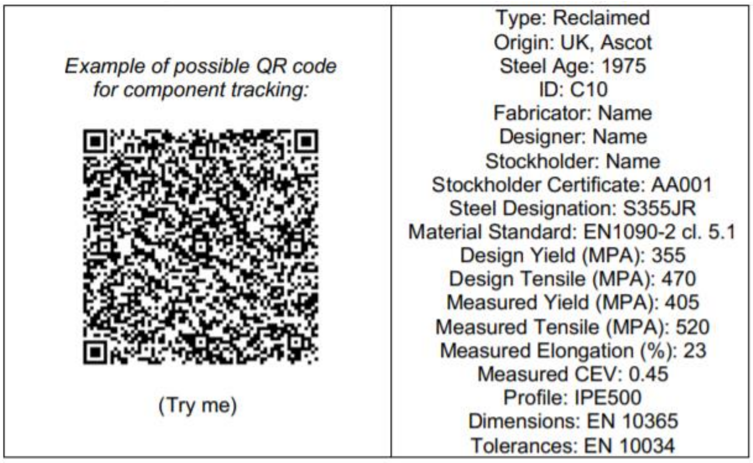
5.2.3 *Improving resource efficiency – waste prevention, life prolongation and recycling*

Electronic passport for construction products
Electronic passports for construction products enable storage and traceability of product properties throughout its life cycle from manufacture, through use to its end-of-life stage (reuse/recycling).

Contactless tag-based identifiers, radio-frequency identification (RFID) and quick-response (QR) codes, combined with authentication markers provide advantages in resource management and material tracking on construction sites. Passports provide digital fingerprints which identify the materials and update their information at each stage of a building's lifecycle. These tags can be embedded in construction components and structural elements cast *in situ* to improve logistics and accounting.

Material or product traceability is crucial for reuse and recycling and it creates trust in the quality of construction products. Material traceability is the ability to trace the source of a specific material to its original identity as delivered from the manufacturer, through proper identification and quality assurance systems. In the construction sector, the use of circular-economy marking is often mandatory for construction products. Suppliers and manufacturers who intend to reuse or recycle materials have to establish an in-house quality assurance system to ensure the traceability of such materials. For the reuse of steel, for example, each product can be marked with a unique identification number for which quality control checks are introduced and recorded. Such unique identification will facilitate future reference to a factory's production control certificate, the manufacturer's test certificate, and the inspection record and/or test report without confusion.

Examples of permanent labels are laser-engraved plates with visible information or RFID tags with information readable by radio frequency scanner:



Example of possible QR code for component tracking:

(Try me)

Type: Reclaimed
Origin: UK, Ascot
Steel Age: 1975
ID: C10
Fabricator: Name
Designer: Name
Stockholder: Name
Stockholder Certificate: AA001
Steel Designation: S355JR
Material Standard: EN1090-2 cl. 5.1
Design Yield (MPA): 355
Design Tensile (MPA): 470
Measured Yield (MPA): 405
Measured Tensile (MPA): 520
Measured Elongation (%): 23
Measured CEV: 0.45
Profile: IPE500
Dimensions: EN 10365
Tolerances: EN 10034

Figure 5.1 Example of a QR code and the information behind the QR code (Coelho et al., 2020)

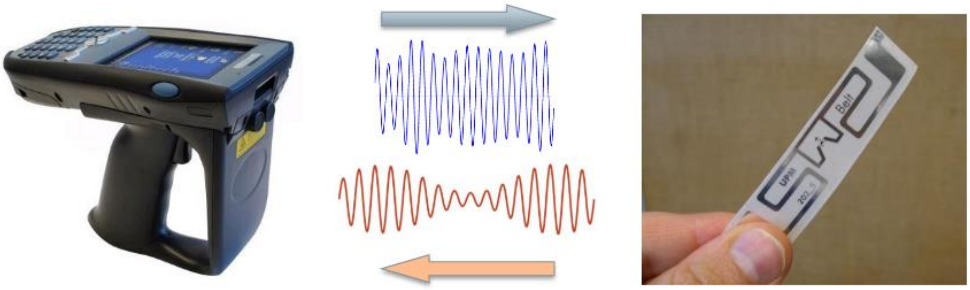


Figure 5.2 Radio frequency reader and identification tag (Jaakkola, 2019)

Output/goals for improvement:	**Underlying technologies**
The service aims to improve the reuse of resources, resulting in less waste and less demand for new materials. For example, multiple reuse loop of steel beams support the better waste management, reuse instead of recycling, and results in significant reduction of carbon dioxide emissions.	• Cloud computing. • RFID, QR codes.

<table>
<tr><th>Data transformation level ↔ resource optimisation capability</th><th>Requirements and preconditions</th></tr>
<tr><td>Wisdom → predictive</td><td>• Choice of identification system (RFID tag or QR code) depends on the product and information needs.
• The use of RFID is not possible for construction products undergoing extreme conditions, such as high temperatures, or in conditions where it can be destroyed or made unreadable.
• Requires data uploading and storage, such as blockchain, and standardised data readers.
• Markets: circular-economy-marking requires product information that can be documented electronically.</td></tr>
<tr><th colspan="2">Other aspects</th></tr>
<tr><td colspan="2">It is essential that digital information – building memos, building information modelling (BIM), etc. – is available throughout the lifecycle of a building and its components for the facility owner and relevant building authorities issuing demolition, renovation and building permits. The reliability of the information contained in declarations and certificates can be guaranteed, for instance by using independent traceability systems such as Tracimat in Belgium, databases managed by building authorities, or manufacturers of construction products responsible for re-certification or blockchains.</td></tr>
<tr><th colspan="2">State of development</th></tr>
<tr><td colspan="2">Radio-frequency identification tags and QR-codes required for material passports are commercially available. Related concepts include smart circular-economy-marking and smart environmental product declarations (EPDs). The solution can be linked to BIM, a concept in which building and management performance-related data, such as planning, processing, requirements and performance, are digitally created, modelled, stored, re-organised and can be published or viewed to support decision making during the whole lifetime of a building.</td></tr>
<tr><th colspan="2">Sources</th></tr>
<tr><td colspan="2">• Girão Coelho, A.M., Pimentel, R., Ungureanu, V., Hradil, P. and Kesti, J. 2020. <i>European Recommendations for Reuse of Steel Products in Single-Storey Buildings</i>. ECCS – European Convention for Constructional Steelwork, Brussels, Belgiou. https://www.steelconstruct.com/wp-content/uploads/PROGRESS_Design_guide_final-version.pdf (accessed 12June 2021).
• Jaakkola, K. 2019. Presentation at ”Rakentamisen kiertotalouden ajankohtaispäivä” 15 November 2019 arranged by the Finnish Environmental Protection Agency.
• World Business Council for Sustainable Development. 2021. <i>Digitalsation of the built environment: Towards a more sustainable construction sector</i>. https://www.wbcsd.org/Programs/Cities-and-Mobility/Sustainable-Cities/Transforming-the-Built-Environment/Digitalization/Resources/Digitalization-of-the-built-environment-Towards-a-more-sustainable-construction-sector (accessed 12 June 2021).
• Veldhuizen, J. and Sturm, C. 2020. <i>Creating a better world: Circularity in Construction</i>. Deloitte, London, UK. https://www2.deloitte.com/ce/en/pages/real-estate/articles/creating-a-better-world.html (accessed 12 June 2021).
• Hradil, P., Talja, A., Wahlström, M., Huuhka, S., Lahdensivu, J. and Pikkuvirta, J. 2014. <i>Re-use of structural elements: Environmentally efficient recovery of building components</i>. VTT Technical Research Centre of Finland, Helsinki, Finland. http://www.vtt.fi/inf/pdf/technology/2014/T200.pdf (accessed 12 June 2021).</td></tr>
</table>

Plastics Cloud

One of the problems with plastic waste is that it has no market value – yet. Another problem is that companies that want to use recycled plastic are having trouble finding it in the market. Hence, there is a need to integrate plastic waste into logistics' chain systems so that it does not seep into the illegal sector. Together with partners, the German multinational software corporation SAP SE is working on extending SAP Ariba, the world's largest business-to-business network, to create a new global marketplace for suppliers of recycled plastics and plastic alternatives. The Plastics Cloud is compiling and processing information that can be used to forecast trends in plastics purchasing, recycling and enabling new services.

Output/goals for improvement:	**Underlying technologies**
Due to marketplace's capabilities to improve the market for recycled plastics, plastic production can be reduced (indirect waste prevention and recycling). The specific amount of plastics saved depends on the use of the marketplace and the amount of plastic recycled material.	• Digital platform/network. • Software including: ▪ data analytics; ▪ machine learning; ▪ predictive analytics.
Data transformation level ↔ resource optimisation capability	**Requirements and preconditions**
Wisdom → predictive	Access to data of produced plastics/materials and appropriate IT and data infrastructure.

Other Aspects

The goal is to use the SAP Ariba network to connect buyers with new recycled plastics suppliers including Bantam Material UK Ltd. and others who are already certified by organisations such as OceanCycle – a social enterprise focused on creating traceability in plastic supply chains and helping businesses integrate ocean plastics into their products.

State of development

Still at a conceptional phase and might take several years to complete. However, there are already quite similar solutions also addressing the plastics sector:

- CirPlus: https://www.cirplus.com/de
- Materials Marketplace: https://go.materialsmarketplace.org/
- RecycleBlu: https://www.recycleblu.com/
- Waste-Outlet: https://www.waste-outlet.com/
- Plastic Resale: https://www.plasticresale.com/about/

Sources

- https://news.sap.com/2019/09/plastics-cloud-pilot-new-global-supplier-marketplace/
- https://www.sap.com/dmc/exp/2019-08-unglobalgoals/12_Responsible_Consumption_Production.html
- https://news.sap.com/tags/plastics-cloud/

5.2.4 Hazardous substances (substances of very high concern /reduction of risk to health)

ARXUM®

In the chemical industry, the complex, multi-stage and globally distributed production processes make tracing the flow from raw materials to a final product a challenging task. From a sustainability perspective, the lack of transparency poses serious problems for social and environmental compliance in particular.

With ARXUM®, a German-based company Arxum offers a middleware suite that uses EOSIO blockchain technology and smart contract business logic to enable transparency within the supply chain. ARXUM® Suite taps into data silos of different supply chain partners, controlled on a blockchain backend by each data owner. Secured by individual rule sets, data exchange and access are fully automated and provide the right piece of information from different sources at the right time. ARXUM® pulls data from any IT system into virtual data buckets. Individual buckets are filled from supplier data lakes and form the basis of concise reports on supply-chain and material information.

Output/goals for improvement	**Underlying technologies**
ARXUM® generates indirect environmental, social and economic benefits by increasing traceability within chemical supply chains through enhanced transparency of the end-to-end production flow by tracking the raw material path. Compliance with social and environmental standards is better observable and controllable. There is an efficiency gain with automated order processing, and disintermediation through the holistic process approach is possible. Besides that, the possibility of tracking carbon dioxide emissions is communicated as well.	• Plug-and-play-module. • Distributed ledger technology: ▪ EOSIO blockchain technology; ▪ smart contracts. • Software including: ▪ middleware; ▪ data integration; ▪ real-time data transfer; ▪ inter-planetary file system (IPFS).

Data transformation level ↔ resource optimisation capability	**Requirements and preconditions**
Information → descriptive	• ARXUM® uses pre-developed software modules and the server infrastructure is provided as a service, smart contract per module. • Connectivity agent for connecting the IT infrastructure with the ARXUM® suite. • User-management system for access control and access to a block explorer service, for monitoring and checking ARXUM® Suite transactions and smart contracts. • Network and data exchange between different parts of the supply chain.

Other aspects

Not limited to the chemical industry but generally to traceability and visibility in the areas of procurement, logistics, manufacturing and sales.

State of development

- The company was founded in 2018/2019.
- Market maturity/productive use.

Sources

- https://arxum.com/arxum-suite/
- https://arxum.com/end-to-end-transparenz-des-produktionsflusses-durch-die-verfolgung-des-weges-des-rohmaterials/
- https://kompetenzzentrum-kaiserslautern.digital/datenaustausch-auf-knopfdruck/
- https://www.chemanager-online.com/news/sicherer-datenaustausch-und-zwischen-unternehmen

5.2.5 Land use/ soil/ food

<table>
<tr><th colspan="2">Marketplace for excess soils</th></tr>
<tr><td colspan="2">Construction sites produce large amounts of surplus earth that are currently treated as waste and end up in landfills. But the costs of extraction and transport of soils soils are high. Maapörssi (soilmarket) is a Finnish digital platform for established for builders to share reusable soil and demolition materials.
The service offers significantly reduced building costs: instead of paying a high price for fresh soil, Maapörssi users can obtain excess soils mined in other construction sites, resulting in a more efficient use of resources.
The aim is also to minimise transport distances, and thus reduce emissions from the transport. The service includes a transport application that helps customer companies manage their material flows and contains features such as real time digital consignment reports.</td></tr>
<tr><td>Output/goals for Improvement:</td><td>Underlying Technologies</td></tr>
<tr><td>The service aims to improve the use of resources, resulting in less waste and less demand for new materials. By minimising the transport distances, carbon dioxide emissions can be reduced.</td><td>• Digital Platform.
• Software.
• Global positioning systems (GPS).</td></tr>
<tr><td>Data transformation level ↔ resource optimisation capability</td><td>Requirements and preconditions</td></tr>
<tr><td>Information → descriptive</td><td>• Installation of mobile transport application.
• Information available on the soil characteristics.</td></tr>
<tr><td colspan="2">Other aspects</td></tr>
<tr><td colspan="2">Additional features in development: calculating and reporting of carbon dioxide emissions, real time tracking of transport based on GPS data.</td></tr>
<tr><td colspan="2">State of development</td></tr>
<tr><td colspan="2">The platform was launched in 2006 as an advertisement website and has since been developed into a digital tool for handling of excess soils and demolition materials. New features are under development. To date, soils and demolition materials have been recycled using Maapörssi in around 3000–4000 construction site projects in southern parts of Finland.
Similar solutions include GreenHands: https://www.greenhands.net.au/</td></tr>
<tr><td colspan="2">Sources</td></tr>
<tr><td colspan="2">• https://www.maaporssi.fi/
• https://www.sitra.fi/en/cases/recycling-service-surplus-excavation-material/
• https://www.skal.fi/fi/system/files/maaporssi_esittely_maarakennusseminaari_2018_skal.pdf
• https://skol.teknologiateollisuus.fi/en/node/9558</td></tr>
</table>

<table>
<tr><th colspan="2">Autonomous field robots</th></tr>
<tr><td colspan="2">Autonomous robots or robot swarms perform tasks including sowing, hoeing, weeding, harvesting and tilling. This technology could lead to a paradigm shift in agriculture.</td></tr>
<tr><td>Output/goals for improvement:</td><td>Underlying technologies</td></tr>
<tr><td>• Enables precision farming with less or no fertiliser use and less or no chemical crop protection. This contributes to less groundwater contamination by phosphates and nitrates, a smaller carbon footprint for food production, and a higher biodiversity through fewer harmful chemicals being used.</td><td>• Satellite positioning.
• Autonomous navigation.
• Geo-information system.
• Cloud computing.
• Telemetric maintenance.
• Sensoring.
• Data analysis.</td></tr>
</table>

<table>
<tr><td>• Uses less energy to operate and some can run on electricity or even solar power instead of diesel. This opens up the capability of crop production with renewable energy and lowering food production footprints.
• Lowers noise and oil emissions in the agricultural sector and significantly reduces soil compaction.</td><td></td></tr>
<tr><td>Data transformation level ↔ resource optimisation capability</td><td>Requirements and preconditions</td></tr>
<tr><td>Knowledge → discovery</td><td>• Digitalised farming.
• Investment.
• Possibly availability of electricity in the field</td></tr>
<tr><td colspan="2">Other aspects</td></tr>
<tr><td colspan="2">• Robots can be equipped with sensors to collect information on soil status and quality.
• Data security and ownership should be considered.
• Mobile network coverage may be required,
• Autonomous work around the clock is possible.</td></tr>
<tr><td colspan="2">State of development</td></tr>
<tr><td colspan="2">There are several companies already selling autonomous robots, others are at the test stage and the technology is being researched and developed further.</td></tr>
<tr><td colspan="2">Sources</td></tr>
<tr><td colspan="2">• https://www.landtechnikmagazin.de/Bestellung-und-Pflege-Artikel-Neue-Generation-des-Saeroboters-Fendt-XAVER-vorgestellt-8885.php
• https://www.fendt.com/de/xaver
• https://www.topagrar.com/technik/news/fendt-xaver-als-saeroboter-live-vorgefuehrt-12342225.html
• https://www.agrarheute.com/technik/ackerbautechnik/diese-feldroboter-gibt-koennen-577138
• https://www.swarmfarm.com/
• https://www.handsfreehectare.com/
• https://www.naio-technologies.com/en/
• https://www.ecorobotix.com/de/
• https://www.agrobot.com/
• https://farmdroid.dk/de/willkommen/
• https://carbonrobotics.com/</td></tr>
</table>

Agri-module smart system
Agriculture is currently facing the challenge of meeting the growing demand for food in combination at a time of unstable environmental conditions. Farmers in developing countries in particular are struggling with low crop productivity and failure, as well as low incomes. Their often arid land requires special management of limited resources and the implementation of sustainable ways of farming. Innovative technology from Solarvibes, a German-based startup, improves transparency and data availability for farmers by using sensors to optimise the use of water, energy and fertiliser. The Agrimodule Smart System (ASS) consists of Agrimodule, Agri Sensors and Agripump; Agrimodule is powered by solar energy and controlled by AI software called Vibes Smart Crop Intelligence (VSCI). Solar-powered sensors in crop fields collect valuable data on temperature, humidity, levels of acidity, etc. This data can then be reviewed by farmers through an app and used to plan and adjust their irrigation, pesticide and fertiliser use. Solarvibes' sensor-based technology has the potential to increase productivity and food production through the optimised use of input factors.

Output/goals for improvement	**Underlying technologies**
Solar-powered internet-of-things (IoT) devices can provide AI-based solutions for precision farming, creating direct environmental benefits. The Agrimodule Smart System helps to reduce the use of energy, fertilisers, pesticides and water in arable farming through providing data from installed solar sensors on the fields. To power the sensors, solar energy is used, increasing flexibility and obviating the need for fossil-based energy. Furthermore, the company specifically wants to reach smallholder farmers with its technology, thus including the social dimension of sustainability.	• AI • Smart farming solutions. • Precision farming solutions. • Soil health analysis. • Crop health analysis. • Sensors: ▪ real-time transfer. • Software including: ▪ data analysis; ▪ cloud computing.
Data transformation level ↔ resource optimisation capability	**Requirements and preconditions**
Wisdom → predictive	• AgriModule combined with VSCI becomes a farmer's assistant: it helps farmers plan their entire cultivation process, operates the irrigation system automatically, introduces new efficient cultivation techniques, etc. • Requires the installation of sensors and farmers need a device to check the data through the app.

Other aspects
• Tests with AI and IoT to develop the app even further. • Maybe demands maintenance intervals depending on the sensitivity,
State of development
• Project-based development and demonstration to farmers in Eastern Europe, company founded in 2019. • Similar solutions: GG-Detector® by PREMOSYS GmbH, https://www.premosys.de and https://www.premosys.de/en/, developed on a project basis.
Sources
• https://www.solar-vibes.com/ • https://www.iof2020.eu/trials/arable/solar-powered-field-sensors • https://katanaproject.eu/katana-top-10/solarvibes/

5.3. Case analysis

In this brief summary, key findings when looking at the investigated cases from a higher perspective are presented In total, nine example cases in five application areas were investigated:

1. Lowering energy use/greenhouse gas emissions;
2. Water protection;
3. Improving resource efficiency – waste prevention, life prolongation and recycling;
4. Hazardous substances (substances of very high concern)/reduction of risks to health;
5. Land use/soil/food.

The cases show how the concept of Industry 4.0, including several sub-concepts and technologies, can be applied to real-world scenarios. Not all of the cases, however, are fully developed. The majority are rather in an experimental or prototyping phase which speaks to the relative newness of such approaches.

Overall, the cases provide insights into current possibilities in the field of manufacturing using a combination of digital solutions for sustainable production. The primary goals of the cases are largely related to economic factors such as efficiency improvement or new business models. They therefore address costs, efficiency and reliability, combined with ecological goals in terms of environmental impact reduction, such as the reduction of water and energy use, the minimisation of waste, and a reduction in carbon dioxide emissions. What all the cases have in common is the improved use of data. In all of them, the collected data represents the basis for resource optimisation capabilities and thus for optimisation in terms of sustainability. The value and purpose of the collected, integrated and analysed data is also emphasised in Figure 3.4.
It must not be underestimated, however, that the underlying hardware, such as sensors in machines and robots, is a prerequisite for data collection, integration, analysis and the application of the solutions. It serves as the fundamental connection between the physical and the digital world. This also applies in the reverse direction. The mere analysis of data in itself has no positive environmental impact, rather it is the feedback and application of the retrieved knowledge into physical action, for example, in manufacturing, which then has a direct impact on the environment and can generate added value in terms of sustainability.

What is also striking is that the requirements and preconditions for most of the examples include access to (high-quality) data, (big) data analytics as well as multi-stakeholder collaboration. Especially the first point, data access, is in many cases realised through the use of IoT technology and sensors. Implementing additional IoT technology, however, is not always sufficient which implies that already available data streams should be optimised in terms of information extraction/knowledge creation. This then represents the fundamental basis for further steps in the interplay of data transformation levels and resource optimisation capabilities (Figure 3.4). In this context, the majority of the examples aim to reach the wisdom-predictive level, which represents the second highest level of the pyramid shown in Figure 3.4.

In terms of geographic clustering, the analysis indicates a focus of such endeavors in Western and Northern Europe but does not provide an holistic picture of the whole of Europe and is not all encompassing; geographical coverage would need to be determined by a larger investigation. This may, however, be important, as it also relates to the digital readiness and adaptive capacity of European regions to adopt digital circular economy approaches and models. Hence, what is provided within this paper is a perspective on scaling future steps towards the combination of Industry 4.0 and reductions in environmental impacts.

Overall, while examples of digital applications in a circular economy exist, they were found neither to be abundant nor implemented at scale, specifically in non-waste management environments (for waste management applications see Berg et al. 2020). An ensuing question is then how far Industry 4.0 has already adopted the idea of contributing to a digitally enabled circular economy.

Key observations

- The examples provide insights into current possibilities in the field of manufacturing through a combination of digital solutions for sustainable production. The majority of the cases found tends to be at an experimental or prototyping phase, which speaks to the relative newness of such approaches.
- What the examples have in common is the improved use of data. The data collected provides the basis for resource optimisation capabilities and thus for optimisation in terms of sustainability.
- In terms of geographic clustering, the analysis indicates a focus of such endeavors in Western and Northern Europe but does not provide an holistic picture of the whole of Europe and is not all encompassing; geographical coverage would need to be determined by a larger investigation.

This may, however, be important as it also relates to the digital readiness and adaptive capacity of European regions to adopt digital circular economy approaches and models.

6 Current development of Industry 4.0 with regard to circular economy and the reduction of environmental impacts

Given the identified potential benefits and the fact that digital industrial transformation is continuing, a matter to be analysed is the current relationship between Industry 4.0, the circular economy and the reduction of environmental impacts on a larger scale. Looking beyond the examples found and presented in Chapter 5, the question arises as to whether Industry 4.0 is in general currently agnostic to, in favour of or antagonistic to the transition to a circular economy and a reduction in environmental impacts.

To shed light on that question, recent literature concerning Industry 4.0 and its relationship to the circular economy was reviewed. In a recent systematic literature review, Rosa et al. (2020) have examined this relationship in a review that considered around 150 publications. Most of these were published in the previous two years, showing a sharp increase in interest in the topic. The authors found that the most common perspective taken was to describe digitalisation in the circular economy and to view it as a way of implementing circular business models. No particular technology was found to be prevalent in the publications under consideration. Rosa et al. show that even though the topic receives much attention, most of the work was done on a theoretical or case study basis.

A similar literature review by Felsenberger and Reiner (2020), which considered a set of 89 papers published between 2010 and 2020. They focus on sustainability in production and operations management in an Industry 4.0 context. Also, in this literature review, most articles referred to conceptual or case study-oriented research.

Even more recently, Romero et al. (2021) performed a similar review on the synergies between Industry 4.0 and the circular economy and identified and analysed 41 papers published in between 2018 and 2020. They concluded that very few of these studies discussing a transition towards a circular economy supported by Industry 4.0 address the impacts on individuals and society.

The picture that emerges from peer-reviewed literature is therefore that many innovative concepts have been proposed on how production could be geared towards more sustainability using Industry 4.0 technologies and concepts. Case studies and pioneering companies have and continue to put these concepts into practice, but widespread adoption throughout entire industries is yet to be achieved at scale.

Box 6.1 Towards sustainable maintenance 4.0

To provide a more detailed literature review of current synergies between circular economy and industry 4.0, Franciosi et al. (2018) carried out an exercise in the field of maintenance for sustainability in the Industry 4.0 context, analysing 68 papers. As highlighted in the case studies (Section 5.2), thanks to the generation of real-time information and data analytics capabilities, maintenance activities of manufacturing equipment are currently evolving from the reactive to preventive approaches. Their study describes future challenges and research opportunities for increasing synergies between maintenance, including Industry 4.0 and sustainability.

Maintenance activities are currently mainly integrated in conventional key performance indicators such as productivity, reliability and asset availability. Only a few studies evaluate the integration of sustainable indicators in maintenance approaches.

For that, further research is also needed in a better understanding of not only economic maintenance-related impacts but also environmental and social ones. According to Franciosi et al., economic impacts such as costs, downtime, breakdowns, waste, low performance, waiting time, defects, extra inventory, or additional transportation are indeed well investigated. However, environmental impacts associated with maintenance practices of manufacturing equipment, such as hazardous emissions, production waste due to malfunctions, inefficient energy use, ineffective resource consumption and waste of stored material, have neither been adequately researched nor implemented. The same logic applies to the social impact of maintenance that could cause unsafe and unhealthy working conditions and accidents.

Aiming at more efficient and reliable operations, the role of maintenance in improving the sustainability of manufacturing activities has recently received some attention, nonetheless Franciosi et al. indicate that this field remains under research and that a clear and commonly agreed definition of sustainable maintenance would be beneficial.

From these insights, it appears that scientific and political actors see sustainability as a major driver of research into Industry 4.0 (BMBF, 2021; Fraunhofer IFF, 2021). To gain further insights and see if this was reflected among those who have applied Industry 4.0, desktop research was extended and non-peer reviewed studies solely dedicated to Industry 4.0 included.

Among this group, the claim does rarely seem to materialise but rather the impression emerges of technological development being the main focus. In six out of nine mainly German studies dedicated to Industry 4.0, neither sustainability nor the circular economy was addressed (Table 6.1). The remaining studies briefly touched on the topics: Reinheimer (2017) sees sustainability as a customer expectation for Industry 4.0, while Vogel-Heuser et al. (2017d) mention Industry 4.0 as an enabler of an energy and material transition.

Thus, this report finds an uneven picture. It appears that for the circular economy community and from a sustainability perspective, Industry 4.0 is seen as an important development, which is able to work as a game changer in bringing circularity to scale. For the Industry 4.0 community, however, sustainability or circularity does not seem to play a major role yet (Derigent et al., 2020). At a large scale, it can currently be seen as somewhat agnostic to circularity, with consciousness of its future role and potential only just emerging.

Table 6.1 Overview of Industry 4.0 studies and inclusion of sustainability and circularity

Source	Sustainability	Circularity
Industrie 4.0 (Reinheimer, 2017)	Is mentioned at one point as user expectancy but not further elaborated.	Circularity is not addressed.
Industry 4.0 (Gilchrist, 2016)	Sustainability is not addressed.	Circularity is not addressed.
Von der Industrie 4.0 zum Geschäftsmodell 4.0: Chancen der digitalen Transformation (Ematinger, 2018)	Sustainability is not addressed.	Circularity is not addressed.
Industrie 4.0 kompakt – Wie Technologien unsere Wirtschaft und unsere Unternehmen verändern (Huber, 2018)	Sustainability is not addressed.	Circularity is not addressed.
Handbuch Industrie 4.0 Bd.1-4 (Vogel-Heuser et al., 2017a, 2017b, 2017c, 2017d)	The need to change production factors is emphasised. Digital technologies are seen as enablers of an energy and material transition (Bd. 4, p. 7 f.). Ecological and social opportunities are briefly discussed (Bd. 4, p.240).	Mentioned (Bd. 4, p.7 f.).
Zukunft der Arbeit in Industrie 4.0 (Botthof and Hartmann, 2015)	Sustainability is not addressed,	Circularity is not addressed.
Industrie 4.0 – Hype oder Revolution? (Roth, 2016)	Sustainability is not addressed,	Circularity is not addressed.
Industrie 4.0: Wie cyber-physische Systeme die Arbeitswelt verändern (Andelfinger and Hänisch, 2017)	Sustainability is not addressed,	Circularity is not addressed,
Leitbild Industrie 4.0 2030 - Digitale Ökosysteme global gestalten. (BMWI, 2019)	Sustainablity is addressed regarding climate protection, and education, while social participation is briefly addressed.	Circularity is not addressed.

To shed more light on this discrepancy, especially from the technological viewpoint, interviews with five experts from the Industry 4.0 community were conducted. The following key points emerged from the conversations.

The experts stated that at present financial aspects are prioritised in ongoing measures and projects. Hence, the primary incentives in Industry 4.0 schemes are, according to the experts, still performance targets and competitive advantage rather than environmental goals. In contrast to the past, however, some companies have identified the lack of environmental aspects in Industry 4.0 concepts, and environmental consciousness is emerging. In one of the conducted interviews, the internal development of a digital twin concept for a zero-impact factory clearly resulted from customer demand.

Regarding the chances and opportunities of Industry 4.0, the experts confirmed the assumptions of an increasing potential for circularity by the application of digital technologies (Chapter 3). They identified, for instance, the potential for new business models, such as the so-called everything-as-a-service business model. Besides that, they also saw opportunities for circular products and process design, which can be created in a more agile and flexible way using Industry 4.0. As an example, data analysis was suggested as a way of developing a better understanding of the customers' needs. In this context, flexible quantity determination was mentioned the aim of which is to produce only as much as the respective customer actually needs, and thus to proactively counteract overproduction and work towards resource efficiency.

Another potential the experts highlighted was increased transparency throughout the entire supply chain. Based on better information from all the stakeholders involved, which can be realised through technologies such as digital twins, AI and real-time applications, the experts believed that optimisation in terms of both costs and sustainability could be achieved.

With regard to a reduction of environmental impacts through Industry 4.0, the experts identified a reduction of greenhouse gas emissions as a focus of economic actors. This, in turn, was associated with the Industry 4.0-enabled orchestration of circular flows of goods. Moreover, by enabling processes to be precisely coordinated within the framework of Industry 4.0, resources can be saved, processes optimised, and thus resource effectiveness increased.

In order to promote the prospects of circularity and impact reduction through Industry 4.0, the experts called for a proactive creation of more awareness for such goals in connection with Industry 4.0 in companies, especially for SMEs. In this regard, SMEs and suppliers were characterised by the interviewed experts as being less proactive and less able to carve out their own strategies in these matters but were rather forced to adapt by their customers and (planned) regulations.

Another point, stated by some of the experts, is the need to find a balance between regulations and rewards. All interviewees agreed that incentives were more favourable for a transition than regulations, as the latter are seen as a form of punishment.

When talking with the experts about easily achievable goals in terms of harnessing Industry 4.0 to create a circular economy and support a reduction of environmental impacts, the experts mentioned the car and automotive industry as one of the most progressive sectors. They see a high awareness for circularity in this industry regarding the flows of goods and materials as well as well-established Industry 4.0 processes and technologies. To them, the automotive industry thus seems to be an industry with very good starting conditions for realising circularity using Industry 4.0. The packaging and aerospace industries were also mentioned as further suitable industries because of circular economy strategies in the supply streams and flows of goods that have already been implemented.

An ensuing question is then if the trajectories of Industry 4.0 and the circular economy do not align yet, what is necessary for replicating and upscaling the use of circular economy positive Industry 4.0 as presented in the previous chapters and cases for environmental protection? Chapter 7 analyses this question.

7 Enabling conditions for and current barriers to a digitally-facilitated circular economy

The conditions that need to be created for Industry 4.0 to enable a circular economy and reduce negative environmental impacts are discussed in the following sections. Indeed, certain conditions must be in place for Industry 4.0 to reach its full potential to support a circular economy and the reduction of environmental impacts, as shown in Chapter 4. *Inter alia*, this means that the core technologies must reach a sufficient level of technological readiness, infrastructure such as broadband access is in place, knowledge of how to apply these technologies is present in companies and authorities, the economic viability of circular approaches with Industry 4.0 has been demonstrated and that the necessary regulations, for example for safe data use and exchange, have been implemented. For a better overview, enabling conditions and current barriers have been subdivided into the following dimensions:

1. culture and mindset;
2. technological requirements;
3. dedicated infrastructure;
4. economic viability and market enablement;
5. regulatory environment.

All these dimensions influence one another. Economic viability, for example, can only be achieved when certain technological requirements have been met and the required infrastructure is available. The following paragraphs discuss and analyse the necessary enabling conditions within these dimensions together with the circumstances that are currently obstructing the application of Industry 4.0 technologies that are beneficial to a circular economy and hence must be removed or fundamentally changed. Implications resulting from these findings are then discussed in Chapter 8.

7.1. Culture and mindset

Among the most important prerequisites for the envisioned realisation of a circular economy by the use of Industry 4.0 technologies are the cultural and intellectual factors that form not only the basis for such a combined view but also for the required practices such as a willingness for an encompassing exchange of data within supply chains and networks. A widely adopted data culture and openness to change are thus among the primary needs for this twin transformation of industries.

7.1.1 Enablers

Overarching data culture
A culture of willingness to create and transfer data across the value chain has to be established throughout the entire value network. In the first place this will require many companies to embrace the opportunities and use data in a new way. While the data economy has already been established in some industries and companies, it is far from being the case everywhere. The 2021 EEA briefing on digitalisation and waste management[3], for instance, discussed the clear heterogeneity in penetration across Europe within this specific sector.

Furthermore, widespread data collection, use and transfer are required to seize opportunities for circular economy enablement (Chapter 3) and hence identify where reductions of negative impacts to the environment can be expected. This does not only encompass data about emissions but also all data points on composition, use and abuse that are needed for high value recycling, predictive maintenance and other circular approaches. While the data collected can sometimes be used in the same company that is measuring it, in many cases the benefit from the extracted data will manifest in later stages of the value chain or in reverse logistics. It is therefore fundamental that the data culture includes a willingness for

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[3] https://www.eea.europa.eu/themes/waste/waste-management/digital-technologies-will-deliver-more

different actors along the entire value chain to share and use data. This implies a need for more openness and less secrecy in data use by companies.

Openness to change

The implementation of digital technologies is often accompanied by a profound change in workflows and established procedures in the production process. The willingness to orchestrate, manage and communicate these changes must be present in managing functions on one hand. On the other, the workforce putting these changes in place must accept and embrace the process.

Appropriateness of efforts

The digital technologies and principles used have to fit the goals being pursued. In terms of circular economy, this requires a mindset of task orientation towards combined economic and ecological improvements. As shown earlier in this study, overengineering or exaggerating the use of digital technologies can lead to harmful effects, in the form of rebounds, for example, or making the environmentally wrong things more efficient. Hence, an approach that sees Industry 4.0 as a means of improving circularity and not as an end in itself, is an important key.

7.1.2 Current barriers

One of the important barriers is a lack of enthusiasm for the circular economy and state-of-the-art digital technologies within companies and especially within SMEs (Stentoft et al., 2020), which could be due to a lack of knowledge about the potential benefits. The experts claimed that at present many manufacturing companies lack both the interest and knowledge to invest into circular economy enhancing technologies and that the ensuing opportunities, such as new business models, are yet to be seen. As a result, investment in the circular economy or impact reduction currently does not appeal to many decision makers and investors when considering investment in Industry 4.0 technologies. From a sustainability perspective, however, this is critical, since Industry 4.0 applications can also lead to adverse effects if sustainability goals are not pursued and thus not sufficiently investigated. An interview also revealed that another a current barrier is the difficulty in convincing large companies' key decision-makers. This difficulty comes from the complexity of the concepts such as digital twins, that need to become intelligible to high-level key decision-makers. Only then will the development of top-down approaches – developing digital twins, having environmental impact reduction of a product/service/factory (among others) at the core of their implementation objectives – become feasible.

With regard to the need for a new data culture, owners at present often do not want to share their data because of strategic considerations, such as intellectual property (IP) protection. According to the interviewed experts, this phenomenon is currently seen as a major challenge in the car and automotive industry. This was mentioned to be the case in the Catena-X project (International Data Spaces Association, 2021), which aims to enable a cross-company data exchange between all involved actors in the automotive value chain.

7.2. Technological requirements

This section addresses enabling factors that affect the technological basis for impact reduction by Industry 4.0 technologies.

7.2.1 Enablers

Access to data

Section 4.1 showed that, to work effectively and at scale, circular economy strategies would benefit from more and larger amounts of information than are available today. Provision of such data is hence one of the most important requirements.

Availability and utilisation of suitable digital technologies
The Industry 4.0 concept and the affiliated processes of data collection, integration, analytics and sharing require a dedicated set of technologies such as sensoring, IoT, analytical tools such as AI, etc. In many cases these technologies need to be combined into dedicated systems to create and transfer information across the supply chain. These technologies need to be available to companies, and the companies need to be able to properly implement and use them.

Common standards and data format
For the implementation of a digitalised circular economy, different stakeholders along the value chain and different software need to work together. To ensure that data can be exchanged between these entities, a standardised data format as well as standardized interfaces are mandatory. The feasibility of such standardisation has been shown in other digital areas, such as Extensible Markup Language (XML) or Portable Network Graphics (PNG). Standards also need to be dynamic to be quickly adaptable and downward compatible, or flexible to cater for changing requirements from innovation.

A safe circular data space
A secure exchange of data and data privacy are fundamental and underlying concepts for data handling in the digital circular economy. Data must somehow therefore be stored safely but, to various extents, needs also to be accessible to different participating actors at the same time. Data needs to be restricted to those actors that are entitled to modify or only read it. Who will implement such a dataspace and how it will be work has yet to be resolved, but it is undisputed that some kind of dataspace or data specification needs to be in place before many digital circular business models can work at scale. The European GAIA-X project or the International Data Spaces (IDS) are trying to implement such a concept (Federal Ministry for Economic Affairs and Energy, 2021; International Data Spaces Association, no date).

Ability to quantify environmental impacts and integrate these parameters in decision-making processes
To judge which technologies should be developed further or promoted with the aim of reducing environmental impacts, the ability to quantify their contribution is required. Some research has been devoted to this but application and integration to actual industrial cases is still rare (Box 4.1). Developing this ability would lay the foundation for fact-based quantifiable promotion of the relevant Industry 4.0 technologies and thus enable a digitalised circular economy.

7.2.2 Barriers

To access the required Industry 4.0 data, in terms of analyses for the circular economy, the following barriers occur.

Lack of data acquisition
At present, data collection capabilities within manufacturing companies are underdeveloped compared to what is possible (Pagoropoulos et al., 2017). Technologically, this concerns all types of sensor technology in the production process and the use of products and materials, as well as the currently limited possibility of data exchange by the (manufacturing) machines themselves. Some data necessary for the implementation of circular economy strategies are already generated by production machines while they are in use, but this data is often not accessible or usable in a form that can be analysed or made available to other members of the product value chain. According to one of the experts interviewed, the following reasons apply: for some machines, the manufacturers have not implemented the capability of downloading data or only use a restricted set of data. In other machines, this capability can be made available for a fee by an upgrade, by different firmware, or by just unlocking the respective capability. In other cases, data is accessible but confined to a proprietary software suite or only exportable with a lot of effort. Figure 7.1 shows different levels of data availability in and across companies.

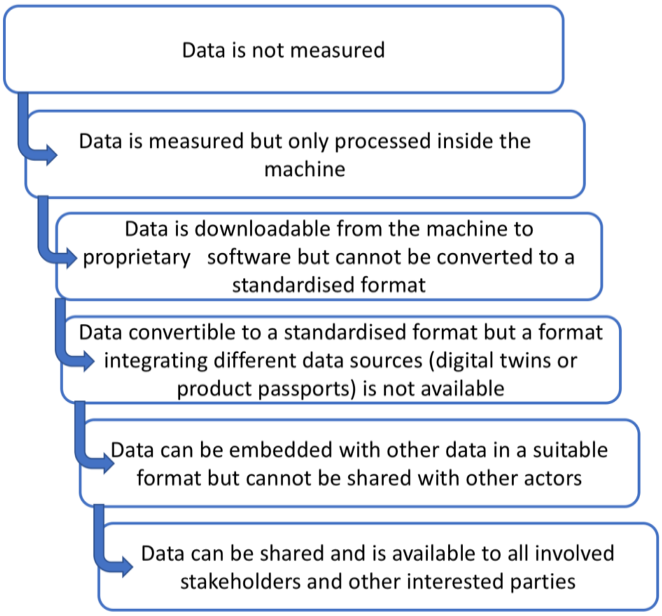

Figure 7.1 Levels of data availability.

Lack of data quality
A circular economy can only be established in a meaningful way if the required data are collected correctly and the extracted information is provided in time. This is not guaranteed today. Next to the lack of technology, companies can be unable to provide the data required due to a lack of capability and knowledge. This barrier can be particularly prevalent in SMEs, where, according to one of the experts interviewed, a lack of digital know-how and organisational resources can lead to incorrect entries if data are entered manually.

Lack of technological ubiquity
Fully digital approaches to concepts such as the digital product passport require a widespread use of Industry 4.0 technologies, for example, to avoid error-prone discontinuities in data transmission. Ideally, from a data analytics perspective, data collection and transfer should be automated at the highest possible level. This is currently not the case, however, as neither within Europe nor within non-European countries is every company equipped with sufficient data collection capabilities. Furthermore, it is difficult, if not impossible, to define what an adequate level of data collection is and will be in the future; this will rather be a dynamic development.

Lack of data storage
Today, storing large amounts of data (i.e. Big Data), such as (IoT) data from supply chains, products, materials, machines and the production processes themselves, is still quite expensive (Agrawal and Nyamful, 2016). Even more important from a sustainability perspective, however, is the enormous amount of resources and energy needed to realise the transfer, storage and the further processing of Big Data. In this regard, different approaches are currently under discussion, such as the debate about centralised versus decentralised data handling (Salman et al., 2015).

Lack of data analytics
Another barrier to the actual implementation of combining Industry 4.0 with circular economy principles is the lack of solutions for the application of data analytics (i.e. Big Data Analytics) (Oliveira and Afonso, 2019; Pagoropoulos et al., 2017). Especially with regard to heterogeneous data, which is often the case when trying to analyse data from supply chains, it is still quite difficult to analyse this in an energy or resource efficient way (Kadadi et al., 2014) and currently, dedicated expert knowledge is required.

7.3. Dedicated infrastructure

Digital technologies can only work in the presence of infrastructure as characterised in the following paragraphs. In addition to such direct requirements, it is undisputed that an electrical power supply based on renewables, and production based on recycled or renewable raw materials are important requirements for a sustainable IT infrastructure.

7.3.1 Enablers

Connectivity

Many circular economy enabling Industry 4.0 solutions such as the digital twin concept or digital product passports rely on connectivity throughout a whole production process, between different production sites or even throughout an entire value chain. This connectivity needs to be established in advance and the necessary investment needs to be made by companies themselves or, for overarching infrastructure, by public actors or telecommunication companies. Connectivity solutions take various forms for different technologies and can range from low-bandwidth, low-range, one-way communications such as RFID, to high-bandwidth long-range systems including satellite-based communication.

IT Infrastructure

Industry 4.0 technologies are not confined to one single machine but are integrated in a digital ecosystem. This ecosystem must be provided at a company level at the production site and beyond. One important step here is the connectivity mentioned above, but other aspects are mandatory as well. Network infrastructure with servers, secure communication channels, data storage, backup-capabilities, firewalls, power and cooling must all be in place. This requires a financial commitment for investment and a maintenance budget. A workforce with the capability of maintaining and continuously upgrading the system must be present in the IT department. Employees using and applying these technologies must be trained accordingly.

7.3.2 Barriers

As of now, the *status quo* in this area is still characterised by some barriers that need to be overcome.

Lack of a dedicated data storage infrastructure

Currently, there is no standardised and scalable infrastructure to store and provide Big Data, extracted from different data sources, safely and securely. It has already been mentioned that activities like GAIA-X and International Data Spaces (IDS) provide ideas for future approaches for this purpose. It seems, however, that these projects and activities are yet to be fully established. Additionally, projects such as GAIA-X include goals in terms of manufacturing, but the circular economy has neither been prioritised nor is a fundamental part of the project so far. This impression has been confirmed by several interviewed experts from industry and science.

Inertia of instalment

With regard to the need for dynamic technological standards, it must be considered that, besides their conceptualisation, their implementation takes a lot of time. According to the interviewed experts, the organisational capabilities, including values and knowledge, and hence adaptive capacities, will play a central role.

Status of communication networks

The technologies required for Industry 4.0 demand high bandwidth over landline and mobile networks. Currently, this is not available everywhere in Europe and is unevenly distributed within European nations (Cable.co.uk and M-Lab, 2020).

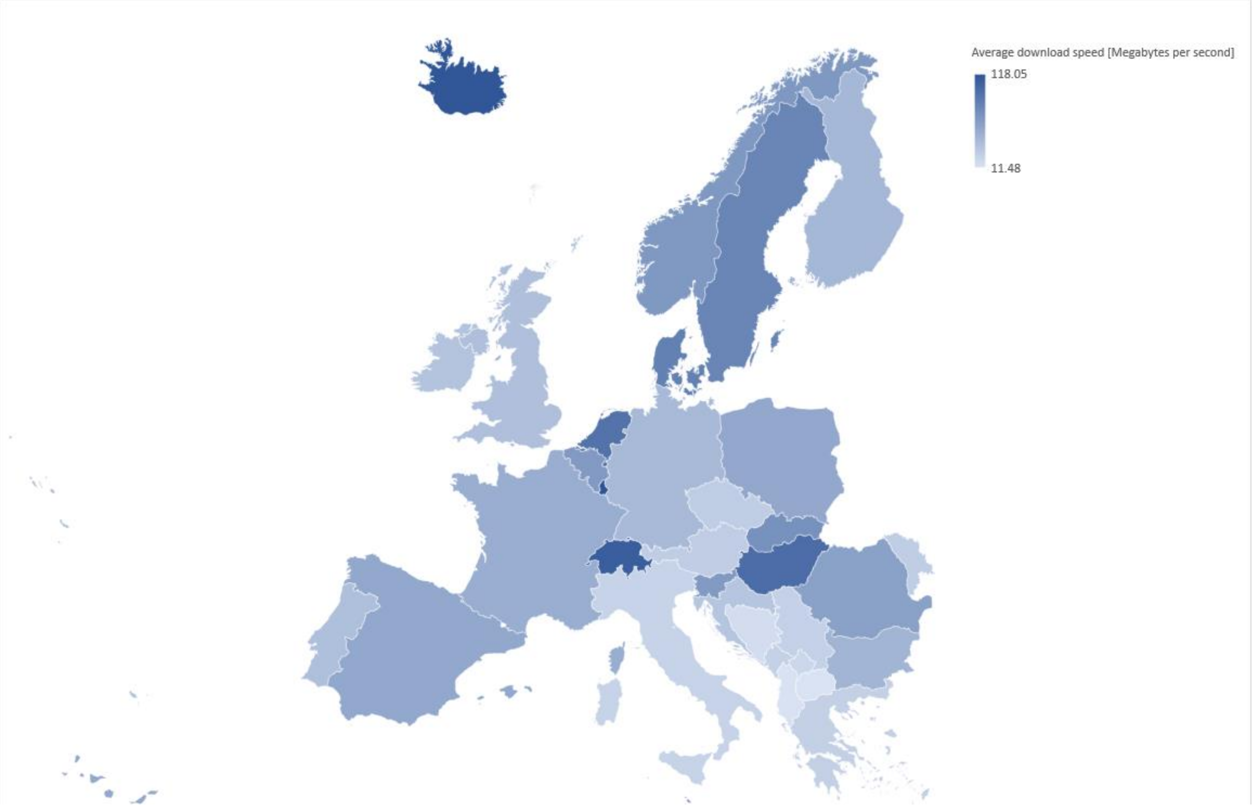

Figure 7.2 Average download speed in European countries, 2020.
Source: Cable.co.uk and M-Lab (2020).

7.4. Economic factors and market enablement

The introduction of Industry 4.0 technologies represents a major investment for many companies. Hence, clear perspectives for a positive return on that investment are required. In connection with circular economy, this implies the clear existence of and knowledge about successful business models and markets. While scaling up the circular economy will profit highly from Industry 4.0 in many ways, it is also a prerequisite for large scale circular economy markets to come into existence.

7.4.1 Enablers

Given the large data needs of circular economy business models, the introduction of business and consumer-oriented information schemes linked to digital twins and digital product passports are potential enablers for business creation and convincing consumers to participate in circular economy schemes such as reuse or remanufacturing.

7.4.2 Barriers

As far as current barriers are concerned, the introduction of digital technologies for a circular economy is a double challenge for many companies, since the principles of both fields are not ubiquitously understood by companies and their combined payoff is not clear.

Moreover, our present economy does not endorse data sharing. Companies perceive protection of their data to be directly associated with protecting their competitive advantage. Consequently, as confirmed by several of the experts interviewed, most companies refrain from sharing their data.

7.5. Regulatory environment

7.5.1 Enablers

Regulations are part of the enabling environment in different ways. Regarding the data requirements of a circular economy, rules need to demand, support and regulate data provision and exchange while managing a potential trade-off between these requirements and data protection (GDPR) as well as IP/know-how protection. The EU's plans for digital product passports lead in this direction but are as of now unspecified. Just as well, new transparency rules that demand higher levels of end-consumer information on the environment will be needed. Such data can in turn be a key-enabling factor in making further regulation of the circular economy more informed and therefore more effective. Norms that provide the infrastructural and technological standards for data creation and transfer are also important enablers.

7.5.2 Barriers

Current inhibitors in this area concern, *inter alia*, data protection issues and the current ability of companies to provide valid information required even by present regulations.

Data protection

Current regulations addressing data privacy, including the usage and forwarding of data, such as GDPR, can hinder effective data handling and data usage. Regulation needs to manage the trade-offs between legitimate data privacy, protection interests and required information sharing. According to the experts interviewed, this challenge is being faced in Germany in particular, as data privacy and data security concerns are especially prominent compared to other countries. Until now, no common and overarching solution has been found for this challenge.

Lack of systematic circular economy-dedicated rules for data provision

Manufacturing companies at present need to fill in a host of databases such as SCIP, EPREL, or REACH ([4]) related databases. Regulation for a single point of truth, where (raw) data has to be stored and then provided for specific applications is still lacking. Such an approach, however, could make the supply of data and its dedicated use for different means simpler.

Lack of compliance due to data provision capabilities

The provision of data or information can be challenging and costly. Companies at present may be unable to provide correct and realistic data. With regards to the latter point, experts mentioned that, particularly in companies with long standing product lines, the information required is often hard to obtain or reconstruct, so that, for example, carbon dioxide declarations can resemble educated guesses rather than hard facts.

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[4] SCIP - Substances of Concern In articles as such or in complex objects (Products), EPREL - European Registry for Energy Labelling, REACH - Registration, Evaluation, Authorisation and Restriction of Chemicals

8 Implications

8.1. A convergence between industrial, digital and environmental European strategies is more necessary than ever

As introduced in Chapter 1, in March 2020 the European Commission released the New Circular Economy Action Plan together with a new Industrial Strategy for Europe for reaching EU Green Deal objectives. This industrial strategy laid the foundations for an industrial policy that will support the green and digital transitions, make EU industry more competitive globally and enhance Europe's strategic autonomy. As part of this strategy, the role of industry in building up a more circular economy and reaching climate objectives was clearly highlighted. Reaffirming the priorities set in March 2020, on 5 May 2021, the Commission released an updated industrial strategy responding to the lessons learned from the COVID-19 crisis, to boost recovery and enhance the EU's strategic autonomy (European Commission, 2021c).

Analysing the impacts of the COVID-19 crisis on the European economy, the EC explains that "*digital and green business models and technologies placed companies that had already embraced this transition at an advantage compared to those that had not and companies that drive the change will continue to enjoy a crucial first-mover advantage*" (European Commission, 2021c). This conclusion supports the ones from a survey conducted by VITO together with Circular Flanders (Vrancken, 2020). This survey explored the resilience to the impact of the COVID crisis of 540 participants from companies, government and non-profit organisations. The results showed that the companies that applied circular principles were less impacted by the COVID crisis. All linear companies reported shortages, while for circular companies, only one-third experienced problems. They suffered less from shortages in raw materials, parts, stocks and demand from customers as compared to linear businesses (Vrancken, 2020).

Still according to the EC, the COVID-19 pandemic has radically changed the role and perception of digitalisation in society and the economy and accelerated its progress. Digital transformation of businesses is therefore one of the four vital points of the European Digital Compass. This is a vision setting the EC's digital ambitions for 2030, establishing a monitoring system, outlining key milestones and the means of achieving these ambitions (European Commission, 2021a). As part of this, the EC has outlined new measures not only to support but accelerate the business case for the green and digital transitions.

- "*Co-creating transition pathways in partnership with industry, public authorities, social partners and other stakeholders, where needed, starting with tourism and energy intensive industries. Such pathways could offer a better bottom-up understanding of the scale, cost and conditions of the required action to accompany the twin transitions for the most relevant ecosystems leading to an actionable plan in favour of sustainable competitiveness.*
- *"Providing a coherent regulatory framework to achieve the objectives of Europe's Digital Decade and the Fit for 55 ambitions, including by accelerating the rollout of renewable energy sources and by ensuring access to abundant, affordable and decarbonised electricity.*
- *"Providing SMEs with sustainability advisors and supporting data-driven business models to make the most out of the green and digital transitions."*

The following two sections provide the implications of the concrete steps required to scale-up the adoption of the circular economy and impact reduction by the application of Industry 4.0 concepts and technologies. Section 8.2 focuses on the systemic level and Section 8.3 on the company level.

8.2. Implications of guiding the future development of a digitally enabled circular economy and impact reduction

Using a European system perspective, this chapter highlights what action and conditions are needed to implement digitalisation in (manufacturing) industry to support the circular economy objectives, with a special focus on reducing environmental impacts – targeting resource efficiency, waste prevention/reduced waste, repair, recycling, etc. Also, key actors are mentioned if they can be identified.

Creation of a common language between circular economy and industry 4.0 communities As discussed in previous chapters, based on literature reviews and stakeholder interviews, Industry 4.0 can in many cases be considered agnostic to the transition to a circular economy, thus typically, environmental impact reduction has, so far, not been the main driver of the development of Industry 4.0, but rather a side effect from improved resource and energy efficiency. To prevent negative effects, including rebound effects and the increasing use of resources, and ensure a positive net effect of the digitalisation of manufacturing industry, a co-evolution of the circular economy and Industry 4.0 is needed for both concepts to work seamlessly together. Thus, a dialogue between the circular economy and the Industry 4.0 communities needs to be established urgently to ensure an effective co-evolution of industrial sustainability and digitalisation. Creation of a common language, ensuring an effective collaboration between these two communities, will be essential. Relying on the development of frameworks, such as the one presented in Figure 3.4, the circular economy community needs to further raise awareness among the Industry 4.0 community about the potential of their technologies in reducing the environmental impacts of production activities. Illustrating this increasing awareness among the Industry 4.0 community and the necessary cross-sectoral dialogue, executive leaders from 26 ICT companies gathered under the European Green Digital Coalition on 19 March 2021 and released a declaration in which they committed to supporting the Green and Digital Transformation of the EU (European Commission, 2021).

Guiding an informed sector-based integration of the twin transition
As reflected with selected case studies (Chapter 5), the twin transition and its implications for integration need to be tailored to challenges faced by each specific industrial sector and ecosystem. To achieve climate neutrality, innovation and rethinking production processes in European energy-intensive industries is essential. Several sectors have already initiated their transformation, using digital technologies to increase their production efficiency and reduce emissions. To ensure the co-creation of sustainable technological transformation pathways, it is now essential to capture existing environmental benefits of implemented solutions (see, for example, the case study on digital twins in manufacturing and production planning in the steel industry in Chapter 5) and then further deploying and scaling their adoption. The successful implementation and uptake of the key action entitled Co-creation of green and digital transition pathways for relevant ecosystems, starting with the tourism and energy intensive industries, proposed in the updated Industrial Strategy can play an enabling role here. In support of this twin transition, the EC has already conducted an illustrative analysis of challenges and opportunities for a competitive and clean European steel industry (EC, 2021b) and explained that the industry-led European Green Digital Coalition will measure the impact and accelerate the deployment of digital solutions, such as digital twins, to additional key green sectors.

Enabling collaborative research and innovation to create a low-impact digital system
To cater for an Industry 4.0 environment that not only enables the circular economy, but also has low environmental impacts, research and development investment in increasing the technology readiness levels of low-impact digital technologies will be essential. Highlighting these needs, a strategic research and innovation agenda for the circular economy has recently been published in the framework of the Horizon 2020 project CICERONE. This agenda puts digital technologies at the core of many key innovation fields, including waste management, industrial symbiosis and product traceability (CICERONE H2020, 2020).

Still at a European level, the EU Budget and NextGenerationEU, particularly the Recovery and Resilience Facility, can support this twin transition. The EC:

- is currently assessing Member States’ national recovery and resilience plans to ensure that at least 37 per cent of its funding will be dedicated to green investment and at least 20 per cent to digitalisation. Furthermore, this updated Strategy suggests that the 2021–2027 cohesion policy funds will have a strong focus on this twin transition.

- will ensure that the next generation of the European innovation ecosystem, particularly the Horizon Europe Programme, will bring private and public funding together to finance research and innovation on low-carbon technology and processes (EC, 2021c).

Ensuring data accessibility and interoperability in common European data spaces

To secure the accessibility of data, open standards have to be developed and propagated. The German Advisory Council on Global Change (WBGU – German Advisory Council on Global Change, 2019), for example, highlights that in the digital age, there is an enormous increase in digitised data and information and knowledge based on this data. It is therefore important to regulate the accessibility to data, which might vary with regard to different stakeholder groups and also the management of the data (for example, the exploitation rights of different stakeholder groups) and how to secure the data. Currently, the digital ecosystems and the IoT are based on the use of different standards for data management – for example, municipalities, municipal companies and end-users often rely on different systems. The promotion of decentralised data infrastructures and data accounts that are based on open architectures, such as open standards, open formats, open interfaces and wherever possible open source, can help overcome these problems.

Today, large amounts of data are often collected and stored by industrial actors without knowing how to use them. This shows that there is an urgent need for an efficient data culture, which in turn is based on the principle of data frugality – only collecting and storing necessary data. Otherwise, the extensive collection, extraction and storage of manufacturing data will lead to wasting capacities and resources. Additionally, even if the issues regarding data access are overcome and the data necessary for sustainability analyses collected and extracted, it is still quite expensive to store such large amounts in a way that is resource efficient and secure (Khan et al., 2017, p. 2).

The digital exchange of information will be more frequent and versatile in a digital circular economy. Indeed, it will be required to foster its emergence. Current legislation, however, may obstruct this. A careful balance between improving information exchange and preventing the emergence of cartels will be required. Reconsidering competition legislation will be necessary, as it might hinder collaboration and understanding of circular design, product development and reverse infrastructure due to possible cartel formation concerns (Rizos et al., 2016).

The introduction of an overarching database as a single point of truth instead of many distinct databases such as SCIP and EPREL should be considered. Such databases are often costly and cumbersome to administer by the companies obliged to participate. Such a system can work on Industry 4.0 principles in combination with digital product passports. In particular, automatic data entry should be investigated as it might both simplify data uptake and support data correctness and validation.

Existing economic instruments could benefit the deployment of such overarching databases. For example, extended product responsibility (EPR) establishes some obligations for producers to carry some end-of-life costs, stimulates action for improving product recyclability and reusability, reduces material usage and downsizes products, and engages producers in a host of other so-called design-for-environment (DfE) activities. As the obligation to be part of an EPR system for certain products, such as electronic equipment, requires a certain market volume, not all producers are part of such a system (not registered) but are so called free-riders. An advantage in case of a single electronic register of producers could be that it could also allow for reporting by non-registered producers. Information sharing along the value chain and especially between manufacturers and recyclers or re-manufacturers particularly needs to be enabled. Furthermore, it is argued that digital solutions, such as blockchain technologies or smart contracts, could promote further development (Liu et al., 2019; OECD, 2018).

Guiding the transition to a sustainable ICT sector

As discussed in Section 3.3, the digitalisation of manufacturing industry has its own and considerable environmental risks. Europe needs a digital sector that focuses on sustainability. Measures to improve energy efficiency and the closed-loop orientation of the ICT sector need to be advanced and promoted. Here, the further development of the existing Ecodesign Directive is proposed to form an important basis for the specific implementation of these initiatives. It is also emphasised that the existing regulatory frameworks and especially the Ecodesign Directive should be used and further developed to manage both transitions together – digitalisation and the development of digital tools for a circular economy, which may help improve the use of natural resources, design, production, consumption, reuse, repair, remanufacturing, recycling and waste management. (Liu et al., 2019). As a concrete illustration, the data centre industry has grown rapidly and generates a large volume of e-waste. Unfortunately, the infrastructure for dealing with this waste is currently underdeveloped. It is essential that this waste generation issue is tackled now and any further harmful effects are prevented. It is important for this industry to be guided and increase its systemic integration of sustainability considerations from the design phase onwards. Extending product lifetimes and enabling their refurbishment are, for instance, key aspects.

While existing sustainability action in the ICT and digital industries are mainly driven by energy efficiency and reduction of greenhouse gas emissions, the availability of (critical raw) materials will become an issue in the near future. The security of supply is already on the European agenda and besides re-mining in Europe, it urges an increase in the recovery of materials from the urban mine. The key bottleneck is the concentration and collection of widely dispersed electronic materials for the available recycling plants (Berg et al., 2020). The EU-funded ProSUM project has identified 49 chemical elements present in waste electrical and electronic equipment (WEEE), many of which could potentially be recycled for use in other products. The EC has listed 18 of those 49 elements as critical raw materials, that is economically important materials with a high supply risk (H2020 ProSUM, 2021).

As part of the Sustainable Product Initiative described in the CEAP and in line with the Ecodesign Directive for imposing design requirements, the Circular Electronics Initiative will be implemented in 2021. While minimum design requirements for phones, laptops and tablets will be established, a feasibility study on new ecodesign measures for IoT devices should also be conducted. Indeed, market research estimated that 9.15 billion IoT devices were installed in 2018, with a projected increase to 41.6 billion by 2025 (IDC, 2020).

There is a need for cycle-wide circular economy aware design assisted by insights from Industry 4.0 applications such as digital twins and digital product passports. For this, the creation of a digital twin–digital product passport system is absolutely required and can only be enabled by Industry 4.0-based technology. It will, for example, enable traceability of products and materials so that the data-enabled practices described in Chapter 4.1 can be realised.

8.3. Implications for supporting companies with regard to their transformation to Industry 4.0, with specific focus on small and medium-sized enterprises and digitally enabled circular business models

This section concentrates on company level implications of a strategy aimed at a digitally enabled circular economy and impact reduction. It focuses specifically on the implications for SMEs with respect to a twin transition to a sustainable and digital economy.

The necessary dialogue between the (scientific) technological community that is focusing on Industry 4.0 concepts and the circular economy community should not forget the needs of a very relevant target group of their efforts, SMEs. These companies represent the backbone of most economies with around 25 million SMEs employing around 100 million people in Europe, making them one of the cornerstones of the EU economy. They generate more than half of Europe's gross domestic product (GDP) and play a key role in creating added value in all economic sectors (EC, 2020c). Supporting SMEs to successfully transition to Industry 4.0 and circular economy business models (CEBMs) is therefore pivotal. Small and medium-sized enterprises often conform to a more traditional and sometimes rigid business culture that does not adopt change easily. Although SMEs are particularly exposed to the consequences of the digital and socio-economic transition, they often lack sufficient financial and human resources to invest and innovate in the short term and hence need more time to embrace the transformation successfully. This is even more true as they are facing not just one major challenge, but several.

This chapter identifies seven areas that are key for technology based CEBMs to thrive, namely organisational management, financial support, digital infrastructure, access to information, markets and supply chain networks, political implications and consumers. The chapter also provides some recommendations on what companies should consider to facilitate the transformation process.

Organisational management

A company’s environmental culture is considered one of the biggest enablers for CEBM implementation. As in many SMEs the manager is also the company owner, the strategic decisions may mainly depend on one decision maker. In addition, conflicts of interest may arise because SME owners and managers might have different perceptions of future risks (Rizos et al., 2016). In this context, the importance of a good leadership style is crucial for the successful integration of a CEBM within Industry 4.0. Senior management should be both inspirational and transformative (Chauhan et al., 2021), and try to align interests. Ensuring an economic benefit for the company in addition to reducing resource consumption can be crucial in convincing management to make a massive shift in technology implementation (Khanzode et al., 2021). Moreover, the twin challenge of digitalisation and circular economy implementation, through a technology-based CEBM, needs to be properly communicated to the staff in order to develop a common purpose and a motivated working atmosphere. It is important to get employees on board, as the successful implementation of new technologies requires a skilled workforce. Around a quarter of SMEs in Europe report that the availability of skilled staff or experienced managers remains a major challenge, with a skills shortage being particularly acute in digitalisation and new technologies – around 35 per cent of the workforce has few or no digital skills (EC, 2020c). Consequently, employees need to be trained to tackle the new challenges that arise in the context of sustainable operations and Industry 4.0 technologies. The organisational culture should motivate employees to stay informed about emerging technologies and future challenges and promote creativity as well as open innovation culture (Chauhan et al., 2021). This could be achieved by providing regular training and continuous education on the one hand and adopting a leadership model that acknowledges the major challenges on the other. One such model that promotes intra-entrepreneurship and at the same time addresses responsibility issues, along supply chain networks, for example; the need for even greater effectiveness and efficiency, for example, with regard to concepts of Industry 4.0; and considers the social value added for society as a whole, is the Leipzig Leadership Model (Kirchgeorg et al. 2017). Furthermore, it is important that the application of technologies is also strategically aligned to an organisation's long-term goals. Indeed, the lack of effective strategic integration of Industry 4.0 with sustainability goals such as the circular economy may lead to unwanted consequences including rebound effects and even the failure of the organisation. The adaptation of strategic management models, such as those discussed can ensure such a long-term perspective.

Financial support

One of the most salient barriers for SMEs is the lack of capital and the fear of misinvestment to implement circular solutions. This perception can be increased manyfold in the face of the twin challenge of introducing circular *and* digital routines at once, when both fields are not well understood. Operations in a firm’s business can increase relative costs due to higher upfront costs, the cost of sustainably sourced materials, higher costs of operations, etc., requiring a substantial amount of time and investment (Rizos et al., 2016; R2PI Project, no date). Implementing a CEBM also demands continuous monitoring and improvement of the product’s lifecycle, forcing a company to allocate a significant amount of resources to keeping employees and customers committed. External financing through EU and state grants or through commercial banks is often not attractive because of the significant bureaucratic hurdles and the difficulty in obtaining the collateral or guarantees required by banks. As an example, in 2019, 18 per cent of SMEs in the EU did not receive the full amount of a planned bank loan, which is a huge disadvantage for SMEs as around 90 per cent of their financing needs are met by banks (EC, 2020c). Here, EU and government grants could facilitate access to funding by, for example, reducing bureaucracy in the application process, especially for SMEs, and providing the necessary collateral for banks. Recent EU projects such as Chambers for a circular economy – Actions to support SMEs' transition to a circular economy are evidence that there is an ongoing dynamic in the regulatory field that acknowledges the need for support (Burlizzi and Rosenmayr, 2020). The EC states in its SME Strategy for a sustainable and digital Europe that there is a need to diversify sources of finance. More private investment needs to be unlocked in Europe, for which the EC will advocate new ways of sharing risk with the private sector, through, for example, the ESCALAR initiative to increase the size of venture capital funds. As of 2021, InvestEU's SME window will support equity financing for SMEs and small mid-caps ([5]) in areas of particular policy interest to the EU, such as sustainability, digitalisation, innovation, deep and green technologies (EC, 2020c). Furthermore, subsidies for research, consulting and implementation of new CEBMs and their integration with concepts of Industry 4.0 should be offered specifically to SMEs in order to identify current challenges and dynamics (Cantú et al., 2021). Unlike multinational companies that can support the development of circular technologies through their research and development activities, SMEs are often dependent on the availability of existing technologies (Rizos et al., 2017).

Digital infrastructure and relevant competencies

With regard to infrastructure, SMEs need failure-free and fast internet if they are to implement Industry 4.0. The installation of an adequate network, especially in rural areas within the EU, should be accelerated and promoted by governments (Chapter 7). As new digital solutions rely heavily on access to public digital infrastructure, the latter should cover all geographical areas and support both high- and low-power/bandwidth networks (Climate-KIC, 2018). For trouble-free operation, it is fundamental for a company to acquire digital-specific skills in collecting, interpreting and using data, as a lack of data hinders optimised flow and traceability (Climate-KIC, 2018). Furthermore, a proper infrastructure also includes a sufficient and stable power supply without power blackouts. Small and medium-sized enterprises are often not large enough to run their own data centres or employ IT experts to provide and maintain a powerful IT infrastructure and therefore have to rely on outsourcing. Targeted, affordable and SME-specific IT consulting would help at this point and its financing should be supported. Fostering collaboration among SMEs with regard to shared IT service providers and experts as well as IT infrastructure can not only help to control costs, but also share relevant competences and knowledge, thereby speeding up the transition process and limiting financial risks (Cantú et al., 2021).

Access to information

As discussed, sufficient digital infrastructure is crucial to facilitate technology-based CEBMs. An established information exchange system between suppliers along the value chain or even between competing companies could facilitate data sharing and foster collaboration for co-production, innovation and effective end-of-life management of products through knowledge transfer and synergies (Rizos et al., 2017). Indeed, lack of access to data is one of the main barriers to enabling technology-enabled CEBMs, as private companies have little incentive to share their own data or they have operational reasons for protecting it. This could be addressed by providing SMEs with more open data sources on industrial activities and research and development to share innovations and enable horizontally or vertically integrated business partners to implement and disseminate a particular technology (Climate-KIC, 2018). Unlike large companies, SMEs might not have sufficient hardware or data volume to process complex data. It is therefore useful to provide data in a simple format and as reduced as possible, so that SMEs do not have to bowdlerise the data set, which would itself take up further resources. Data should thus only contain the relevant aspects that are useful for further processing in CEBMs. This particularly applies to external data (Section 8.1). If the data are generated in proprietary processes, the required format for its processing for up- and downstream firms or partners should be easy to implement for SMEs – no special hard- or software, for example, should be needed to transfer data. A common standard on the EU-level could be useful if it is easy to implement. Furthermore, SMEs report that there is a lack of access to streamlined data and that data from public institutions in particular, on, for example, recycling, is difficult

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[5] Typically companies with a market capitalisation of USD 2-10 billion

to gather and use because the methods of collection and dissemination are different (Climate-KIC, 2018). This is where the European Strategy for Data will play an important role, as the EC aims at broadening data accessibility to enable the flow of data between companies and governments through the establishment of common European data spaces for trustworthy and secure data exchange. The focus will be on ensuring fair access for all companies, especially SMEs (EC, 2020c).

Markets and supply chain

As SMEs have little bargaining power and powerful stakeholders across the value chains may resist change (Rizos et al., 2017), it is essential for SMEs to network and collaborate with other SMEs. Ultimately, the successful implementation of CEBMs requires the cooperation of all parties along the supply chain. Asymmetric bargaining power is also reflected in unfair business practices towards SMEs, such as restricted access to data, but also in late payments: around 60 per cent of companies in the EU are not paid on time and these late payments are responsible for a quarter of insolvencies among SMEs in the EU. The EC wants to tackle this issue more strictly by equipping the Late Payments Directive with strong monitoring and enforcement mechanisms (EC, 2020c). The lack of support from the supply and demand network is one of the main barriers cited by SMEs. Suppliers and service partners may be reluctant to get involved in innovative circular economy processes owing to perceived risks to their competitive advantage or due to a mindset that does not prioritise circular economy practices (Rizos et al., 2017). More awareness raising and education on the long-term benefits of CEBMs among supply chain partners might be needed. Incentives, such as more favourable long-term bilateral contracts with better conditions, could be considered as well. Particularly for very small companies, one of the major barriers is the lock-in of distribution channels, as well as the unpredictable return flow of materials, which hampers the efficient retrieval of products, in circular practices involving the remanufacturing and reuse of products (Rizos et al., 2017). Here, it would be important to open up new distribution channels and for the market to be guaranteed a minimum quantity of available material, ensured by the government. As many digital solutions are developed in closed innovation, it is crucial for companies to establish partnerships with all stakeholders to increase the interoperability of datasets. Indeed, lack of interoperability can increase the risks and costs of integrating new software into existing corporate IT architecture (Climate-KIC, 2018).

Political implications

There is a need to implement a concrete, coherent, strict and yet to some extent flexible legislative framework within the European market, such as in the EU waste legislation for the classification of waste material to facilitate waste management and recovery between Member States (Rizos et al., 2017). This should include adequate data management legislation that provides legal certainty by, for example, promoting standardised data formats. Complex regulatory frameworks that require companies to access legal or technical expertise to remain compliant can, however, be overwhelming for small businesses (Climate-KIC, 2018). Regulation that sets targets for the circular economy can open the door for the deployment of digital solutions (Climate-KIC, 2018). Since economic uncertainties discourage SMEs from investing (Braun et al. 2018), governments can address this by paving the way for a circular future through incentives and regulation, thus providing certainty for businesses to invest. Furthermore, economic benefits of CEBMs need to be communicated (Braun et al. 2018), both in terms of costs and competitive advantage (Cantú et al., 2021). Finally, monitoring and regular reports should be compulsory and not overcomplex but easily to develop through key performance indicators (KPIs) (Braun et al., 2018). Here, administrative burdens need to be reduced as green business practices such as monitoring and reporting environmental performance data are often considered complex and barely affordable for SMEs (Rizos et al., 2017). EU policy makers are, however, aware of these obstacles and the EC is strongly committed to reducing current and future regulatory burdens for SMEs, for example, through the regulatory fitness and performance (REFIT) programme, under which the EC systematically reviews existing EU legislation to reduce burdens and simplify legislation. The EU SME Envoy and the network of national SME Envoys play a key role in this respect, as they promote SME interests and encourage SME-friendly regulation and policy-making in all EU countries (EC, 2020c).

Consumers

There is still insufficient consumer awareness of the benefits of green products and a lack of understanding of what circularly sourced products are. When it comes to digital solutions that connect customers and businesses, they need to be intuitive and accessible. There is a greater chance of getting the customer on board if the interface is easy to use (Climate-KIC, 2018). Digitally enabled consumer information can then contribute to more informed choices on the side of (private) end consumers. In this case, regulators can help motivate consumers to change their demand in favour of sustainability, and additionally, the government can also run public awareness campaigns on digitalisation and sustainability (Braun et al., 2018). This can lead to substantial pressure from the demand side, which may be needed for smaller organisations to meet sustainability criteria or develop a CEBM (Rizos et al., 2017). To make technology-based CEBM products attractive to customers, products and services need to be competitive on price, quality and convenience in the long run, and they need to be scalable (Climate-KIC, 2018). Furthermore, this needs to be combined with a sufficient shift towards an innovation-friendly mindset among consumers. Appropriate communication to improve trust in digital business models or technologies such as AI should be developed to increase acceptance on the demand side. This is not only to encourage more sustainable consumer behaviour, but also to increase trust in technology and Industry 4.0.

Box 8.1 Example of a circular economy business model in manufacturing industry

Remanufacturing: circular water meters

- **Company:** Lorenz Water Meters is a German medium sized, family-owned business located in the southern state of Baden-Württemberg
- **Vision:** The company aims to use industry 4.0 technology to remanufacture water meters, save resources and maximise efficiency
- **Value proposition and business model:** the smart water meters of the medium-sized family-owned company enable precise flow measurement, efficient and secure data transmission and intelligent analysis in water networks. This prevents water wastage and significantly simplifies the processes of water suppliers, municipalities and metering services. As the water meters are made of high-quality materials and their longevity and reusability is ensured and Lorenz can take them back after use and reuse them or their components within a remanufacturing process.
- **Circular economy principles:** the product design and entire production process serve the purpose of enabling the remanufacturing business model. At the heart of the idea is to sell the same product several times without loss of quality, but with a high degree of value added in each product use cycle.
- **Impact:** Circular Smart Eater Meters save hundreds of tonnes of raw materials and millions of kilowatt hours of electrical energy every year, as well as the associated environmental effects and carbon dioxide emissions. Significantly lower material costs for production makes production in Germany competitive with low-cost products from low-wage countries.
- **Further Information:** https://www.lorenz-meters.de/en/aktuelles/circular-economy-and-smart-metering-lorenz-receives-german-innovation-prize-for-climate-and-environment/

9 Conclusion

This study analyses the potential of Industry 4.0 and its underlying technologies to support the reduction of environmental impact of manufacturing. A focus was set on the introduction of a circular economy as the overarching strategy for reduction approaches. This was based on an analysis of current circular economy goals and policies, and a delineation of Industry 4.0 as both a technological concept and a new industrial strategy. From this, ensuing benefits were deduced and it was shown that these specifically hinge on the creation and provision of data and information by Industry 4.0 technologies. These can subsequently be used to improve existing practices to promote a circular economy or devise new instruments for impact reduction, ranging from circular design to supply chain reconfigurations based on intelligent products and processes. The nexus of the circular economy and Industry 4.0 in creating such benefits was illustrated by ten case studies. These findings suggest a close connection between a circular economy and Industry 4.0 as envisioned by the scheme of a twin transition by the EU, but an investigation into the current status of both developments revealed that this was still at a very early-stage. While high hopes on the utilisation of Industry 4.0 to indeed facilitate a circular economy were expressed on the side of circular economy proponents, it was found that, with few exemptions, Industry 4.0 is agnostic of its potential role for resource efficiency and impact reduction, and an awareness for this is only just emerging. Based on these findings, key enabling factors to realising the potential of Industry 4.0 were identified and presented along with the current barriers to it. Implications were then drawn on three levels:

1. implications for the design and shaping of future systemic development to create a widespread amalgamation of circular economy and Industry 4.0;
2. requirements on the micro level with a specific view on the inclusion and enablement of SMEs as well as CEBMs; and
3. inferences for European Policies.

This concluding chapter provides more overarching insights and highlights needs for further research beyond the implications discussed in the previous chapter which focused on imminent and political measures.

Limitations of this study are threefold. Firstly, it was not possible to obtain or develop more quantitative data beyond that which could be found through desktop research and interviews. This was true especially for the benefits of Industry 4.0 and the case studies presented. A more distinct quantification of the benefits, potentials and pitfalls of the approaches identified is an important desideratum revealed by this study. Secondly, this study did not include an analysis of the social dimension of the twin transition. Given that a new industrial regime marked by a digitally-enabled circular economy may profoundly impact many Europeans' ways of life and work, this notion may require distinct and continuous investigation. Thirdly, this study should be seen as an early investigation into this emerging field. It was able to reflect the early phase that the twin transition is in, and to highlight the promise and real relationship of a circular economy and Industry 4.0. It revealed both the promises and the many open questions that exist and the many, often rather ground laying measures that are still required. Further research will have to look more deeply into the details of this transition. Issues surrounding the use of data, access to data, and infrastructure may be the most urgent in this regard.

Several overarching findings were made. They emphasise the benefits that a circular economy may derive from digitalisation in terms of both enabling circular economy practices and scaling them. It was shown that many new circular economy approaches can only be created by the application of Industry 4.0 and digital technologies. Furthermore, many existing circular economy strategies, such as refurbishment or recycling, can greatly profit from the data and knowledge generated by digitalisation. With their help, existing information deficits can be lowered, which could result in a reduction of transaction costs, an improvement in market transparency, and a lessening of reservations about circular economy-related products and services. At the same time, it was found that a digital circular economy transcends the borders of existing industry and sector classifications. For example, it was shown that Industry 4.0 concepts can be used to increase circularity and resource efficiency in farming and housing. With reverse logistics, a move from linear supply chains to value networks could be accelerated. Future approaches to the circular economy should be aware of these circumstances which, *inter alia*, may imply a less sectorally focused approach to circular economy policy.

One further key lesson should be emphasised here. On the system level, the indication of two as yet largely distinct developments stresses the nature of the twin transition as a twin challenge. While there are promises and existing examples, a concrete and widespread unified emergence of digitally enabled resource and energy effectiveness on the basis of a circular economy is still far from a reality. The analyses undertaken here, however, show the existence of many promising bottom-up approaches and technologies as well as a general understanding of the opportunities provided by the so-called twin transition on the level of political decision makers in Europe. A major and urgent necessity is therefore the action-oriented creation of a unified approach to the circular economy and Industry 4.0. The urgency derives from the observation that, without digital technologies, it will not be possible to meaningfully scale up the circular economy, especially not in a digital world. At the same time, Industry 4.0 without a clear steer towards the circular economy is indeed a danger to climate protection and impact reduction goals as it may trigger tremendous effects of unchecked resource consumption. Consequently, what is now expressed as a twin transition should be seen and managed as one transition throughout. While not every circular economy approach may require digitalisation and not every digital development is relevant to a circular economy, the overall connectedness dominates. Open questions for enablement and co-evolution are not just in the detail, but ground-laying issues that need to be addressed. This includes most importantly clear measures and steering guardrails at the systemic level and enablement at the micro level. New tasks therefore emerge for the management of the transformation towards a resource and energy effective economy that will be both digital *and* circular. The inclusion of digital aspects implies, for example, addressing notions of data governance that weigh the need of privacy and intellectual property protection against the opportunities ensuing from more open data provision along supply chains, value creation networks and among private consumers. Answering the ensuing questions currently requires more exploration.

It is important to acknowledge that time is of the essence in several dimensions. In terms of scale, digital technologies are more advanced than the circular economy, as the automation of manufacturing has been going on for several decades now and Industry 4.0 is only the latest level of development. Every further investment agnostic to circular economy may lead to a path of dependencies on a wrong trajectory, enacted by sunk costs and factor specificity. Merging both strategies into one therefore has to happen soon. And while Industry 4.0 and digitalisation are developing fast, we are also in a decisive decade when climate protection and resource reduction goals must be achieved if the world is to remain within the planetary boundaries and avert disaster. The major resulting question is then how can this transition and the realisation of the potential of a digitally enabled circular economy be managed? Next to the obvious fact that research, development and innovation for this need to be harnessed, an even more fundamental necessity emerges. Given the speed of both technological development and the urgent need for action in an exceedingly complex environment, it may be necessary to constantly rethink the approaches taken to advance the transition. Acknowledging the fact that its speed can hardly be reduced, the political and administrative cycle of monitoring, understanding and steering thus needs to be continuous and fast to maintain an overview. At the same time, it will have to be accepted that a full understanding of the developments before taking action may never be achievable. Exploration and management may have to happen with agility in a piecemeal way without losing sight of the greater goals. Such new ways of politically managing the transition require deeper research. However, digital technologies can help in all these aspects, too, by, for example, enabling fast and large-scale analyses of current developments. The intertwined concepts of digital twins and digital product passports can take a decisive role here. They can enable data-based circular economy strategies and at the same time allow real-time monitoring of the circular economy's development, ideally directly linked to the assessment of environmental impacts and implications. This report has shown, however, that many challenges concerning their widespread adoption are still to be solved including issues of design, infrastructure and data governance. Further research in this area is therefore absolutely necessary.

Key messages

The twin transition needs guiding and the co-creation of an integrated approach towards sustainability

- The green and digital transitions of EU industry are today characterised as a twin transition. This should be seen as one challenge in the industrial transformation towards sustainability. It needs to rely on an integrated approach, based on co-created transformation pathways. If not considered as one single challenge, the opportunity of reaching both climate neutrality and EU industrial competitiveness will be missed.
- Awareness for the circular economy is only just emerging in the digital community of Industry 4.0 manufacturing, while the sustainability community already has high hopes that digital technologies will accelerate the transition to a circular economy. A close and continuous dialogue between manufacturing, information and communications technology (ICT) industries, and sustainability communities, together with a and strong push of the Industry 4.0 landscape towards environmental impact reduction, is required.
- The technological requirements for a synergetic convergence of green and digital transitions specified for a circular economy and Industry 4.0 need to be met. Creating standards for data interoperability, standardised interfaces and a clear definition of the DPP are among the immediate requirements for this, as well as the provision of a dedicated and functioning ICT infrastructure.
- The twin transition is systemic. Efforts need to be made at all levels, and transformation pathways need to be created with and for industry, research and public authorities as well as societal and sectoral actors.

Digitalisation for transitioning to more sustainable production systems

- Digitalisation by Industry 4.0 has the potential to provide the overall architecture, concepts and technologies for enabling circularity and transitioning to a more sustainable production system. Such approaches, however, need further research and development, while existing approaches need scaling.
- Industry 4.0 and its digital technologies can provide the conceptual and technological basis for the DPP as envisioned by the EU. The DPP is a key ingredient to enable circular economy and sustainable decision making.
- Without digital technologies, the circular economy will not be able to be meaningfully scaled up, especially not in a digital world. At the same time, Industry 4.0 without a clear focus on a circular economy is indeed a danger to climate protection and impact reduction goals.
- The window of opportunity is open now to initiate this technological development in the current decisive decade. Any delay will cost precious time in solving immediate challenges related to climate change and circular economy. Moreover, the risks of disadvantageous lock ins, stranded assets and retrospective sunk costs increase with the rapid advance of digitalisation without a clear link to environmental impact reduction.

Need for further research

- Digitalisation has its own considerable environmental risks. General problems concern the respective technologies' needs for resources and energy. These need close monitoring and additional research to understand their environmental impacts. Ensuring the sustainability of digital manufacturing is key. Any rebound effects need to be prevented. Environmental assessment methodologies need to evolve and provide the basis for future indicators in the quantification and measurement of actual (and net) benefits.

- The progress of digitalisation and the transition to a circular economy in Europe needs to be understood and measured to ensure cohesion. Relevant metrics and data streams need to be identified.
- The speed of digitalisation and the imminence of many environmental challenges – climate change, toxins, plastic pollution, etc. – may require new strategies for fast and effective intervention from political and administrative decision makers.
- Digital circular business models need to be better understood and enabled. As digitalisation will facilitate the shift towards a more service-based manufacturing, the viability of integrating circularity parameters that enhance the service value proposition should be further investigated.
- The progress of digitalisation and the transition to a circular economy throughout European countries and in Europe needs to be measured and understood as a whole to ensure cohesion.

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Annex

Standardised format for cases

<table>
<tr><th colspan="2">Name of the example</th></tr>
<tr><td colspan="2">Introduction: A short paragraph introducing the case to the reader</td></tr>
<tr><td>Output/goals for improvement:</td><td>Underlying technologies</td></tr>
<tr><td>This item presents the different ways that the technological solution presented contributes to sustainability. It is stated if the environmental benefits are direct or indirect. If data or estimations on quantified effects are available these are provided.</td><td>This item lists the underlying technologies needed or used for this case.</td></tr>
<tr><td>Data transformation level ↔ resource optimization capability</td><td>Requirements and preconditions</td></tr>
<tr><td>This item describes the technology according to the categorisation presented in Figure 3.3.</td><td>Technologies, regulation and other aspects that are prerequisites for the presented technology to be used are presented under this item. For example, most technologies are integrated into a digital ecosystem and need certain other technologies, such as (broadband) internet access, a (broadband) cell phone network or the installation of sensors, to be available so they can function.</td></tr>
<tr><td colspan="2">Other aspects</td></tr>
<tr><td colspan="2">important other aspects that do not fit under one of these items but need to be mentioned to provide a complete picture of the presented technology are given here.</td></tr>
<tr><td colspan="2">State of development</td></tr>
<tr><td colspan="2">The case’s state of development and the state of development of similar solutions are rated. They can range from theoretical concepts and early prototypes to solutions that have been on the market for several years.</td></tr>
<tr><td colspan="2">Sources</td></tr>
<tr><td colspan="2">The sources for the information presented are provided under this item.</td></tr>
</table>

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